Engineering Pedagogy: Waypoints & The Limitations of the Lecture Method

A Research Paper Submitted to the Department of Engineering and Society

Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements of the Degree
Bachelor of Science, School of Engineering

Zachary Bilmen

Spring, 2021

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

Table of Contents

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Sociotechnical Synthesis

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During my time as Professor Floryan's research assistant we primarily focused on the analysis and development of engineering pedagogy at the University of Virginia. We had routine discussions on typical student experiences and what changes could be made towards their general benefit. Floryan focused on optimizing the student relationship with content knowledge, changing how students interacted with information and prove their mastery through assessment. I was interested in education at a general level, exploring alternatives to the sedentary style of lecture learning, placing a greater emphasis on more active methods of pedagogy like problem-based learning. We both have adjusted our viewpoints on education over the course of the past two years of research which led to the development of Waypoints, a novel method of pedagogy giving students an active role in their interaction with course material. A direct product of our discussions, I was interested in driving a conversation around alternative methods of learning from lectures. To motivate conversion, I framed the critical limitations of lectures and posed alternatives which directly solved or mitigated them. We begin with Waypoints, an explicit solution to the issue of inadequate mastery in CS2150.

Waypoints is a method of teaching oriented around mapping the pathways students can take in learning content. This method was motivated from the observation that students were graduating from the University of Virginia's CS2150 without a mastery on fundamental topics in the class. Using a TecMap (Dragon, 2019), a class can be organized into an ordered forest (multiple ordered trees), where students start by learning topics at the root of a given tree and completing topic-specific assessments as the class continues. The order of completion is not enforced, giving students the ability to retest knowledge from earlier in the semester they may not have fully mastered. Waypoints is primarily designed to be visualized in an online format where students can see which topics they have mastered, and teachers can refer to the graded

TecMap for course iteration/redesign. By design, each topic is covered explicitly through a lecture and it is around lectures that I focus the STS portion of my thesis.

In an interest to frame an argument around the transition from lecture-based engineering curriculum to some other more active alternative, I wrote on the limitations of the lecture model. The focus is primarily on its limitations as a contextual tool to introduce the Oxford Tutorial and Harkness Discussion Methods. To balance out contextual bias, limitations of the tutorial and Harkness methods were also addressed. The purpose of this paper is to give professors the tools to analyze the limitations of their own classes and motivate the adoption and further research in student-active teaching methods. There is a dearth of research in tutorials and discussion-based learning in engineering curriculum, partially because there is a lack of motivation to change from the lecture model. Clearly defining the drawbacks and limitations of the lecture model as well as framing other methods as solutions to those limitations is a first step in inspiring curiosity towards the question of change.

Professor Floryan and I had different interests when it came to developing engineering pedagogy. Floryan with an interest in content and me with an interest in general method. Through conversation, we both began to approach each other’s way of thinking. The following reflects the development of two years’ worth of discussion and thought around engineering pedagogy and where we see it moving in the future.

Acknowledgements:

To Professor Floryan for always treating our discussions as peers. One of the highlights of my week, it was an enlightening experience where we were able to speak truthfully and intelligently in conversation, reaching compromises, and finally into the following cumulative work. It was a pleasure to work with you.

References

Dragon, T., & Kimmich Mitchell, E. (2019). TECMap: Technology-Enhanced Concept Mapping for Curriculum Organization and Intelligent Support. In B. M. McLaren, R. Reilly, S. Zvacek, & J. Uhomoibhi (Eds.), *Computer Supported Education* (pp. 191–213). Springer International Publishing. https://doi.org/10.1007/978-3-030-21151-6_10

The Waypoint Model: a teaching model to get students back on track

(Technical Topic)

Applying Harkness to University Engineering Programs: Inspired by the Oxford Tutorial Method

(STS Topic)

A Thesis Project Prospectus Submitted to the

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Be advised, this Prospectus is not a complete reflection of the following STS Topic. The Prospectus can be considered preliminary research in motivating the STS Topic.

Introduction

At the university level, it's not hard to find classes with a variety of engagement levels. If you were to ask a professor with a concern for education, "Pedagogy should at its best be about what teachers do that not only help students to learn but actively strengthens their capacity to learn," encapsulating the importance of student engagement. (Parsons, 2011) As it turns out, student engagement is a resource that not every classroom has, but is one every class should strive to pursue. For the purpose of this paper, engagement is the ownership and involvement that students demonstrate with the work in a class. Even for educators with an explicit desire to solicit engagement, garnering it can become increasingly difficult as the size of a class grows. In a not all too uncommon case, students that fall behind or struggle in a large classroom can have a very hard time engaging with their course. (Slavin and Madden, 1989) In large classrooms, since the distribution of skill levels in the room is so wide, the ability to engage students universally is all the more important. In conjunction with Professor Mark Floryan, the technical portion of my capstone will involve the development and testing the Waypoints model, a new education model that classes can adopt. The model is designed to give students greater control, flexibility, and certainty when progressing through the course. But what traditional learning and the Waypoints model do not consider is inter-student and student to professor interaction. The STS portion will explore the Harkness method, a discussion-based learning model and education philosophy centered around student interaction, and how it can be applied to engineering disciplines. The proposed Harkness model will be contrasted to and built upon the Oxford Tutorial method.

Technical Topic

The Waypoint Model: A Teaching Model to Get Students Back on Track

In a normal lecture style classroom, a teacher gives a lecture, assigns homework, and requires few exams to be taken before students leaves at the end of the semester. Day to day, a student may have other responsibilities and start to fall behind. Because this is a closed system, one without direct student feedback, the class progresses in a way that may not support students on an individual level. These students who fall behind are unable to re-take exams, such as a Midterm from the beginning of the semester, or fix mistakes on homework assignments. Even if students later on in the class have the content knowledge, they are unable to demonstrate that knowledge without previous assessments holding them back. Similarly, teachers using this traditional system do not know specifically what knowledge a given student has when leaving the classroom. A perfect grade can indicate a student knows everything satisfactorily, but anything lower than that can lead to a range of possibilities. In short, a traditional class as described above is rigid and ambiguous. It does not provide students who don't quite match the pace of the class the ability to perform at their best. And it does not provide teachers with the appropriate feedback for students in mastering specific content knowledge.

The Waypoints model is based in part on Mastery Learning. Mastery Learning is a learning model that requires students to master well-defined, prerequisite material before moving onto future topics. Learning leading to mastery is time dependent, creating a tradeoff where some students need significantly more time to complete a course but do so with a tremendous grasp on its content (Arlin, Marshall, and Webster, 1983). In Waypoints, prerequisite ordering is not strictly adhered to, allowing students to move onto future material and go back to un-mastered content. Different students move at different paces, so there is a need for asynchronous assessments. Waypoints adopts Carnegie learning's *Cognitive Tutor,* an online quizzing system to assess knowledge; in practice Carnegie quizzing results in extremely high assessment scores (Koedinger, K., Corbett, A., Ritter, S., & Shaprio, L, 2000). A drawback to Waypoints' freedom is that there still remains the possibility for students to leave everything to the last minute. Students should be incentivized to pursue the course at a healthy pace. Gamification and incentive structures provide a mechanism that rewards students for behaving well, or in the case of a Waypoints classroom, to keep students on track to complete the course successfully (McGonigal, 2011). From the teacher perspective, in a traditional classroom, it can be hard to see which students struggle at which points in the class, and what exactly students know when leaving the classroom. It is not unknown for the grade of a student in a class to not be fully respective of their understanding of material (Garfield, 1994). With incremental quizzing and Mastery Learning, it is very clear which subjects provide problems. The Waypoints Model gives students a more intuitive and self-paced experience to the curriculum through Mastery Learning, flexible assessment through incremental quizzing, and an incentive structure for completing course material through gamification.

