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Developing Engineering Habits of Mind in the First Year

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Introduction

Many educators and practitioners anecdotally note that one important outcome for engineering students is that they learn to "think like engineers." But what does this mean, and how can we, as educators, facilitate this type of learning in a first-year engineering program? One model that attempts to explain this is the Engineering Habits of Mind framework (EHoM) proposed by Lucas and Hanson in 2016 [1]. This model is depicted as a set of concentric rings centered around a core engineering mindset surrounded by six engineering habits of mind with an outer ring that represents several broader learning habits of mind that are applicable across a wider range of disciplines. By identifying habits of mind that are tailored to engineering thinking while still recognizing the types of thinking applicable to all learners, the EHoM model can provide insight into how engineering thinking may (or may not) be developed in first-year engineering courses and beyond.

Beyond the EHoM, we know that engineering is shaped by a distinctive professional culture. Godfrey and Parker (2010) describe this culture through two key dimensions—An Engineering Way of Thinking and An Engineering Way of Doing—which together illuminate the values, norms, and practices that underpin engineers' approaches to problem-solving and their engagement in professional work [2]. These cultural dimensions complement the EHoM and a broader set of Learning Habits of Mind (LHoM) by situating individual habits of mind within the wider sociocultural context of engineering, highlighting that students are not only developing cognitive dispositions but also learning to participate in a particular community with shared ways of reasoning and acting. First-year courses can help engage students in this broader culture.

While habits of mind have been a common theme in K-12 educational research as a method to encourage interest in the field for young learners by emphasizing the breadth of the field of engineering, fewer studies have investigated how these habits are maintained or further developed in a university setting. First-year engineering programs are uniquely situated at the intersection of these two educational environments—in the U.S., students often enter these programs directly from a K-12 learning environment, and one of the roles of the program is to help them successfully navigate that transition and set them up for success in their subsequent disciplinary engineering studies.

This paper looks at a first-year general engineering course at Virginia Tech, a large land-grant university in the Southeast U.S., to study how habits of mind may be developed for students enrolled in the program. We also provide a critique of the strengths and weaknesses of this model when used to evaluate courses or programs at a university level.

Relevant Literature and Theory

Habits of Mind (HoM) in education has been discussed at least as far back as the late 1980's, when the American Association for Advancement of Science used this terminology to identify a set of "thinking skills" important for K-12 STEM education [3]. Taking a broader approach, the importance of HoM development among learners was notably emphasized by Costa and Kallick who identified sixteen habits of mind "that human beings display when they behave intelligently" in their 2000 work [4]. Additional work over the years has targeted more specific habits of mind that are confined to domains such as science, math, engineering, and creativity [5], [6], [7], [8]. *Engineering* habits of mind have been a focus of study since at least

2009 when the National Academy of Engineering (NAE) included EHoM development as one of three core principles for K-12 engineering education and identified six habits of mind: systems thinking, creativity, optimism, collaboration, communication, and ethical considerations [7].

Lucas and Hanson proposed a new EHoM model in 2014 which was refined in 2016 as a response to critique of the generalized nature of some of the NAE's original six habits of mind [1], [9]. In this updated model, a new set of six EHoM were proposed: systems-thinking, problem-finding, visualizing, improving, creative problem-solving, and adapting. These form an inner ring around a "core engineering mind," which they define as "making 'things' that work and making 'things' work better." To provide necessary context for the analysis of this study, we have included the framework's definitions for each of these habits of mind below [1]:

Systems-thinking: Seeing whole systems and parts, and how they connect, pattern-sniffing, recognizing interdependencies, synthesizing.

Problem-finding: Clarifying needs, checking existing solutions, investigating contexts, verifying.

Visualizing: Move from abstract to concrete, manipulating materials, mental rehearsal of physical space and of practical design solutions

Improving: Relentlessly trying to make things better by experimenting, designing, sketching, guessing, conjecturing, thought-experimenting, prototyping

Creative problem-solving: Applying techniques from other traditions, generating ideas and solutions with others, generous but rigorous critiquing, seeing engineering as a "team sport."

Adapting: Testing, analyzing, reflecting, re-thinking, changing (physically and mentally).

