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The Snail Progression of Ethical Instruction: Nurturing Ethical Mindsets Across the Biomedical Engineering Curriculum

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Abstract

In response to the growing importance of ethical consciousness in the realm of biomedical engineering, we present a comprehensive educational initiative designed to seamlessly integrate ethics across the entire curriculum. This endeavor involved close collaboration with faculty members and the provision of summer salary support to develop substantial ethical thinking exercises within key technical courses, including Modeling Cells and Cellular Systems, Imaging Systems, Instrumentation, Biomaterials, and senior capstone design classes. This initiative, aptly named the "Snail Progression of Ethical Instruction," introduces a structured framework spanning four years, each emphasizing essential ethical virtues. Through this, we foster an appreciation among students and faculty on ethical codes of conduct and character traits we hope biomedical engineers will uphold in their careers, preparing them to navigate complex ethical dilemmas with confidence and integrity.

The journey commences in Year 1 with a focus on humility. Students are encouraged to balance the inherent challenges of failure with the pursuit of truth, laying the foundation for a humble and resilient ethical mindset. Year 2 amplifies the journey with curiosity, urging students to explore the origins of materials and contemplate the consequences of their use, irrespective of utility. This curiosity fosters a deep understanding of ethical implications, encouraging critical thinking in material selection and application. In Year 3, the focus shifts to imagination. Students are challenged to envision the far-reaching consequences of innovations, emphasizing the intricate web of system-wide effects. This imaginative exploration equips students with the ability to anticipate and address unintended consequences, instilling a sense of responsibility in their innovative endeavors. Year 4 revisits complexity, underscoring the necessity of deep knowledge, skill integration, and practical experience in ethical decision-making. Good engineering design is viewed as a holistic process, demanding a nuanced understanding of ethics that can only be achieved through a multidisciplinary approach.

Through focus groups and survey reports of our students, we begin to quantify and compare our longitudinal progress in integrating ethical inquiry within engineering technical knowledge. Our surveys focus on characterizing the climate of students' perceived value of ethics while our focus groups demonstrate student ethical knowledge. We aim to demonstrate a positive relationship in both over time.

This initiative not only enriches the educational experience but also molds students into ethical leaders capable of upholding the highest standards of integrity within the field of biomedical engineering. The Snail Progression of Ethical Instruction stands as a testament to the transformative power of structured ethical education, ensuring that the next generation of biomedical engineers is not only technically proficient but also ethically astute, embodying the virtues of humility, curiosity, imagination, and complexity management in their professional journeys.

Introduction:
In the dynamic realm of biomedical engineering, the demand for innovation and progress is unrelenting. As aspiring biomedical engineers embark on their educational journey, it becomes increasingly important to equip them not only with technical prowess but also with a profound sense of ethical responsibility. While ABET accreditation and expected student outcomes require students to "[…]recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts" [1], we contend that beyond certification lies the university's pivotal role in forming professional engineers who comprehend the ethical implications inherent in the development of medical technologies. Recent high-profile cases in biotechnology, such as Theranos's faulty diagnostics [2] and He Jiankui's gene-edited babies [3], underscore the heightened significance of engineers' ability to identify ethical dilemmas, discern judgments swiftly in the rapidly advancing technological era, and intentionally act with human-centered engineering design [4] at the core of engineering practice.

In contrast to programs that introduce ethical instruction in introductory courses, or institutions where ethics is delegated to non-engineering entities, we advocate for a more integrated approach to teaching ethical content. We posit that embedding ethical instruction within the biomedical engineering curriculum is essential. This approach ensures that students forge a meaningful connection between their burgeoning technical expertise and the ethical responsibilities integral to their roles as future biomedical engineers. Table 1 (adapted from Bairaktarova & Woodcock [5]) summarizes approaches undertaken by undergraduate engineering departments to leverage teaching of ethical knowledge. Mitcham & Englehardt [6] have reviewed efforts at institutions, including the Colorado School of Mines, Illinois Institute of Technology, and Utah Valley University to develop "ethics across the curriculum" (EAC) in engineering; however, these approaches leverage non-engineering department ethics courses in general education requirements and do not emphasize technical content integrated with ethical decision making.