Waypoints gives students control and ownership over how they learn in the classroom without losing track or unintentionally falling behind. And for teachers, the model provides direct insight to the progress of each individual student. With Waypoints, students have the ability to fulfill the deliverables of a class at their own pace in parallel to lectures. Homework assignments and quizzes, where questions are randomly sampled from a large pool, are repeatable for each well-defined knowledge module. This means that even if a student does not understand a concept while it is being lectured, they can still demonstrate knowledge later on in the class with more time to spend on it. Each module is defined to directly reflect a student learning outcome, meaning that the teacher can directly track where an individual student has demonstrated knowledge and where they have not.

Professor Floryan and I needed to verify that the model, in practice, performs as expected. Professor Floryan taught DSA 1 (Data Structures and Algorithms) in the style of the Waypoints Model. He wrote up a pool of quiz questions for each waypoint and replaced each lab section with an opportunity to take up to two proctored quizzes. This gave students the opportunity to catch up with waypoints they have not previously mastered on a weekly basis. This test occurred during the Full 2019 Semester. I analyzed the quiz mastery and homework completion progress for each student and compared the distributions to CS 2150, a similar incarnation of DSA 1, taught in a traditional teaching style. This work is nearly done, and is in the process of being written for publication.

STS Topic

Applying Harkness to University Engineering Programs: Inspired by the Oxford Tutorial Method

There are other methods of soliciting student engagement besides the Waypoint model. One of which is the Harkness method; a discussion-based learning method with a heavy focus on student-to-student discussion (Williams, 2014). Discussion is, by its very nature, an engagement tool because in discussion students are required to engage in the course material at a high intensity. This discussion is moderated by a teacher, driven by specially designed resources to inspire questions and curiosity. This includes homework, readings, notes, etc. digested before class time. (Williams p. 4, 2014) “The underlying assumption for this seems to be that it is important to make room for the authentic voice of the student, to provide encouragement, build confidence, and to embed positive attitudes to learning." (Williams p. 4, 2014) Harkness is a philosophy which is deliberately designed to evolve students' perception of learning at large and not purely a student's engagement with certain content. Because of the benefits the method provides to students in terms of general learning, Harkness has been adopted at a handful of top performing elite secondary schools in the US.

Harkness, though, is not widely adopted in universities in the US. The only analog to Harkness that exists at the university level is the tutorial system at Oxford. Oxford's Department of Engineering Science offers a diversified learning experience which includes bi-weekly tutorials (University of Oxford, 2020). Tutorials are discussions between a group of one to two students and their tutor, a professor or expert in a field of student. (University of Oxford, 2020) Notably, assignments and independent work are assigned at the tutorial level and lectures are presentations to disseminate knowledge, independent from the assignments themselves. This is already dramatically different from traditional teaching methods at public universities in the United States. Despite Harkness being "partly inspired by the Oxford tutorial system and the Socratic concept of dialogue," Harkness discussions can be markedly different from tutorials. (Williams p. 1, 2014)

"[T]he tutorial relationship should be one in which two minds worked on the same problem and that it is an opportunity for intellectual growth … in which the student should gradually acquire independence from their tutor." (Ashwin, 3, 2005) A major difference between the tutorial system and the Harkness method is Harkness's decentralization of knowledge from an expert from the get go, in tremendous contrast to expert-centric tutorials. (Williams p. 4, 2014) That being said, there are contrasting viewpoints on the philosophy of the Oxford tutorial with regards to professor-centricity and the student-professor relationship. "Its function is not to instruct: it is to set the student the task of expressing his thought articulately and then to assist him in subjecting his creation to critical examination and reconstructing it." (Ashwin, 3, 2005) Another view point states, "[i]t may be noted that the famous Oxbridge tutorial is firmly teacher centered and, except for the most able students, may not normally lead to deep learning.'' (Ashwin, 3, 2005) The Oxford tutorial method does not prohibit 'instruction,' at a systemic level, allowing the tutorial to be interpreted differently from professor to professor, especially with regards to its focus the student. The Harkness method explicitly places the focus on students, removing any interpretation that instructors should inculcate academics upon their students.

The largest tradeoff within the Harkness method is the significant time investment towards unguided exploration of content. Within a more rigid curriculum where the value of time is high, students may leave a class with a more limited breadth of knowledge. In addition, if a given class is a student's first experience with Harkness and the class itself is not well-designed, then the student's learning outcomes will suffer. This may especially be true at the engineering level where many classes have expansive amounts of curriculum that is expected to be covered.

Oxford's Tutorial system is a far cry from the America's traditional schooling at public universities, but is still divided from Harkness in terms of unbiased exploration. Since pure Harkness may be a difficult endeavor to incorporate into Engineering curriculum, a hybrid teaching method may be necessary. At Oxford, the tutorial system is matched with lectures, labs, study periods, and other mechanisms of pedagogy used to deliver knowledge to be utilized in the tutorial. Harkness would benefit, similar to the tutorial system, from a hybrid class environment, where external content can be used to inform Harkness discussion.

The Harkness method, a discussion-based learning method, has not been applied to any engineering programs, but can by being modeled after the Oxford Tutorial method. Like

Waypoints, Harkness encourages student engagement in individual classes, giving educators a greater ability to care for each individual in the classroom. Harkness is unique because the model realizes the importance of student-to-student interaction and seeks to welcome it as a critical part of the learning experience. Harkness has a place in engineering curriculum, and this paper seeks to formalize how Harkness can be implemented at an institutional level.

Conclusion

The Waypoints Model and Harkness method are both viable means of soliciting student engagement in the classroom with different focuses on the student experience. Where the Waypoints model makes an effort in developing a student’s independent organization skills, the Harkness method develops self-sovereignty, curiosity, and confidence in learning. The two models differ from traditional, primarily rigid lecture learning with different levels of departure, Harkness being more extreme than Waypoints. Both focus on developing a student’s personal skills in conjunction with content knowledge. Waypoints is still in its nascent stages, being tested in classrooms at the University of Virginia’s Department of Engineering. Conversely, Harkness is not currently implemented at the university level but its derivative, Oxford Tutorial Learning is. A radical change to engineering pedagogy lies within the Harkness method, but the question remains of how it can be done. Where can Harkness fit in a similar hybrid environment to Oxford’s and how can it specifically be applied to engineering disciplines?

Bibliography

Fredericksen, E., Pickett, A., Shea, P., Pelz, W., & Swan, K. (2019). Student satisfaction and perceived learning with on-line courses: Principles and examples from the SUNY learning network. *Online Learning*, *4*(2). https://doi.org/10.24059/olj.v4i2.1899

Leshed, G., & Sengers, P. (2011). "I lie to myself that I have freedom in my own schedule". *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*. https://doi.org/10.1145/1978942.1979077

Saleh, D., Camart, N., & Romo, L. (2017). Predictors of stress in college students. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.00019

Arlin, Marshall, and Janet Webster. "Time costs of mastery learning." Journal of Educational Psychology 75.2 (1983): 187.

McGonigal, J. (2011). Reality is broken: Why games make us better and how they can change the world. Penguin.