In their text, they define both *making* and *things* quite broadly, recognizing that not all engineering involves physical manifestations of work. Surrounding the EHoM is a set of seven more general learning habits of mind (LHoM). By situating EHoM and LHoM separately, this model recognizes that some habits of mind are more specific to the engineering discipline than others (Figure 1). It should be noted that Lucas and Hanson did not specifically include details about the definitions of LHoM in their model, so the analysis of these was based on review of applicable literature and the authors' judgement as to what might be considered included in each.

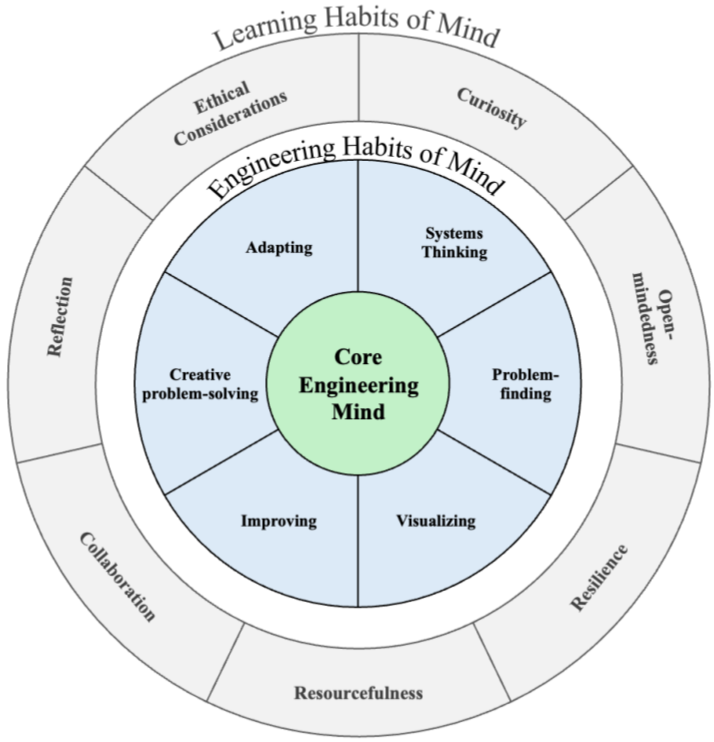

Figure 1: EHoM Model Adapted from Lucas and Hanson [1]

Most current literature focuses on the development of EHoM in K-12 education, possibly due to the 2009 NAE report's focus on this context. However, some work has investigated the habits of mind of engineering students as well as practicing design engineers [10], [11], [12]. Little research has been conducted specifically towards how EHoM might be developed (or not developed) in first-year engineering programs (FYP).

FYP serve a wide range of roles in an engineering curriculum, with considerable variability between institutions and even within them. Reid et al. developed a taxonomy in 2018 to help better define the coverage of first-year engineering programs [13]. This taxonomy identified and further broke down eight dimensions: Academic Success, Communication, Design, Engineering Profession, Engineering-specific Technology/Tools, Math skills and application, and Latent curriculum/professional skills. Other frameworks have also been developed to help classify and emphasize the importance of various aspects of first-year programs. For example, EMIFY—a program developed by the KEEN Network, part of the Kern Family Foundation, to promote an entrepreneurial mindset in first-year engineering education—categorizes FYP with a number of concepts into four overarching categories: Engineering Doing/Design, Career Connections, Team Based Professional Development, and Individual Professional Development [14]. Frameworks such as these are valuable in that they highlight the breadth of topics covered by first-year engineering programs.

Introducing EHoM as a framework to evaluate coverage of FYP can be valuable to ensure that in addition to technical/topical coverage, we are encouraging the types of thinking that have been deemed important for graduates of engineering programs and provide consistency with K12 programs that students may have experienced prior to beginning their studies in a university setting.

Findings: Habits of Mind in a First-Year Engineering Course

To gain insight into how first-year programs can influence the development of engineering and learning habits of mind, we have analyzed learning outcomes, class topics/activities, and assessments used in a first-year engineering course at a large public university that typically enrolls on the order of 2,500 first-year engineering students each year. Students entering the engineering program at the study institution begin as general engineering students and declare one of fourteen different engineering degree programs following the completion of their first-year program requirements, which include first-year engineering courses, math, physics, and English.