Table 1: Approaches and challenges for teaching ethics to undergraduate engineering students

	Ethics course within social sciences/humanities department	**Modules in introductory and capstone design courses**	**Ethics Across the Curriculum (a.k.a. Embedded Ethics)**
Approach	General Engineering Ethics: Safety, Welfare, Equity	Design-focused interventions and service to client/community	Brief discussions, typically centered around case studies
Topics	Moral theories and argumentation, consequentialism vs. deontology	Intellectual property, conflicts of interest, competition, sustainability, privacy	Broader themes built off technical content to show connections between ethics and practice
Challenges	Some programs may offer major-specific ethics, but otherwise broad	May be relevant to practicing engineers, but fails to leverage the full educational track	Takes effort to integrate into rigorous engineering coursework and faculty buy in

Character Education and Moral Virtues in Engineering Education:
While many engineering (and introductory) ethics courses approach balancing moral principles from two dominant theories of consequentialism (a.k.a. utilitarianism) and deontology (a.k.a.

Kantian ethics, duty- or rule-based ethics), these frameworks do not prepare engineers to resolve dilemma in our increasingly complex world [7]. Such formulaic approaches to ethical reasoning may focus too much on the actions that the engineers take and too little on building their intuition that will allow them to resolve dilemmas. Jon Schmidt [7], Charles Harris Jr. [8] and Richard Bowen [9] argue that these two frameworks do not recognize the vocation of engineering as valuable in helping people to design for humanity, and thus do not serve the same purpose for engineering ethics curriculum.

In recent years, significant attention has been afforded to virtue ethics and moral character education as a better framework for preparing undergraduate engineers for their professional responsibilities [10]. Rooted in Aristotelian ethics, virtue ethics prioritizes moral character and the traits of the individual as central to a well-lived life [11]. In contrast to consequential or deontological ethics, virtue ethics and character formation are focused on how an individual lives versus individual actions, yet the education and positive character development can be taught by modelling such behaviors [12]. Within biomedical engineering, there is a focus on practical wisdom (i.e. phronesis) in the medical ethics community "which enables us to perceive, know, desire and act with good sense" [12]. A better approach is to build engineering curriculum that combines intellectual virtues (e.g., curiosity, critical thinking, autonomy), moral virtues (e.g., compassion, humility, integrity), civic virtues (e.g., awareness, service), and performance virtues (e.g., motivation, perseverance, resilience, teamwork) to create responsible, discerning, and thoughtful professional engineers.

Conceptual Framework for Embedded Ethical Learning in Biomedical Engineering Curriculum:
Fink's Significant Learning Outcomes [13] emphasize the complex nature of education that impacts various dimensions of learning that integrate with previous and future coursework. Fink outlines six categories of significant learning to instill in professional engineers:

- <u>Foundational Knowledge</u> connects with intellectual virtues of critical thinking.
- <u>Application</u> connects with intellectual virtues of curiosity and reasoning.
- <u>Integration</u> connects with performance virtues of teamwork.
- <u>Human Dimension</u> connects with civic virtues of citizenship, community, and service.
- <u>Caring</u> connects with moral virtues of humility, compassion, and justice.
- <u>Learning How to Learn</u> connects with intellectual virtues of reflection.

When compared to other taxonomies of learning and ethical frameworks, Fink's Significant Learning Outcomes and virtue ethics embraces the educator's role in developing wisdom rooted in context, experience, & good engineering practice. As an integrative taxonomy that has been applicable in other engineering disciplines [14], we utilize this conceptual framework to emphasize that ethics and character are "coming along for the ride" in professional engineering practice.