Garfield, J. (1994). Beyond Testing and Grading: Using Assessment to Improve Student Learning. *Journal of Statistics Education*, *2*(1). https://sites.google.com/a/shs-wasc.info/www/Assessment--BeyondTestsandGrading.pdf

Koedinger, K., Corbett, A., Ritter, S., & Shaprio, L. (2000). Carnegie learning's cognitive tutor: Summary research results. *Carnegie*

Learning. http://pact.cs.cmu.edu/pubs/Koedinger,%20Corbett,%20Ritter,%20Shapiro%2000.pdf

Williams, G. (2014). Harkness learning: principles of a radical American pedagogy. *Journal of Pedagogic Development*, *4*(3). https://uobrep.openrepository.com/handle/10547/335887

Song, H., Grabowski, B. L., Koszalka, T. A., & Harkness, W. L. (2006). Patterns of instructional-design factors prompting reflective thinking in middle-school and college level problem-based learning environments. *Instructional Science*, *34*(1), 63-87. https://doi.org/10.1007/s11251-005-6922-4

Seifert, K., & Mandzuk, D. (2006). Student cohorts in teacher education: Support groups or intellectual communities? *Teachers College Record*, *108*(7), 1296-1320. https://doi.org/10.1111/j.1467-9620.2006.00694.x

Personalised learning. (2020). University of Oxford. https://www.ox.ac.uk/admissions/undergraduate/student-life/exceptional-education/personalised-learning

Slavin, R. E., & Madden, N. A. (1989). What Works for Students at Risk: A Research Synthesis. *Educational Leadership*. https://d1wqtxts1xzle7.cloudfront.net/38057120/el_198902_slavin.pdf?1435742788=&response-content-disposition=inline%3B+filename%3DWhat_Works_for_Students_at_Risk_A_Resear.pdf&Expires=1605473558&Signature=dkMPdRkyV-kItfHNRonViH3c33ZTe3M2EckXug87V~wnl0ANeTEZbVlh3RXnWksfEDCURx4g6SmyRrfUbyIWfgiaFPEV7b~RDDIpnT0p5jNmceUrwI8DIcPRwUqmefyPKtdeg2wG4tInnJOW5QDWfXYaHeWzSML3HjdSf8e2cytof3Xm1ybqMqcbd9H-C3CeQB2x4LTfrXaJZDrWW-yyw~P8td1y6m84LiQwPIRlbxrSWGUickGQSoU~~0djx40zm0Qcx9rBKCh-b-HBnEO4RKjcu8IqOugbkuJDZEG-GqpgPRkZ2poYTI8ynKgunr0ZCM7XclE-PHScA0OwPU3bfw__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

Engineering science. (2020). University of Oxford. https://www.ox.ac.uk/admissions/undergraduate/courses-listing/engineering-science

Ashwin, P. (2005). Variation in students' experiences of the 'Oxford tutorial'. *Higher Education*, *50*(4), 631-644.

Parsons, J., & Taylor, L. (2011). Improving student engagement. *Current issues in education*, *14*(1).

Waypoints: Theory Paper

Capstone – Technical Report

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Waypoints

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***Abstract*—This article introduces a model called Waypoints, designed to mitigate or solve some of the problems apparent in Computer Science classrooms at public universities in the United States. The article begins by identifying and addressing modern issues in college course structure, assessment, and learning outcomes. From students who fall behind in courses to those who excel and wish to go further, the model we put forth addresses the needs of each category of student. The model we set forth is called Waypoints. Informed by Mastery Learning, inspired by the Carnegie Tutor, with room for gamification: Waypoints is driven by six major principles: Well Specified Goals, Freedom to Fail, Meaningful Choice, Assessment Driven Feedback, Concrete/Permanent Milestones, and Visibility. From the student perspective, students have the freedom to progress through a class how they see fit and understand their standing and trajectory as the semester progresses. Similarly, teachers will be able to track the progress of each student, provide help, and better understand how students are performing in their class. We finalize the paper by outlining implementation templates for different forms of class as well as FAQs for some of the design and tradeoff decisions when creating a class with Waypoints.**

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

Within a large classroom, there is a wide distribution of students. Within that range, there are students who move through the class with ease and those who fall behind. A traditional teaching format, as defined by public universities in the United States, does not fully serve either of these student bodies. With weekly assignments and monthly Midterms, students are expected to learn at the rigid pace in line with the due dates of each assessment. In reality, not all students move at the same pace nor at the pace a given class sets. (Gallegos et. al, 1968) This can be mitigated by investing copious amounts of Teacher Assistant resources, but does not solve the problem of pacing.

Many students and teachers alike make compromises and face uncertainty in the classroom. Strict deadlines can be a bane for students who fall behind and the class's direction may not be clear. For teachers, it may not be clear where students get stuck or what an individual student knows when leaving the class.

This does not encompass every student in a large classroom, but does describe the behavior of students who fall behind and don't quite keep pace. How can a class better serve students who fall behind and take more time to learn at the scale of hundreds? Students should be able to move at their own pace, understanding how assessments connect with the knowledge taught in lecture. Teachers should be able to see where specific students struggle and understand what those students know throughout the course. We define an intermediate CS class as a case study, describe our motivating observations, and define Waypoints, our solution informed by the symptoms present in our case study.

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II. Motivation

For many decades, researchers have been working to study novel approaches to education including (but clearly not limited to) inquiry learning (Lazonder, 2013), flipped classrooms (Kerr, 2015), or maker education (Hsu, 2017). However, most college STEM courses still use a traditional lecture model (Stains et al.) and a traditional grading scheme: the final grade is a weighted average of homework, exams, etc. This article does not aim to take the position that traditional college courses are necessarily ineffective. In fact, there is a great deal of research on optimizing lecture-based strategies (Jordan, 2019) (Bligh et. al, 2000) Instead, this article identifies specific issues in college courses at a large public university in the United States, and aims to develop alternative approaches for courses that alleviate these issues. We shall introduce these issues using a case study.

A. Case Study

One symptomatic course is a large (n=437) course in Computer Science. The course is the third in the course sequence and covers data structures and algorithms as well as low-level processing of data. The course is highly technical, content-rich, and challenging for students. It has a traditional course structure including lectures, weekly homework (45% of grade), and three exams (two midterms at 15% each and one final exam at 25%). In the most recent iteration of the course, several troubling trends have appeared:

1) Performance in Proctored vs. Unproctored Assessments: The first trend is that the achievement gap between many students' non-proctored assessments (homework) and proctored assessments (exams) is high. During Fall of 2018, the students averaged 20.76 percentage points higher on non-proctored assessments than proctored ones. For students who passed with less than an A (i.e., C- through B+), that difference is 25.9 percentage points. While a higher score on non-proctored assessments is expected, the size of this difference is alarming and implies that at least one of these measurements is not a useful indication of student learning. The pessimistic concern is that students are moving through coursework without learning the material. This prompts the question of what do students really know?

Exams test an aggregate of topics within a course. The final result of that exam corresponds to how much of that pool that you know. Coming out of the Exam, a letter grade does not indicate which specific topics students are proficient in.

2) Letter Grades and correlation to Knowledge: Another discouraging trend is the wide variety of knowledge distributions that map to the same letter grade. When using traditional grading schemes, there is not a clean mapping from letter grade in a course to the distribution of grades that produced it. For example, in the aforementioned course, one B student earned a 76.77% and 73.77% on exams and homeworks respectively while another B student earned a 58.34% and 97.53% on exams and homework respectively. This implies a wide range of skill levels even among B students, and the letter grade offers little intuition on a student's topic-level knowledge in the course.

Investigating this effect in more detail leads to another potentially problematic symptom. A letter grade does not in itself give instructors (say, future instructors in later courses or accreditation agencies) the information to assess what topics are in need of remediation. To this end, a concept graph was developed by course staff. These concept graphs (dragon et al. 1)(dragon et al. 2) describe the topics of a course along with the inter-relationships between those concepts. In addition, exam data was coded by which topic it covered so that mastery of individual topics in the course could be observed. This was meant as an exploratory activity to identify issues in topic coverage, topic assessment, or student weaknesses in the material. The graph was then colored by the average grade students achieved on each topic on proctored assessments. These graphs were further dissected and organized by each final letter grade rewarded in the course.

Figure 1 shows the topics in the course (one per box) and the prerequisite structure of material (arrows) between topics. The topics are ordered chronologically from bottom to top. Table 1 shows the same graph for multiple letter grades earned in the course. The coloring of each topic denotes the degree of mastery (Red, Orange, Yellow, Green). Not surprisingly, the top students have a high degree of mastery in every topic. However, as final grades deteriorate, the lack of mastery in the course topics appears almost completely in the earlier topics. For example, B students tend to struggle slightly with the first topics in the course, and then eventually regain footing and succeed moving forward. This pattern continues through progressively lower letter grades.