This study looks at whether engineering and learning habits of mind are found in an introductory course, Foundations of Engineering Practice, which contains all the material covered in the first-year program at the study institution. Most students at the study institution take engineering courses across a two-semester sequence with two credit-hours each. A combined one-semester, four credit-hour course that covers all the first-year topics is also offered to accelerated students who otherwise meet all requirements to matriculate into one of the disciplinary departments; we have chosen to use this consolidated course to study for a more concise analysis of the representation of HoM within the first-year program and feel that it serves as an appropriate proxy for the more common two-course sequence.

To help ensure that we have a complete picture of the course, we look at three dimensions borrowed from Constructive Alignment Theory, which posits that deeper learning is more likely to occur when these three parts of a learning experience are well-aligned with each other [15], [16].

1. Learning outcomes,
2. Course topics, and
3. Assessment methods

While evaluating alignment itself is not the primary intent of this study, we feel that it is important to evaluate the prevalence of habits of mind across each of these three dimensions to gain a comprehensive understanding of the essence of the course. This gives us insight into how well we balance what we want students to learn (Learning outcomes), what we do in the course to facilitate that learning (Topics), and how we are measuring what is learned (Assessment). Further, it shows how the L/EHoMs are weighed in relation to each other. The results of this analysis across all these three dimensions can be found for EHoM in Figure 2, and LHoM in Figure 3. The incidence depicted for learning outcomes refers to the percentage of learning outcomes, course topics, and assessments that have some relationship to each HoM. The following three sections will take a closer look at each of these dimensions.