The 'Snail Progression of Ethical Instruction'
In this paper, we propose the Snail Progression of Ethical Instruction (Figure 1) as a novel way to embed ethical content across the biomedical engineering curriculum. As biomedical engineers, our students are uniquely poised at the interface of technology and human health and therefore the ethical challenges are uniquely unpredictable and impressively varied. Biomedical engineers will encounter machine learning models contaminated with significant bias [15], to new drugs

with limited effectiveness, to implantable or wearable technologies that impact human health. Our students need to be ready for the complexities we can only imagine.

The progression starts in freshmen year where students pursue a design project for a real client that encourages students to embrace failure through learning, fostering humility and encouraging students to discover the complexity of the world they live in. In year two the progression continues by encouraging students to develop their curiosity, uncovering how materials are sourced for biomedical devices and implants and forcing them to think of the consequences of various materials choices on cost, efficacy, and utility [16]. Students develop ethical reasoning by exploring recent biomedical engineering case studies that have been carefully collated such as biomedical engineering devices such as Norplant have been used in unethical ways and students discuss if the engineer has culpability when a device they manufacture is used improperly [17]. In year three, students continue to explore the complexity of the ethical challenges they will face with recent examples including discussion of Alzheimer's drugs and the cost of pharmaceutical interventions as well as medical technologies that are only accessible to the wealthy [18]. The last year, students revisit ethical complexity with a culminating design experience that forces them again to embrace failure and utilize their technical knowledge along with their ethical reasoning skills to develop a biomedical device or new biotechnology tool where they make their own ethical choices at every turn. In this way, ethical content can build across all four years of the biomedical engineering curriculum and work to build student character and prepare biomedical engineers for the many and varied ethical challenges they will face in their careers.

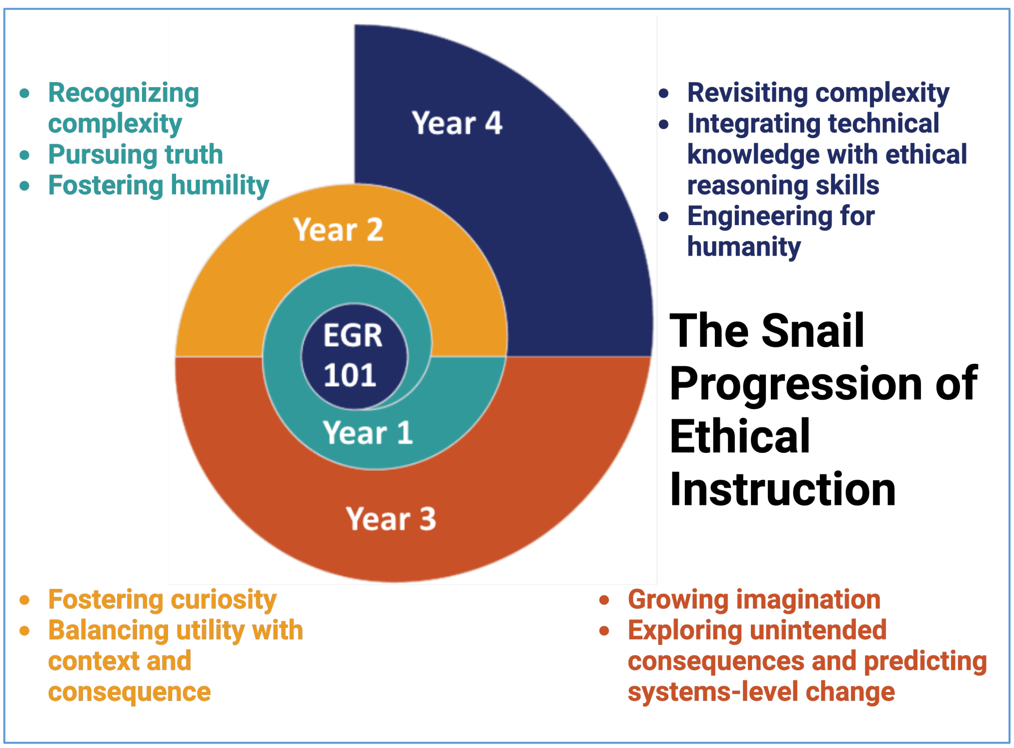

Figure 1: The Snail Progression of Ethical Instruction from the first course in Engineering Design to the final year of capstone design. Virtues and moral growth are slowly radiating from the central point to the professional formation of biomedical engineers that foster curiosity, humility, and imagination in their practice.