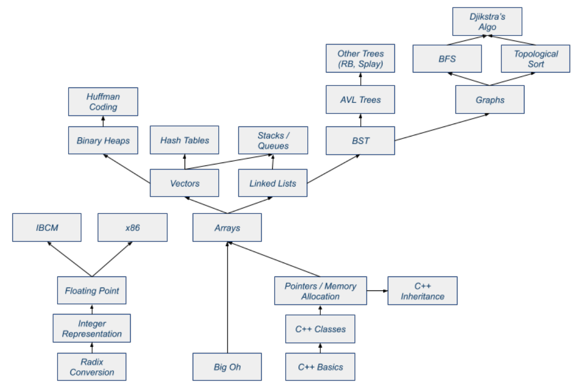

Fig. 1. A topic-level description of the course was developed by the instructor with prerequisites between topics shown as arrows

III. Background

The trends described (the gap in homework/exam performance, difficulty in assessing student knowledge from letter-grade alone, and weak performance in early course topics) motivate the design of a new course structure to potentially alleviate these issues. A mastery learning approach (Bloom)(Cohen) appears promising because of the observation that students tend to struggle early in the semester. Students seem to eventually get their footing, but only after they have lost much credit early on. A mastery learning approach might allow students to more deeply reflect and work on those early topics, allowing for more successful proctored assessments later on in the course. Specifically, Keller's Personalized System of Instruction (PSI) (Keller et. al.) describes high level approaches to applying Mastery learning in a college setting, many of which have been adopted in this new approach (see Course Design below). Research has suggested these approaches are effective (Guskey and Gates, 1986)(Kulik,Kulik, and Bangert-Drowns, 1990). Additionally, modern technology has proved useful in scaling Mastery Learning approaches in recent years. For example, Carnegie Learning's Cognitive Tutor (Ritter et al.)(Alenven, 2010) uses technology-based mastery learning to teach Mathematics at scale.

Mastery Learning approaches are promising in reformulating the course structure to focus on tackling course topics individually. Other techniques can be adopted to potentially optimize the interaction. In particular, there is concern Mastery Learning must 1) take ordering of topics and structure into consideration, 2) consider motivation and engagements of students, and 3) plan strategies for efficiency (of grading, assessments, etc.).

For the first challenge (topic order), we revisit the Concept Map (dragon et al. 1)(dragon et. al. 2). This activity produces a directed-acyclic graph denoting the topics of the course,

TABLE I

A TOPIC LEVEL BREAKDOWN OF PERFORMANCE IN THE LARGE, STANDARD COURSE. AS LETTER GRADES DETERIORATE, POOR PERFORMANCE TENDS TO APPEAR AT THE EARLIEST TOPICS FIRST. THIS PATTERN CONTINUES

and allows for a course structure that corresponds to any topological ordering of the nodes.

For challenge 2 (motivation and engagement), one can consider the literature on Gamification. Many gamification and motivational strategies exist (Francisco et al., 2013) (Werbach et al, 2015) (Werbach et al. 2, 2014), and these are constantly being applied to many fields (e.g., Floryan et al. TBM). Because gamification often focuses on giving “players” concrete goals, digestible tasks, and permanent rewards (eg. McGonigal, 2015), the mechanics of these models is compatible with Mastery Learning. Other models, such as Octalysis (Chou, 2019), present specific mechanics of gamification but don’t focus on the inner motivation each addresses. Thusly, applying aspects of gamification (e.g., agency in players, small irrevocable rewards, meaningful goals) can help optimize motivation in a Mastery Learning setting.

For the final challenge (efficiency), one can look to the literature on efficient assessments (e.g., Nilsen’s Specification Grading) (Nielsen, 2015). Specification grading describes a model for assessment in which requirements are described as a specification (checklist for the threshold the instructor requires). Laborious tasks like grading are expedited as the instructor merely asks themselves if the items in the specification are met, and if the work is “above threshold”.

Given the motivation presented and the wealth of alternative approaches to course construction, the goal of this study was to redesign a college-course in Computer Science using a unique amalgamation of Mastery Learning design, motivational / gamification elements, and technology-based Concept-Mapping as described above.

IV. WAYPOINTS

Well Specified Goals, Freedom to Fail, and Meaningful Choice are all pillars of gamification strategy. If a student is to independently drive their own assessment of mastery over material, they need to understand what that material is, to be able to try to master it again and again, and feel that they have control over that mastery. To support this effort, students should have a short feedback loop so that they know where they are in a class, clear, permanent waypoints so that students do not have to worry about re-assessing mastery, and what future waypoints there are in the course so that they can plan ahead. This maps to the Assessment-Driven Feedback, Concrete / Permanent Milestones, and Visibility principles of Waypoints. Below we introduce and elaborate on Waypoints in more depth.

The Waypoints model aims to provide general guidance on providing students a mastery based approach to learning synergized with motivation principles. This model urges instructors to not just provide courses designed for mastery (e.g., freedom to fail) but to also provide incentive structures from gamification literature (e.g., irrevocable achievements, meaningful choice, well defined goals) and work towards implementing these features efficiently (e.g., assessment-driven feedback). In this way, Waypoints is designed to encourage instructors to aim for mastery while simultaneously increasing student agency.

TABLE II
NAME AND DESCRIPTION OF SIX DESIGN PRINCIPLES OF THE WAYPOINTS MODEL

Waypoints Principle	**Short Description**
Well Specified Goals	• Course mechanics all directly relate to students' primary objective (e.g., learn, earn letter grade, earn prize, etc.) • Requirements for goals is well-defined and communicated clearly
Freedom to Fail	• Students always have a path to success, even if that path is changing and fluid. • All assessments, tasks, etc. have unlimited attempts.
Meaningful Choice	• Students can make meaningful decisions in how they reach their goals. • There are multiple unique, equally feasible, paths to success.
Assessment Driven Feedback	• Failure and success are provided on a fine-grained scale, as often as possible. • Feedback is immediate, or as close to as is possible.
Concrete / Permanent Milestones	• Milestones are developed for students that are fine-grained, concrete, and understandable. • Milestones are permanent and irrevocable.
Visibility	• Students have a clear view of their current status. • The steps to achieve the next milestone are communicated clearly.

A layered view of Waypoints can be seen in figure 2. The model is built on the conceptual underpinnings of mastery learning, enhanced by common techniques in gamification, and made efficient through techniques such as technology-based assessments, specification grading, etc. We can abstract the pillars of Waypoints into three mutually inclusive layers: Foundational, Motivational, and Efficiency.

1) Foundational Layer: The Foundational Layer defines principles of Waypoints that determine how a class should be organized in terms of structure and content. Within the Foundation Layer, well-specified goals state that the course design should explain, up-front, the requirements for achievement in the given course. Most college courses already do this (in the form of a syllabus or similar). The visibility principle states that students should be able to see this structure at all times and understand where they stand in relation to this structure.

2) Motivational Layer: The motivational layer focuses on principles that provide agency and/or engagement to students. Overlapping with the Foundational Layer, Concrete Milestones provide students with tangible achievements and waypoints throughout the class, making it easier to chart a clear path to success. Assessment Driven feedback allows students to understand where they are in a class at any given time and plan their course of action from that information.

3) Efficiency Layer: The Efficiency Layer totally overlaps with the Motivational Layer for two principles. Freedom to fail allows students to fearlessly engage with course content until success is reached, without being held back by misunderstandings or mistakes. Meaningful choice states that students should be able to make decisions regarding how they would like to approach reaching each waypoint in a class.

Some elements of the model overlap multiple layers because they incorporate each other. For example, Concrete / Permanent Milestones is a foundational principle in the sense that it helps define the course-structure and content. However, these permanent milestones are also motivational because students can always work to reach the next Waypoint.