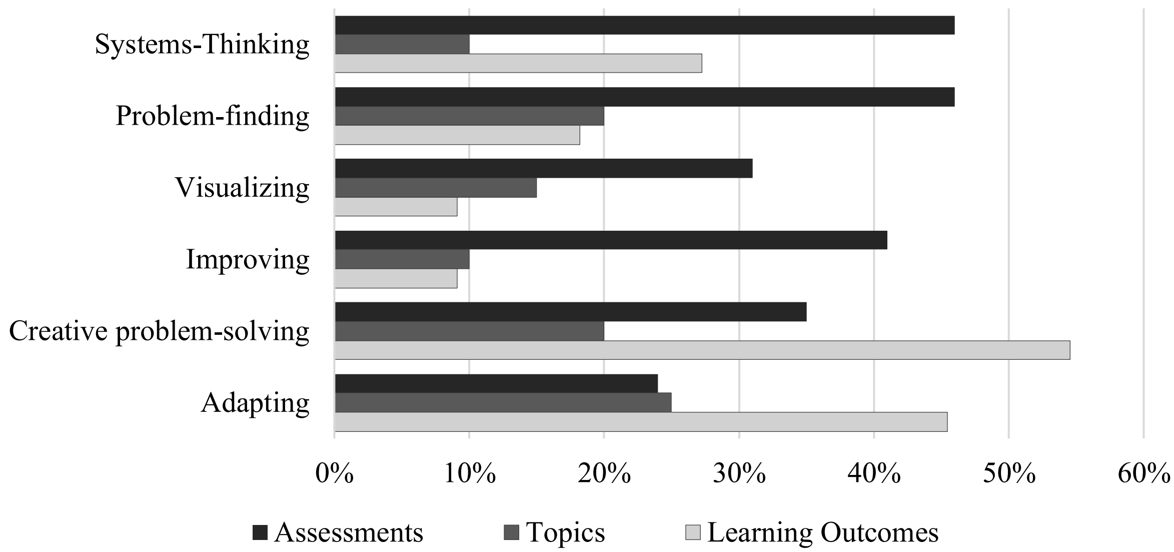

Figure 2. Engineering Habits of Mind Incidence

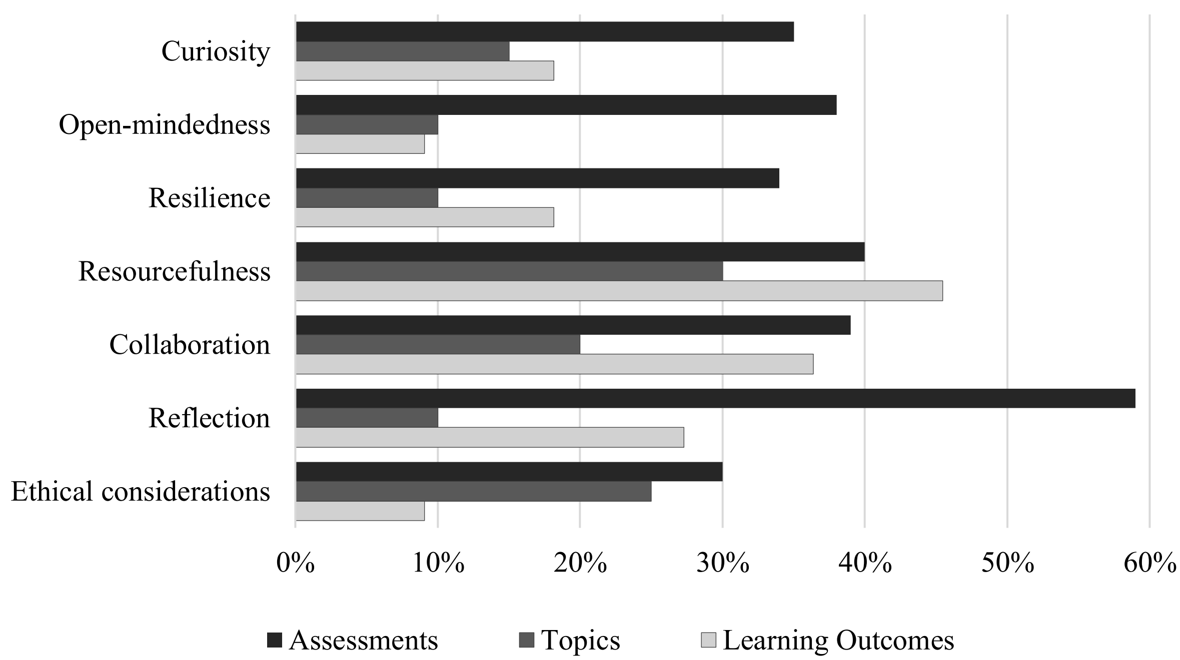

Figure 3. Learning Habits of Mind Incidence

Course Learning Outcomes and Habits of Mind

Broadly speaking, the course learning outcomes are related to a variety of topics such as an introduction to engineering as a discipline and associated majors, introductory coding with MATLAB and 3D CAD modeling, engineering problem solving through a systems thinking perspective, engineering design, professional skills such as teamwork and communication, and development of self-regulatory practices. These learning outcomes also reflect the course's role in providing a first-year experience intended to help incoming students develop the academic and professional skills necessary to be successful in a university setting. The course contains eleven learning outcomes (LOs) as outlined below:

LO 1. Explain the contributions and collaborations of various engineering disciplines / majors in the development of products, processes, or systems and evaluate their relevance to personal career goals.

LO 2. Write and execute basic code that aids in solving an engineering problem to demonstrate skills in computer programming as an engineering tool.

LO 3. Use CAD software to create basic 2-D representations and 3-D objects that aid in solving an engineering problem to demonstrate skills in Computer Aided Design software as an engineering tool.

LO 4. Explore an engineering problem from a systems-level perspective through the identification and relation of relevant design constraints, stakeholders, and needs.

LO 5. Use systematic engineering design methods to identify design criteria and constraints, evaluate, and iterate on designs that solve a problem.

LO 6. Communicate aspects of engineering problems or products with supporting evidence to inform peers of the scope of engineering problems as well as engineers' roles in products or processes through both written and verbal methods.

LO 7. Communicate aspects of engineering problems or products with supporting evidence to justify engineering design decisions to relevant stakeholders through both written and verbal methods.

LO 8. Elaborate upon the holistic and complex relationships between social issues, ethical implications, engineering problems, and engineering solutions.

LO 9. Collaborate effectively within an engineering design team, contributing productively and equitably by developing, implementing, and critically assessing strategies that foster a safe, inclusive, and equitable team environment.

LO 10. Demonstrate reflective and corrective practices and behaviors to develop individual professional skills such as time management, learning strategies, and approaches to finding resources and help seeking.