Methods:
This study employed a systematic approach to integrate ethical instruction into the undergraduate biomedical engineering curriculum, particularly focusing on courses with relevance to Biomedical Instrumentation, Biomaterials, Modeling Cellular/Molecular Systems, and Medical Imaging. The initiative began during the annual end-of-year reviews for each required undergraduate course, where it was proposed to embed explicit ethical discussions and content throughout the curriculum. This process was convened starting in the Summer 2021:

1. **Selection of Courses:**
    - During the end-of-year reviews, courses deemed suitable for ethical instruction were identified by current faculty that teach them.
    - For the first iteration, a junior-level class BME 354L: Intro to Medical Instrumentation and a sophomore-level class BME 221L Biomaterials were initially chosen due to their alignment with important biomedical ethics principles as well as the time of intellectual development for students, and were considered as test cases for future course expansions.
2. **Faculty Collaboration and Development:**
    - Over the subsequent summer, a faculty cohort, guided by an ethics expert from outside engineering, convened to initiate the development of ethical modules and learning exercises with engineers in mind.
    - The focus was primarily on identifying ethical content for the medical instrumentation and biomaterials classes that presented ethical and character dilemmas.
    - Faculty members teaching these classes actively participated in the collaborative development process and attended a book club on ethics guided by the ethics expert to improve faculty comfort with ethical content and with teaching ethical concepts.
3. **Initial Implementation:**
    - The developed ethical modules and learning exercises were successfully implemented in both courses following the first summer.
    - The effectiveness of these modules was assessed through qualitative feedback and iterative improvements, discussion with students, and reports from faculty.
    - ABET Learning outcomes 2 and 4 data was acquired for both BME 354L and BME 221L.
    - As other faculty taught these required courses in the spring semester, handoffs to other professors was carefully crafted to clearly communicate the work that had been completed and connections were made to bridge the gap in successive semesters.
    - In some cases, additional instructors were brought in to cover ethical modules.
4. **Expansion to Additional Courses:**
    - Encouraged by the positive outcomes, the following summer saw another faculty group convene to extend the integration of ethical instruction.
    - A sophomore-level Modeling Cellular/Molecular Systems and junior-level Medical Imaging course were selected for the expansion, again due to their alignment with biomedical ethics principles.

- This phase involved bi-weekly meetings, incorporating readings on ethics, and discussions led by engineers to foster a comprehensive understanding of potential ethical dilemmas that could successfully be embedded in the curriculum.

5. **Development Process:**
    - Course content, homework exercises, and discussion points were collectively developed, ensuring alignment with the engineering disciplines and real-world ethical challenges.
    - Character formation and the role of virtues such as curiosity, humility, and discernment were discussed as to how to embed these character traits through projects or problem-based learning that allowed for ethical learning outcomes to be achieved.
    - Faculty worked to ensure the ethical principles across both courses were distinct, yet complementary to the learning performed in the prior courses.
6. **Implementation Assessment:**
    - Ethical modules were implemented in the expanded set of courses to gauge their impact.
    - Ongoing assessments, student feedback, and faculty reflections were collected to refine the ethical instruction continually.

This approach aimed to systematically incorporate ethical instruction across the engineering curriculum, promoting a holistic understanding of ethical considerations across a wide variety of biomedical engineering disciplines. The collaborative and iterative development process ensured the relevance and effectiveness of the integrated ethical content.

To quantify the effect of this model on our students, we sent out a department wide survey using Qualtrics modeled after the 'Mind the Gaps' study done by Robert McGinn [19] between 1997-2001, 25 years prior to our work. This study was approved by Duke University Campus Institutional Review Board (IRB #2023-0381) at a private university in the southeastern United States. Our goal was to measure how our student's perception of ethics changes as they progress through our curriculum. In particular, we modified questions from the original McGinn survey to reflect a biomedical engineering focus as outlined in a previous conference proceeding [20]. Our survey consisted of 46 students with had a completion rate of 56.5% (26 students). Of these 46 students, 12 were sophomores, 18 were juniors, and 16 were seniors.