The Waypoints Model is composed of ideas that have been brought forth before and in isolation are not unique to this paper. Waypoints' value is in the synergy brought forth in each of its principles being implemented in a class together. The intended end result is a class where students progress through their class with greater agency: taking risks and understanding where they are in the class and which paths to take to complete their waypoints before the end of the semester.

V. APPLICATIONS OF THE WAYPOINTS MODEL

In an effort to ascertain the benefits and drawbacks of the Waypoint Model, the model is being applied to a range of classes from foundational level curriculum to electives in Computer Science. Different courses need to be treated differently as the Waypoints Model is being applied to it.

1) Lecture based, Foundations Class: Foundation level classes usually contain multiple symmetrical pathways that each student has to fulfil. This is because most foundation level classes have multiple entry points for knowledge, such as in Fig. 1. For students to achieve similarly in the class, they must complete similar milestones by the end of the course. The waypoints model can be applied directly to this class format in two steps. Organize the class hierarchically

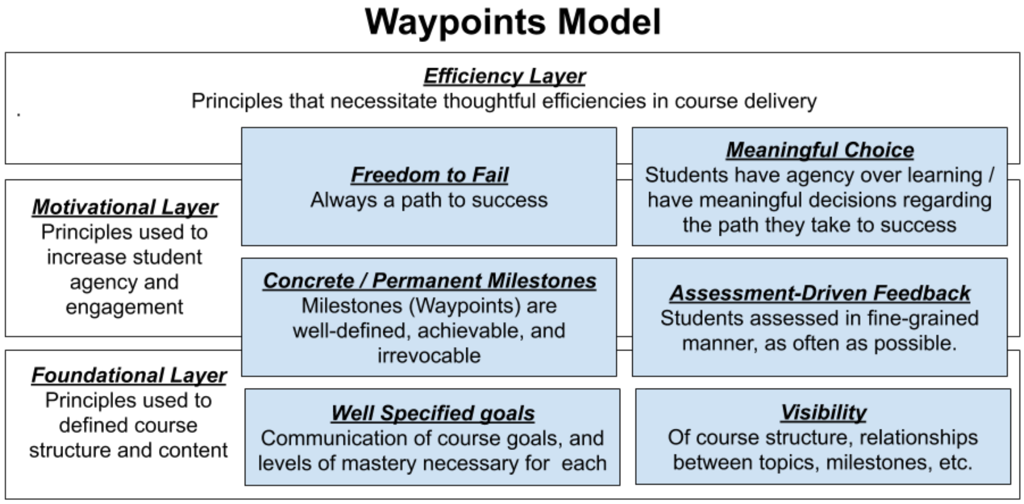

Fig. 2. A layered view of the six principles of the Waypoints model. The principles inform course design as foundational / structural, motivational, and have an effect on efficiency

so that prerequisite topics come before future topics. Replace midterms with repeatable milestone relevant quizzes.

TABLE III
NAME AND APPLICATION OF SIX DESIGN PRINCIPLES OF THE WAYPOINTS MODEL

Waypoints Principle	Short Implementation Description
Well Specified Goals	Class is organized into ordered, interconnected waypoints starting with skills/topics students are expected to leave the class with a demonstrated mastery.
Freedom to Fail	Students have the ability to re-assess themselves on previous waypoints as the class continues. This includes resubmitting assignments and re-taking quizzes
Meaningful Choice	Students choose when and in what order to complete waypoints throughout the class
Assessment Driven Feedback	Quizzes and Homeworks are given for each waypoint with a reasonably fast turnaround time for grading.
Concrete / Permanent Milestones	Once a student exhibits mastery for a given waypoint, they do not need to be assessed again. The waypoint and its expected learning outcomes should be well-defined.
Visibility	The status of the student in the class including their current grade and the paths available to receive a higher grade is obvious to the student.

Note: Implementation of repeatable quizzes can be found in the FAQ at the end of this paper.

2) Group Project Based, Elective Class: Group projects, especially those that are unique will require a more flexible approach. The hierarchical structure that a student will take can be designed by the student, or the teacher if there are more generalized roles to fulfill. For example, in a Game Design class, different students may be given different roles on their teams; being game engine design, level design, etc. and each of these roles will be given a different hierarchy.

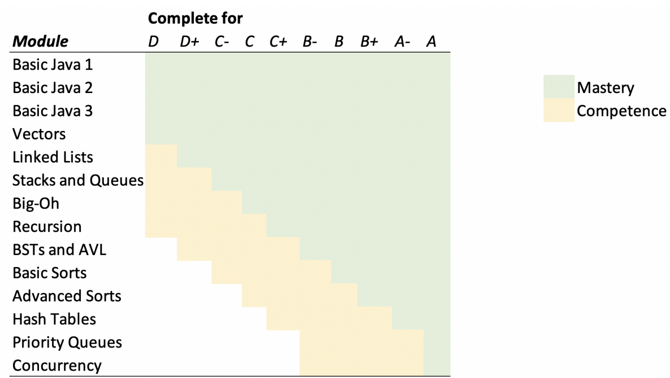

Fig. 3. Ordered Class modules and Passing criteria associated with each grade. In this grading scheme, there is a direct correlation between specific topic mastery and the final grade.

3) Courses with many independent topics: Some Survey courses that have a tremendous breadth of knowledge will have a greater number of root nodes in its Topological Waypoint Map. The same treatment from the foundation class should be applied to this one. A consequence may be certain topics in the Survey class may not be completed. To prevent this, topical waypoints are distilled into smaller, more manageable waypoints that students will have a greater ability to complete. This allows them to cover the full breadth of topics. The converse effect is that some students may not be able to delve as deeply into this each given topic. This will have to be balanced at the teacher's discretion.

TABLE IV
NAME AND APPLICATION OF SIX DESIGN PRINCIPLES OF THE WAYPOINTS MODEL

Waypoints Principle	Short Implementation Description
Well Specified Goals	Class is ordered into waypoints similarly to a Foundation course. Students and/or teachers can add branching waypoints
Freedom to Fail	For introduction material, the class can be formatted similarly to a Foundation course. Since in a Group Project, some steps/waypoints may be necessary to complete across students before moving on, some hard deadlines for specific waypoints may be necessary.
Meaningful Choice	Same as Foundation class with a greater emphasis on the order of completion for the Group Project.
Assessment Driven Feedback	Same as Foundations class.
Concrete / Permanent Milestones	Same as Foundations class.
Visibility	Same as Foundations class.

Note: Implementation of repeatable quizzes can be found in the FAQ at the end of this paper.

VI. FUTURE WORK IN APPLICATION OF WAYPOINTS TO COURSES

Currently, we are collecting and compiling data for a foundations level class. With this data, a quantifiable comparison between a traditional class and a Waypoints class can be made. This is expected to be the results of another paper.

We will test this method on the following classes:

Data Structures and Algorithms (DSA) I: A foundations level course in Computer Science designed to teach students above introductory level data structures such as Arrays, Vectors, and Hash Maps as well as everyday algorithms such as Quick-Sort and Merge-Sort. This is similar to the "Lecture based, Foundations Class" case study described above.

Game Design: A primer in Computer Game Design teaching students the fundamentals of the field and culminating in a large scale group project. This is similar to the "Group Project Based, Elective Class" case study described above.

We are currently running data collection on the DSA course and will present a paper on the findings and reflections from that experience.

VII. POSSIBLE CRITICISMS / FAQ

Isn't there too much responsibility on students to relearn "how" to do the course? Time management and ownership of work is a skill the students are required to grasp before leaving university. Waypoints is a means of providing this independence to students so that they may learn in the best way possible. This growing period may certainly exist in the first class a student will take using Waypoints, but students should become more comfortable with the freedom offered to them as they take more classes using this method.