LO 11. Demonstrate reflective and corrective practices and behaviors to develop collaborative professional skills such as project management, effective interpersonal communication, and conflict resolution.

Given that the course serves as an introduction to engineering studies while also supporting students' transition into university-level learning, we have taken these eleven learning outcomes and mapped them as closely as possible to both the Engineering HoM and the broader Learning HoM. While not all learning outcomes are intended to be weighted equally in the course with respect to content and assessment, this gives us insight into how frequently each habit of mind occurs within this list and, therefore, some indication of its importance to the course designers (Table 1).

Table 1. Incidence of EHoM and LHoM in Course Learning Outcomes

Learning Outcome	Engineering HOM						Learning HOM						
	Systems-Thinking	Problem-finding	Visualizing	Improving	Creative problem-solving	Adapting	Curiosity	Open-mindedness	Resilience	Resourcefulness	Collaboration	Reflection	Ethical considerations
LO 1							X					X	
LO 2		X			X					X			
LO 3			X		X					X			
LO 4	X	X					X	X					
LO 5				X	X	X				X			
LO 6					X	X					X		
LO 7	X				X	X					X		
LO 8	X												X
LO 9					X						X		
LO 10						X			X	X		X	
LO 11						X			X	X	X	X	
Total:	3	2	1	1	6	5	2	1	2	5	4	3	1

We can see from this analysis that, in this first-year program, the Creative Problem Solving and Adapting EHoM are found the most frequently within the learning outcomes, with six and five occurrences each (represented as a relative percentage in Figure 2). This is likely in part because of the broad nature of both of these HoM: Creative Problem Solving includes critique, teamwork, ideation, and application of techniques, while Adapting includes analysis and reflection. Among the LHoM, Resourcefulness and Collaboration have the highest incidence, followed closely by Reflection (represented as a relative percentage in Figure 3).

Course Topics/Activities and Habits of Mind

While incidence of HoM in learning outcomes gives us one perspective, we also look at how they manifest themselves in the student-facing topics and material throughout the semester. The most recent course proposal for the Foundations of Engineering Practice course approved by the University curriculum committee includes a topic syllabus that breaks down the percentage of each subject covered throughout the semester. Table 2 depicts the incidence of EHoM and LHoM with respect to each topic as well as a summary of the total percentage.

Table 2. Incidence of EHoM and LHoM in Course Topics

		Engineering HoM						Learning HoM						
Topic Syllabus	Percent of Course	Systems-Thinking	Problem-finding	Visualizing	Improving	Creative problem-solving	Adapting	Curiosity	Open-mindedness	Resilience	Resourcefulness	Collaboration	Reflection	Ethical considerations
Engineering disciplines/majors	5%							X	X				X	
Engineering problem-solving (breakdown below)														
Defining problems (stakeholders, constraints, criteria, ethical considerations)	10%		X											X
Complex problem relationships	5%	X												
Finding, evaluating, and citing evidence	5%							X			X			
Design process (breakdown below)														
Understanding stakeholders (incl. ethical considerations)	5%							X	X					X
Conceptualization, evaluation, and selection of design solutions (incl. ethical considerations, design criteria and constraints)	10%		X											X
Data collection, analysis, and modeling	5%	X		X							X			
Testing and iteration of design solutions	10%				X		X			X				
Engineering tools (breakdown below)														
Algorithms & Programming	10%					X					X			
Graphical representation and CAD	10%			X		X					X			
Engineering Communication	10%											X		
Engineering Teamwork	10%						X					X		
Reflective and Corrective Practices	5%						X						X	
Topic Percentage Total:		10%	20%	15%	10%	20%	25%	15%	10%	10%	30%	20%	10%	25%

When viewing how habits of mind emerge in the course through this lens, we can see several differences when compared to only looking at learning outcomes. Similarly, for EHoM, Adapting and Creative Problem Solving still have some of the highest representation; however, Problem-finding and Visualizing emerge as more prevalent themes covered. Resourcefulness and Collaboration LHoM have a fairly high prevalence, similar to the LO analysis, with the addition of Ethical Considerations as one of the most prevalent LHoM covered throughout the semester. Figures 2 and 3 provide a graphical representation of course topic HoM incidence in the context of all three course dimensions.