Results:
After three summers of work across a diverse array of biomedical engineering faculty, we have reached a steady state in terms of ethical instruction at our institution. Ethical instruction has been incorporated into four required BME sophomore and junior level courses.

Our survey results are as follows. Including demographics, we asked the students 25 questions. Three questions of particular interest are:

> **Q14:** "To what extent has your undergraduate education helped prepare you to thoughtfully and effectively address possible engineering-ethical challenges you may encounter in your career?"

Q22: "In what courses, if any have you seen (ethics) being demonstrated or taught?"

Q23: "In the course of your biomedical engineering education at Duke, to what degree have you gotten the message to the effect that there is more to being a good engineering professional in today's society than being a state-of-the- art technical expert?"

In response to **Question 22**, students listed the following courses as ones where ethics was demonstrated or taught.

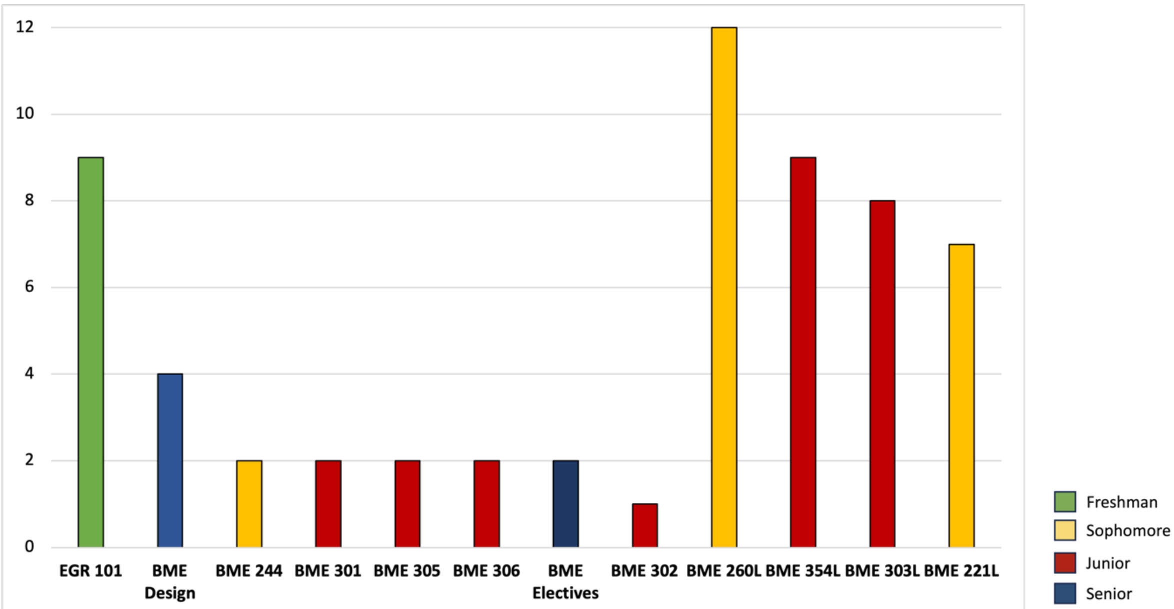

Figure 2: Student responses to what courses they have seen ethics taught in. The legend to the left outlines which year each course belongs to. Courses BME260L, BME354L, BME303L, and BME221L (right) are the target courses for ethics incorporation.