How does Waypoints approach the classic time versus mastery trade-off? Some students will not complete all the waypoints in a course. That is a very real and reasonable consideration to have. The Waypoints model clearly shows who falls off and where they do so. Waypoints does not leave this problem to the imagination like in a traditional classroom. In light of the time trade off from Mastery learning we have considered issuing certificates for students who complete all waypoints of a course any time after the course ends. This can sufficiently reward students who are invested in a class and continue with it during breaks. The certificate solution can market students better on their resumes.

Waypoints will be harder on TAs because they must be ready to grade anything each week To fulfill Assessment Driven Feedback, quizzes and homeworks need to be graded with a fast turnaround time. In the best case scenario, this can be somewhere between an instantaneous or day-to-day response. At the moment, automation of the classroom is relatively limited for in-person learning, and the brunt work of grading relies on human/TA labor. To rely less heavily on TAs for grading, there would have to be an online grading system for homeworks and quizzes alike. For homeworks, tools like Gradescope exist for coding assignments with specific test cases. For quizzes, there currently isn't a system which is satisfactory to us, so we are currently developing one for this purpose.

How can you re-assess students when you are using an assessment tool like a quiz? Following the example of the Carnegie Mellon Cognitive Tutor, you can create a pool of assessable questions and randomly choose the questions for every admission of a quiz. This can be done either by paper, physically printing out the random questions, or online using a quizzing tool. New questions can be added every semester to continue to grow the pool of questions.

What if students don't master every topic in a class and go to the next class in the series? Won't they get left behind? Under this model, students should only be passed if they have the necessary prerequisites mastered to achieve satisfactory in the next class. A given class in a series should be designed so that students leave the class with mastery in a satisfactory range of topics/waypoints so that they can perform well in subsequent classes. Depending on the rigor of the class in question, the waypoints needed to pass the class should be adjusted.

Follow Up: Does that mean that classes built using this model will have buffer knowledge that students don't need for future classes? A syllabus for a class is an ideal representation of what knowledge students should leave a class with, but this is not necessarily reflective of reality. Waypoints provides a greater amount of control of what students know when they leave a course by requiring mastery on certain topics to pass the class. It is up to the educator to decide what these topics are and how many of these constitute the class. The optimization of this balance should be the topic of a future paper.

REFERENCES

[1] Vincent A. W. M. M. Aleven and Kenneth R. Koedinger. "An effective metacognitive strategy: learning by doing and explaining with a computer-based Cognitive Tutor". In: *Cognitive Science* 26.2 (2002). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1207/s15516709cog2602_1, pp. 147–179. ISSN: 1551-6709. DOI: https://doi.org/10.1207/s15516709cog2602_1. URL: https://onlinelibrary.wiley.com/doi/abs/10.1207/s15516709cog2602_1 (visited on 04/17/2021).

[2] Marshall Arlin and Janet Webster. "Time costs of mastery learning". In: *Journal of Educational Psychology* 75.2 (1983). Place: US Publisher: American Psychological Association, pp. 187–195. ISSN: 1939-2176(Electronic),0022-0663(Print). DOI: 10.1037/0022-0663.75.2.187.

[3] Jeffrey H. Barsuk et al. "A Comparison of Approaches for Mastery Learning Standard Setting". In: *Academic Medicine* 93.7 (July 2018), pp. 1079–1084. ISSN: 1040-2446. DOI: 10.1097/ACM.0000000000002182. URL: https://journals.lww.com/academicmedicine/FullText/2018/07000/A_Comparison_of_Approaches_for_Mastery_Learning.33.aspx (visited on 04/29/2021).

[4] Donald Bligh and Beverly J. Cameron. "[What's the use of lectures?]" In: *The Canadian Journal of Higher Education* 30.1 (2000). Num Pages: 192-196 Place: Toronto, Canada Publisher: Canadian Society for the Study of Higher Education, pp. 192–196. ISSN: 03161218. URL: https://search.proquest.com/docview/221140852/abstract/B6DC34CD7EA9417FPQ/1 (visited on 04/09/2021).

[5] James H. Block and Robert B. Burns. "Mastery Learning". In: *Review of Research in Education* 4 (1976). Publisher: [Sage Publications, Inc., American Educational Research Association], pp. 3–49. ISSN: 0091-732X. DOI: 10.2307/1167112. URL: https://www.jstor.org/stable/1167112 (visited on 04/29/2021).

[6] Benjamin S. Bloom. "A Response to Slavin's Mastery Learning Reconsidered". In: *Review of Educational Research* 57.4 (1987), pp. 507–8. (Visited on 04/29/2021).

[7] Ward Canfield. "ALEKS: A Web-based intelligent tutoring system". In: *Mathematics and Computer Education* 35.2 (2001). Num Pages: 7 Place: Old Bethpage, United States Publisher: Mathematics and Computer Education, pp. 152–158. ISSN: 07308639. URL: https://search.proquest.com/docview/235901507/abstract/DC7F9EEB64E04B3DPQ/1 (visited on 04/29/2021).

[8] Yu-kai Chou. *Actionable Gamification: Beyond Points, Badges, and Leaderboards*. Google-Books-ID: 9ZfBDwAAQBAJ. Packt Publishing Ltd, Dec. 3, 2019. 500 pp. ISBN: 978-1-83921-077-8.

[9] Scotty D. Craig et al. "The impact of a technology-based mathematics after-school program using ALEKS on student's knowledge and behaviors". In: *Computers & Education* 68 (Oct. 1, 2013), pp. 495–504. ISSN: 0360-1315. DOI: 10.1016/j.compedu.2013.06.010. URL: https://www.sciencedirect.com/science/article/pii/S0360131513001619 (visited on 04/29/2021).

[10] Jean-Paul Doignon and Jean-Claude Falmagne. *Knowledge Spaces*. Google-Books-ID: yxnsCAAAQBAJ. Springer Science & Business Media, Dec. 6, 2012. 349 pp. ISBN: 978-3-642-58625-5.

[11] Jean-Paul Doignon and Jean-Claude Falmagne. "Spaces for the assessment of knowledge". In: *International Journal of Man-Machine Studies* 23.2 (Aug. 1, 1985), pp. 175–196. ISSN: 0020-7373. DOI: 10.1016/S0020-7373(85)80031-6. URL: https://www.sciencedirect.com/science/article/pii/S0020737385800316 (visited on 04/29/2021).

[12] T. Dragon and C. Lindeman. "Automated Assessment of Students' Conceptual Understanding: Supporting Students and Teachers Using Data from an Interactive Textbook". In: *2017 IEEE International Symposium on Multimedia (ISM)*. 2017 IEEE International Symposium on Multimedia (ISM). Dec. 2017, pp. 567–572. DOI: 10.1109/ISM.2017.111.

[13] Toby Dragon. "Turning the Tables: Authoring as an Asset Rather than a Burden:" in: *Proceedings of the 10th International Conference on Computer Supported Education*. 10th International Conference on Computer Supported Education. Funchal, Madeira, Portugal: SCITEPRESS - Science and Technology Publications, 2018, pp. 308–315. ISBN: 978-989-758-291-2. DOI: 10.5220/0006761503080315. URL: http://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0006761503080315 (visited on 04/29/2021).

[14] Toby Dragon and Elisabeth Kimmich Mitchell. "Improving Course Content While Creating Customized Assessment and Support at the Conceptual Level:" in: *Proceedings of the 10th International Conference on Computer Supported Education*. 10th International Conference on Computer Supported Education. Funchal, Madeira, Portugal: SCITEPRESS - Science and Technology Publications, 2018, pp. 110–121. ISBN: 978-989-758-291-2. DOI: 10.5220/0006710101100121. URL: http://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0006710101100121 (visited on 04/29/2021).