The following list provides a selection of example teaching and learning activities that highlight EHoM in course topics:

Systems-thinking: Overview of organizational systems and how the university is structured; creation of concept diagrams for "everyday" problems around campus connecting various components.

Problem-finding: Team stakeholder scavenger hunt to investigate direct and indirect stakeholders for designed elements around campus.

Visualizing: Class discussion on various ways that data can be visualized and how that influences engineering decision-making; introduction to spatial visualization using CAD.

Improving: Periodic/regular check-ins between instructional team and student teams to guide them through an iterative design process.

Creative problem-solving: Using MATLAB and CAD tools as part of a larger design project.

Adapting: Regular class discussions on development of self-regulatory practices on an individual level, such as time management, and in an engineering team setting, such as adjusting goals as a design progresses.

Course Assessments and HoM

Finally, we look at how students are assessed throughout the semester with respect to HoM. The implementation of Foundation of Engineering Practice being analyzed contained seventeen main assignments distributed throughout the study semester in Fall 2024 (Table 3). It should be noted that in this first-year program, instructors are offered autonomy to design assignments and assessment structures based on their own strengths and preferences, within the bounds of guidelines set by the department. As such, while these assignments are representative of the program as a whole, the authors expect that there would be some variation in the outcomes of this analysis if other instructors' versions of the course were analyzed. The assignments for this semester were divided among individual, denoted by an "I" in the table below, and team project assignments, denoted by a "T." The percentage total was calculated based on a summation of all assignment percentages related to each habit of mind. While in practice an entire assignment may not be related to each habit of mind, for the purposes of this analysis we believe this gives adequate insight into the prevalence of habit of mind development in the course assessment structure.

Table 3. Incidence of EHoM and LHoM in Course Assessments

			Engineering HOM						Learning HOM						
Ind./Team	Assignment Name	Course Grade %	Systems-Thinking	Problem-finding	Visualizing	Improving	Creative problem-solving	Adapting	Curiosity	Open-mindedness	Resilience	Resourcefulness	Collaboration	Reflection	Ethical considerations
I	Planning to be an Engineer	5%							X	X				X	
I	Ill-structured problem scoping	5%	X	X					X	X		X		X	X
I	MATLAB basics	5%													
I	If Statements and Loops	4%													
I	Final MATLAB challenge	4%		X			X		X			X			
I	CAD Skills	5%			X										
I	Low Fidelity Prototype + CAD Model	8%	X	X	X	X			X	X	X	X		X	
I	Ethics Write-Up	5%	X		X		X						X	X	
I	Self-Directed Skill Dev.	4%		X			X				X		X	X	
I	Reflect & Correct Prompts	4%						X			X			X	
T	Team Startup	2%		X			X			X			X		
T	Problem Definition	5%	X	X			X		X	X			X	X	X
T	Data Collection	3%	X	X	X	X			X	X	X	X	X	X	
T	Data Vis. and Analysis	5%	X	X	X	X			X	X			X		
T	Design Proposal	5%	X	X		X	X			X		X	X	X	
T	Testing and Validation Plan	5%	X			X	X	X			X	X	X	X	X
T	Final	10%	X		X	X	X	X			X	X	X	X	X
	Percentage Total		46%	46%	31%	41%	35%	24%	35%	38%	38%	40%	39%	59%	30%

Figures 2 and 3 provide a graphical representation of course assessment HoM incidence in the context of all three course dimensions. The following commentary provides selected examples of assessments and how they relate to engineering habits of mind:

Problem Definition Report: This assignment requires student teams to create a concept map-style system diagram of their project topic including elements such as stakeholders, relevant organizational structures, and technical components, which involves *systems thinking*. Student teams were tasked with identifying a relevant campus problem to explore throughout the semester, which relates to *problem-finding*. *Creative problem-solving* is encouraged by asking teams to propose at least three different types of approaches that they could take to improving the campus problem that they are investigating.

Data Visualization and Analysis: In this assignment, student teams analyzed data that they collected related to their project theme and made recommendations for potential design approaches for how to improve their chosen campus problem. This process requires *visualization*, *problem-finding,* and *systems thinking* in that students are able to form concrete recommendations related to a larger, more abstract problem system. Finally, the recommendations require an *improving* mindset for how this system can be made better.