Table 2: Percent of students to respond affirmatively for ethics in BME course by year

Seniors saw ethics in…	Percent of Students	Juniors saw ethics in…	Percent of Students
BME221L	36.4% (4/11)	BME221L	37.5% (3/8)
BME260L	36.4% (4/11)	BME260L	25.0% (2/8)
BME303L	36.4% (4/11)	BME303L	50.0% (4/8)
BME354L	45.5% (5/11)	BME354L	50.0% (4/8)

Given the cohort of survey students covering multiple years and timing of students enrolling, we broke down the student responses in Figure 2 to show the identified courses of ethics exposure. In addition, given the implementation of the program, it is possible for students in each year to have missed the introduction points, especially for the senior 4th year students. This was not an original question on the McGinn study and is used as an internal metric for success of program.

The McGinn study did ask survey respondents in question S8: "Has any engineering-related ethical issue ever been *discussed* (not just mentioned) in any of your technical engineering classes at Stanford?" (emphasis in original McGinn survey), which best matches to this question. Students enrolled in McGinn's class reported an overall response of 12/56 (21.4%), while a class survey of peers outside of the class reported 50/183 (27.3%) in the affirmative. With modest gains from the McGinn study, we are assured that more BME students are discussing ethical issues in technical courses beyond a mere mention of its important in practice.

The following responses were given for **Question 14**. There responses are further broken down based on school year and reported as an average response score.

> ***Q14:*** *"To what extent has your undergraduate education helped prepare you to thoughtfully and effectively address possible engineering-ethical challenges you may encounter in your career?"*

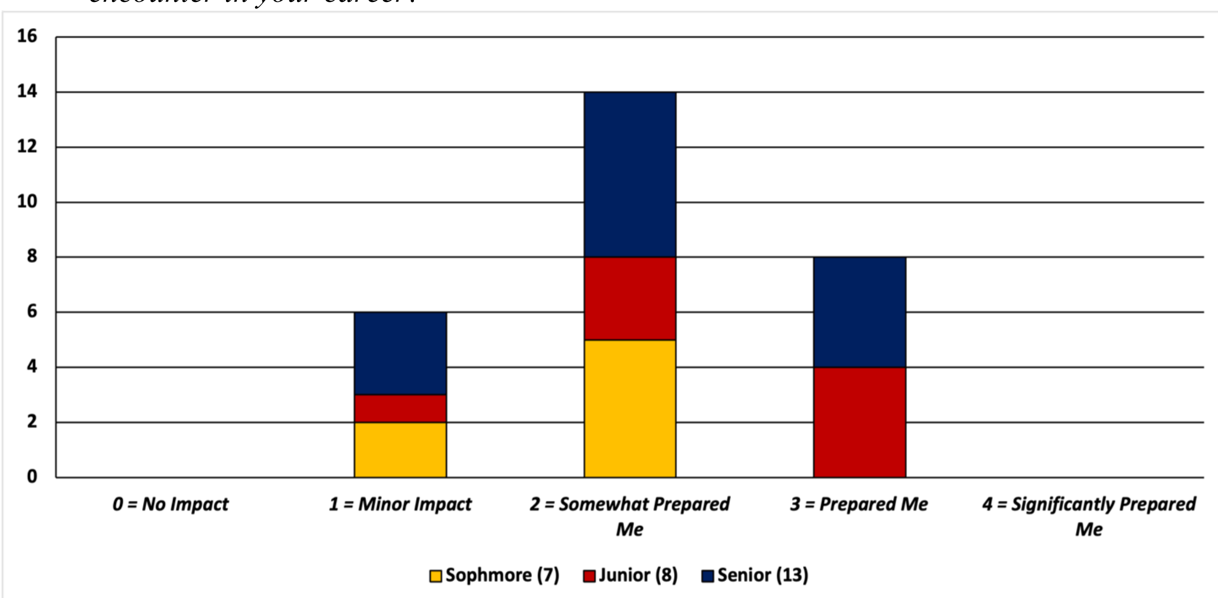

Figure 3: Student responses to what extent they believe their undergraduate education has prepared them for ethical challenges they may face in their future careers. A) This table represents the breakdown of responses by year in school as well as their average response. B) The graph depicts the overall landscape of student answers.