[15] Toby Dragon and Elisabeth Kimmich Mitchell. "TECMap: Technology-Enhanced Concept Mapping for Curriculum Organization and Intelligent Support". In: *Computer Supported Education*. Ed. by Bruce M. McLaren et al. Communications in Computer and Information Science. Cham: Springer International Publishing, 2019, pp. 191–213. ISBN: 978-3-030-21151-6. DOI: 10.1007/978-3-030-21151-6_10.

[16] Ying Fang et al. "A meta-analysis of the effectiveness of ALEKS on learning". In: *Educational Psychology* 39.10 (Nov. 26, 2019). Publisher: Routledge _eprint: https://doi.org/10.1080/01443410.2018.1495829,

pp. 1278–1292. ISSN: 0144-3410. DOI: 10 . 1080 / 01443410.2018.1495829. URL: https://doi.org/10.1080/01443410.2018.1495829 (visited on 04/29/2021).

[17] Mark R Floryan, Lee M Ritterband, and Philip I Chow. "Principles of gamification for Internet interventions". In: *Translational Behavioral Medicine* 9.6 (Nov. 25, 2019), pp. 1131–1138. ISSN: 1869-6716. DOI: 10.1093/tbm/ibz041. URL: https://doi.org/10.1093/tbm/ibz041 (visited on 04/29/2021).

[18] Arnold M. Gallegos. "A Study and Comparison of Experimenter Pacing and Student Pacing of Programed Instruction". In: *The Journal of Educational Research* 61.8 (Apr. 1, 1968). Publisher: Routledge _eprint: https://doi.org/10.1080/00220671.1968.10883693, pp. 339–342. ISSN: 0022-0671. DOI: 10 . 1080 / 00220671 . 1968 . 10883693. URL: https : / / doi . org / 10 . 1080 / 00220671 . 1968 . 10883693 (visited on 04/17/2021).

[19] Jianxiong Gao, Bei Pang, and Steven S. Lumetta. "Automated Feedback Framework for Introductory Programming Courses". In: *Proceedings of the 2016 ACM Conference on Innovation and Technology in Computer Science Education*. ITiCSE '16. New York, NY, USA: Association for Computing Machinery, July 11, 2016, pp. 53–58. ISBN: 978-1-4503-4231-5. DOI: 10.1145/2899415.2899440. URL: https://doi.org/10.1145/2899415.2899440 (visited on 04/29/2021).

[20] Layna Groen et al. "The Mathematics Problem and Mastery Learning for First-year, Undergraduate STEM Students". In: *International Journal of Learning, Teaching and Educational Research* 11.1 (Apr. 30, 2015). Number: 1. ISSN: 1694-2116. URL: http://ijlter.org/index.php/ijlter/article/view/303 (visited on 04/29/2021).

[21] Thomas Guskey and Sally Gates. "Synthesis of Research on the Effects of Mastery Learning in Elementary and Secondary Classrooms". In: *Educational Leadership* 43.8 (May 1, 1986), pp. 73–80. URL: https://uknowledge.uky.edu/edp_facpub/23.

[22] Gary Hagerty and S. Smith. "Using the Web-Based Interactive Software ALEKS to Enhance College Algebra". In: *Mathematics & Computer Education* 39.3 (2005), pp. 183–194. ISSN: 07308639. URL: http://proxy01.its.virginia.edu/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eft&AN=507834304&site=eds-live (visited on 04/29/2021).

[23] *How Mastery Learning Works at Scale — Proceedings of the Third (2016) ACM Conference on Learning @ Scale*. URL: https://dl.acm.org/doi/abs/10.1145/2876034.2876039 (visited on 04/29/2021).

[24] *How Mastery Learning Works at Scale — Proceedings of the Third (2016) ACM Conference on Learning @ Scale*. URL: https://dl.acm.org/doi/abs/10.1145/2876034.2876039 (visited on 04/29/2021).

[25] Yu-Chang Hsu, Sally Baldwin, and Yu-Hui Ching. "Learning through Making and Maker Education". In: *TechTrends* 61.6 (Nov. 1, 2017), pp. 589–594. ISSN: 1559-7075. DOI: 10.1007/s11528-017-0172-6. URL: https://doi.org/10.1007/s11528-017-0172-6 (visited on 04/17/2021).

[26] Jaime Jordan et al. "Optimizing Lectures From a Cognitive Load Perspective". In: *AEM Education and Training* 4.3 (2020). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/aet2.10389, pp. 306–312. ISSN: 2472-5390. DOI: https://doi.org/10.1002/aet2.10389. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/aet2.10389 (visited on 04/17/2021).

[27] Fred S. Keller. "Ten Years of Personalized Instruction". In: *Teaching of Psychology* 1.1 (Oct. 1, 1974). Publisher: SAGE Publications Inc, pp. 4–9. ISSN: 0098-6283. DOI: 10.1177/009862837400100102. URL: https://doi.org/10.1177/009862837400100102 (visited on 04/17/2021).

[28] B. Kerr. "The flipped classroom in engineering education: A survey of the research". In: *2015 International Conference on Interactive Collaborative Learning (ICL)*. 2015 International Conference on Interactive Collaborative Learning (ICL). Sept. 2015, pp. 815–818. DOI: 10.1109/ICL.2015.7318133.

[29] Chen-Lin C. Kulik, James A. Kulik, and Robert L. Bangert-Drowns. "Effectiveness of Mastery Learning Programs: A Meta-Analysis". In: *Review of Educational Research* 60.2 (June 1, 1990). Publisher: American Educational Research Association, pp. 265–299. ISSN: 0034-6543. DOI: 10.3102/00346543060002265. URL: https://doi.org/10.3102/00346543060002265 (visited on 04/29/2021).

[30] Ard W. Lazonder. "Inquiry Learning". In: *Handbook of Research on Educational Communications and Technology*. Ed. by J. Michael Spector et al. New York, NY: Springer, 2014, pp. 453–464. ISBN: 978-1-4614-3185-5. DOI: 10.1007/978-1-4614-3185-5_36. URL: https://doi.org/10.1007/978-1-4614-3185-5_36 (visited on 04/17/2021).

[31] Cathie Marache-Francisco and Eric Brangier. "From The Consideration of Gamification To Its Practical Implementation". In: (2013), p. 6.

[32] Cathie Marache-Francisco and Eric Brangier. "From The Consideration of Gamification To Its Practical Implementation". In: (2013), p. 6.

[33] Jane McGonigal. *Reality Is Broken: Why Games Make Us Better and How They Can Change the World*. Google-Books-ID: yiOtN_kDJZgC. Penguin, Jan. 20, 2011. 301 pp. ISBN: 978-1-101-47549-2.

[34] Jane McGonigal. *Reality Is Broken: Why Games Make Us Better and How They Can Change the World*. Google-Books-ID: yiOtN_kDJZgC. Penguin, Jan. 20, 2011. 301 pp. ISBN: 978-1-101-47549-2.

[35] Elizabeth Kimmich Mitchell. "Automated Intelligent Group Suggestions Based on Students' Conceptual Understanding". In: (), p. 1.

[36] Linda B. Nilson. *Specifications Grading: Restoring Rigor, Motivating Students, and Saving Faculty Time*. Google-Books-ID: UrCpCwAAQBAJ. Stylus Publishing, LLC, Mar. 1, 2015. 191 pp. ISBN: 978-1-62036-244-0.

[37] Steve Ritter et al. "How Mastery Learning Works at Scale". In: *Proceedings of the Third (2016) ACM Conference on Learning @ Scale*. L@S '16. New York, NY, USA: Association for Computing Machinery, Apr. 25, 2016, pp. 71–79. ISBN: 978-1-4503-3726-7. DOI: 10.1145/2876034.2876039. URL: https://doi.org/10.1145/2876034.2876039 (visited on 04/29/2021).