Final Demonstration: This assessment culminates the semester by requiring student teams to synthesize their scoping (*systems thinking*), data collection and visualization (*visualizing*), and design work through creation of a prototype, CAD model, and programming component for an approach to help improve the campus problem they identified. The format of the assessment is a poster session that includes a demonstration of interactive components. Teams are asked to describe their design process and make recommendations for future work related to their project topic (*improving, creative problem-solving,* and *adapting*).

Reflect & Correct Prompts: Throughout the semester, students are asked to respond to reflective prompts approximately once per week to help them build self-regulatory skills. Prompts range from questions about time management, dealing with team conflict, how to approach learning new skills, and work-life balance. These skills most closely relate to the *problem-finding* and *adapting* EHoM.

Discussion, Conclusions, and Future Work

All Engineering Habits of Mind (EHoM) and Learning Habits of Mind (LHoM) were found to be represented across learning outcomes, class topics, and assessments in the first-year course we examined. Notably, every HoM was present in at least 20% of course topics and assessments, which demonstrates the capability of first-year engineering courses to emphasize and develop engineering ways of thinking. As expected, the analysis indicates an incongruity between the prevalence of HoM across the curriculum, the teaching approach, and the assessment of work. For certain subjects like reflection and creative problem-solving, this discrepancy is significant, shedding light on areas of course development which may necessitate re-evaluation of the focus across the board, which in turn requires a determination of which HoM should be emphasized. Similar incongruities have been noted in prior work on engineering capital, which suggests that while engineering ways of thinking may be present in curricula, their educational impact depends on how explicitly they are framed, valued, and legitimized through instructional and assessment practices [17].

However, these findings do not necessarily indicate that the course lacks alignment between outcomes, topics, and assessments. For example, *systems-thinking* and *reflection* both appear to have a relatively low incidence when solely looking at course topics (~10%); however, they appear quite frequently in student-assigned work. This finding suggests that while there may be limited instruction time dedicated to these topics, both systems thinking and reflection require frequent practice on the part of students to be developed in a first-year course. This trend is found to be similar for most habits of mind, with *adaptin*g being a notable exception, appearing roughly equally in both topics and assessments - perhaps due to the time constraints of the semester which limit the assessment of adjustments/adaptations within a 15-week timeframe.

Overall, nearly every course learning outcome, topic, and assessment could be mapped to an EHoM. *Selecting an engineering major* was the only learning outcome that did not closely align, which instead matched more closely with broader learning habits of mind, likely because major and career exploration are not unique to the field of engineering. Similarly, topics related to finding and evaluating evidence did not squarely fit within engineering habits of mind as it is also a skill common across many STEM and non-STEM disciplines. All but three assessments were found to be related to at least one EHoM: a major exploration assignment and two formative MATLAB assignments. The major exploration assignment did not relate for reasons described previously, and the MATLAB assignments did not relate due to the closed-ended nature; their primary purpose was to help students develop foundational coding skills, which students later demonstrated in an engineering context through a subsequent summative assessment.

While the EHoM model appears to offer a valuable lens for analyzing first-year courses such as this, we recognize that it has several limitations. With the prevalence of programming in many, if not most engineering disciplines, it could be helpful to more explicitly include algorithmic thinking in the framework to fully capture the cognitive processes students should develop in introductory courses and beyond. While we initially set out to only evaluate *engineerin*g habits of mind, we quickly found that it was important to also recognize the role of first-year courses in helping students develop *learning* habits of mind as well. This model could be improved by the addition of more details for each of these dimensions. Overall, despite these limitations, we found that the EHoM is a helpful framework that highlights the value and importance of first-year engineering learning experiences to those who may be unfamiliar with their pedagogical goals.

Recognizing that student learning does not happen in a singular class, we recommend future work to focus on how EHoM and LHoM manifest themselves throughout the curriculum. This approach could include evaluation across all classes students take in a single semester as well as across multiple years of study. This work is important to identify potential gaps that may exist, such as in the middle years, and inform the ways in which first-year courses can serve as a cornerstone for helping students learn to think and act like an engineer.

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