Year in School	**Average Response**
Sophomore (7)	1.714
Junior (8)	2.375
Senior (13)	2.077

In response to questions 14 and 23, students were asked to rank their responses on a Likert scale of 0-4. (0 – *Not at all*, 1 – *A little bit*, 2 – *Somewhat, 3 – A good deal*, 4 - *A great deal*).

This question is slightly modified from the McGinn study as question S13: "*How much* has your undergraduate education helped prepare you for coming to grips thoughtfully and effectively with engineering-ethical challenges that you might encounter in your career?" (Emphasis our own to show difference in original) Using the same 0-4 Likert scale, students enrolled in McGinn's class in 2001 reported an average response of 1.084 (n=59) while outside respondents had an average response of 1.623 (n=183). Our reported average of all survey students is 2.071 (n=28). In addition, out of the McGinn study of in-class students, only 6.8% reported that they felt "a good deal" or "a great deal" prepared for engineering-ethical challenges, while our survey shows 28.6% (Figure 3). It is important to note that McGinn's study is not broken down by engineering discipline, and this may speak to other elements of a BME's professional formation with other ethics courses beyond the BME curriculum.

The following responses were given for **Question 23**. There responses are further broken down based on school year and reported as an average response score.

> ***Q23:*** *"In the course of your biomedical engineering education at Duke, to what degree have you gotten the message to the effect that there is more to being a good engineering professional in today's society than being a state-of-the- art technical expert?"*

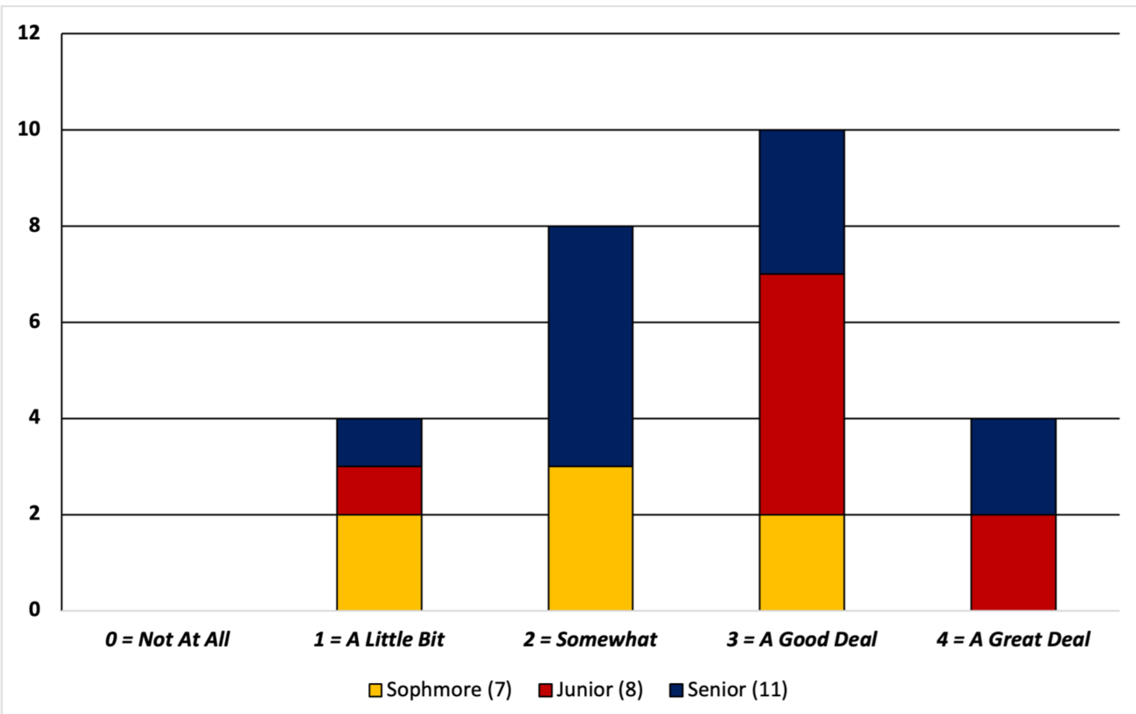

Figure 4: Student responses to what extend they believe they are taught that is there is more to an engineer than technical ability. A) This table represents the breakdown of responses by year in school and their average response. B) The graph depicts the overall landscape of student answers.

Year in School	**Average Response**
Sophomore (7)	2.000
Junior (8)	3.000
Senior (11)	2.545

The McGinn study asked this question as a binary yes/no question in S22: "In the course of your engineering education at SU have you ever gotten a message to the effect *that there is more to being a good engineering professional in today's society than being a state-of-the-art technical expert?*" (emphasis in original McGinn survey). We believe that the Likert scale would better quantitate the significant learning outcomes related to foundational knowledge and the human dimension. In McGinn's original survey, 21/57 (36.8%) reported this as no, which stands in contrast to our findings where no students reported 'not at all.' We place a caveat on this as students may feel guilty in responding with 'not at all' given the professional conduct expected of engineers in society. However, the fraction of students reporting as 'a good deal' or 'a great deal' is 14/26 (53.8%) stands out as an important element of BME formation and recognition of greater objectives to learning beyond technical content (Figure 4).

Discussion:

Though the data we collect we can see overall trends in responses. Question 22 demonstrates that students identify that they are receiving ethical education, in the courses BME260L, BME354L, BME303L, and BME221L, which were the department targets for incorporating ethical instruction. Questions 14 and 23 demonstrate relative growth over time in both student perceived preparedness as well as perceived education. Our junior students present the highest average levels of confidence in their ethical education, while both our junior and senior students demonstrated improvement over our sophomore cohort. Further study is warranted as it would be interesting to see how these responses change as our juniors become our seniors. One possibility for this current difference is the seniors were not beneficiaries of the targeted ethical instruction and are part of the previous iteration. While the reasons for changes in ethical awareness may be unclear, our results do indicate levels of growth from year two, demonstrating our students are more aware of the importance of ethical reasoning in their line of work.

While we strive to understand student perception and the ethical climate at our institution, we recognize that there is a growing emphasis on virtue and character ethics in engineering (see [10]). Embedding virtue ethics into our student's education is fundamental to growing their understanding of the complexity of issues. While developing our student's ability to ask questions and reevaluate their perspective is critical in the formation of their character. However, these merits can be difficult to measure.

Over the past few years of developing and integrating our ethics model into our curriculum, we have collected a multitude of student responses through end of semester course evaluations. Some of these responses are recorded below.

Student A taking BME 354L wrote *"I'm also thankful for your inclusion of ethics in this class. I think it worked especially well in this class, given how practice-oriented the labs and some lectures were, and it was the first time I had discipline-specific ethics content in an engineering class."*

Student B having completed same course wrote *"I also enjoyed [the course instructor's] attempt to add consideration about ethics into the course (including the guest lecturer) as ethics-content is generally absent in the BME program. I applaud [the instructor's] efforts to include considerations about ethics into the course, and I think some content about ethics could be included earlier in the semester."*

Student C after completing BME 303L wrote *“We discussed ethical implications involved with these technologies and their current limitations. Its inspired me to consider future avenues where I might be able to integrate this knowledge into personal projects and inquiries.”*

While these responses may not qualify as data to quantify the effectiveness of our model, it does depict a level of success within our ethics integration. These students demonstrate that they not only possess ethical awareness but are excited about and receptive to these teachings. Furthermore, through these responses we can see that our students are being exposed to a variety of perspectives which will develop their ethical reasoning and in turn will contribute to the formation of their character.

Conclusion:

While it may be too early to conclude that the snail progression for ethics integration is the optimal method for embedding ethics into our curriculum, we demonstrated that it is effective at developing our students ethical reasoning and that our students recognize its importance.

Further testing will occur throughout this year and years to come. We plan on conducting focus groups to quantify the ethical reasoning of our students through different case studies and measure this change over time. We also look to developing a robust method for measuring virtue ethics and character formation in our students. Furthermore, we hope to evolve this study into a longitudinal one where we measure our student's knowledge and perception of ethics throughout their time in undergrad and post grad life.

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