[38] Steve Ritter et al. "How Mastery Learning Works at Scale". In: *Proceedings of the Third (2016) ACM Conference on Learning @ Scale*. L@S '16. New York, NY, USA: Association for Computing Machinery, Apr. 25, 2016, pp. 71–79. ISBN: 978-1-4503-3726-7. DOI: 10.1145/2876034.2876039. URL: https://doi.org/10.1145/2876034.2876039 (visited on 04/29/2021).

[39] Steven Ritter and Stephen Fancsali. "MATHia X: The Next Generation Cognitive Tutor". In: *EDM*. 2016.

[40] Robert E. Slavin. "Mastery Learning Reconsidered". In: *Review of Educational Research* 57.2 (June 1, 1987). Publisher: American Educational Research Association, pp. 175–213. ISSN: 0034-6543. DOI: 10.3102/00346543057002175. URL: https://doi.org/10.3102/00346543057002175 (visited on 04/29/2021).

[41] M. Stains et al. "Anatomy of STEM teaching in North American universities". In: *Science* 359.6383 (Mar. 30, 2018). Publisher: American Association for the Advancement of Science Section: Education Forum, pp. 1468–1470. ISSN: 0036-8075, 1095-9203. DOI: 10.1126/science.aap8892. URL: https://science.sciencemag.org/content/359/6383/1468 (visited on 04/29/2021).

[42] Kevin Werbach. "(Re)Defining Gamification: A Process Approach". In: *Persuasive Technology*. Ed. by Anna Spagnolli, Luca Chittaro, and Luciano Gamberini. Lecture Notes in Computer Science. Cham: Springer International Publishing, 2014, pp. 266–272. ISBN: 978-3-319-07127-5. DOI: 10.1007/978-3-319-07127-5_23.

[43] Kevin Werbach. "(Re)Defining Gamification: A Process Approach". In: *Persuasive Technology*. Ed. by Anna Spagnolli, Luca Chittaro, and Luciano Gamberini. Lecture Notes in Computer Science. Cham: Springer International Publishing, 2014, pp. 266–272. ISBN: 978-3-319-07127-5. DOI: 10.1007/978-3-319-07127-5_23.

[44] Kevin Werbach and Dan Hunter. *The Gamification Toolkit: Dynamics, Mechanics, and Components for the Win*. Google-Books-ID: RDAMCAAAQBAJ. Wharton School Press, May 5, 2015. 46 pp. ISBN: 978-1-61363-068-6.

[45] Kevin Werbach and Dan Hunter. *The Gamification Toolkit: Dynamics, Mechanics, and Components for the Win*. Google-Books-ID: RDAMCAAAQBAJ. Wharton School Press, May 5, 2015. 46 pp. ISBN: 978-1-61363-068-6.

Limitations of the Lecture Model in Engineering Education and Proposed Alternatives

A Research Paper Submitted to the Department of Engineering and Society

Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements of the Degree
Bachelor of Science, School of Engineering

Zachary Bilmen

Spring, 2021

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

Introduction

The traditional mechanism of pedagogy for engineering in the United States is through lectures. Lectures can be characterized as a teacher, in the role of a field expert, inculcating a large group of students through oratory presentation. We define the *lecture model* to be where activities inside and outside of the classroom, such as homework, are directly associated with individual lectures. The lecture model is the basis of what a traditional engineering class looks like in the US (EurekaAlert, 2018). Despite its position as a standard in engineering education, the lecture model is not the only system of engineering pedagogy to exist. These other models can be characterized by what teaching environment they focalize around, whether it is a one-on-one tutorial or a discussion section. The lecture model is not perfect, and neither are the previously mentioned models. This paper is designed to clarify the benefits and limitations of the lecture model and provide alternatives which are not restrained by the same limitations but inherently bring some of their own. The alternative models we will discuss are the Oxford Tutorial method and Harkness discussion method.

Common Ground on Lectures

Lectures have been empirically proven, through sheer popularity in adoption, to be an effective tool for "transmission of conceptual and systemic knowledge," (Bruce G, 2006) but lacks in other aspects of student learning. To elaborate, lectures are powerful as an "authority structure" centered around the lecturer and can be used as "an instrument for focusing attention" on curriculum-defined content knowledge (Bruce G, 2006); the content students learn in lectures is clear and focused. However, one criticism is that lectures depart from real world experience (Matheson, 2008) (Schmidt, 2015). There are commonplace examples of augmentations to lecture teaching which have been effective to mitigate some of the criticisms such as adding projects, case studies, labs, and discussion sections (Bligh, 2000). These modifications and amendments to individual lectures are part of what encapsulate the lecture model. Given that lectures are still the primary source of information, most of the modifications are still tethered to individual presentations. This requires projects and discussions to be determined by lecture material. This dependency can become an issue if students do not understand the lectures satisfactorily. To further mitigate this within the lecture model, there can be redundant sources of information such as textbook chapters that associate with each individual lecture. As with any model, students should have multiple, fundamentally different opportunities to learn material in case one method is not effective for retention (Wiley, Voss 1999). We have described limitations of the lectures rectified by the lecture model, but there remain limitations that have not been solved by the lecture model in practice.

Figure 1 Example lecture classroom

Student-Teacher interaction

Within a lecture, the teacher-student relationship is unilateral. Lectures involve professors communicating with students but bears no rule for students to interact with professors or each other. Without a control loop where teachers understand where each student is, students are more likely to fall behind and not understand course material (Bernard, 2017). In recent years student-to-teacher interaction has become a standard within the lectures (Scheele, 2005), but this feedback can be coarse due to the size of a lecture and the unique questions and quandaries individual students may have. Office hours too have become standardized in the lecture model (Smith, 2017). Students have a more catered experience in office hours and "can benefit greatly from *active* and *consistent* interaction with faculty" (Smith 2017). "Frequent student-faculty contact in and out of classes is the most important factor in student motivation and involvement. Faculty concern helps students get through rough times and keep on working." (Smith, 2017)

But how often do students attend office hours and for what reasons? According to Smith, this opportunity is underutilized. (Smith, 2017) Within the lecture model, a student's attendance of office hours must be in relation to some lecture material, but students may not deem attendance necessary because all the relevant information is within the lecture. In the exceptional case, attendance is prompted through an "emergency" where "… [the student] was completely lost in all the concepts covered in lecture and/or discussion/lab" (Smith, 2017). Based on Smith's literature, this dependency implies that most students do not use office hours as an opportunity to explore a topic in more depth or develop a motivation for class. This limitation similarly occurs when considering scope of learning a topic. Since lectures only cover certain knowledge, the expectation is that students become experts within that scope. Even if a student's interests go elsewhere, to other spheres of knowledge, there is no substantive opportunity for them to explore it within a curriculum adhering to the lecture model. If student learning were more independent, where students were expected to drive their own learning experience, then the issues of scope and depth in the learning experience could be rectified. If students had sufficient, independently driven, critical thinking skills, then this reality would enter the realm of possibility.

Critical Thinking

Aside from its benefits in academia, critical thinking is a skill all engineering students need to be adept in to critique implementation, design, and safety decisions on the job. Despite the high importance of cultivating this skill among students, this too is one of the limitations the lecture model (Amin, 2020) (Schmidt, 2015). We define critical thinking as "being able to identify questions worth pursuing, being able to pursue one's questions through self-directed search and interrogation of knowledge, a sense that knowledge is contestable and being able to present evidence to support one's arguments" (Soden, 2000). A necessary characteristic of critical thinking is a feedback loop. A continual criticism of an idea until it is refined into knowledge that is informative and understandable. This can be done independently by students, on their own or in groups, but is not explicitly required by lectures. Lectures by default do not contain a student driven feedback-loop, though lectures have been adapted to allow for students to ask questions in class and even complete activities based on live lecture material. There are various limitations to these remedies including time: the time taken from lecture to indulge in critical thinking, and scope: the content being covered in the lecture. How much time should be sacrificed from the teacher's presentation to allow for student driven discussion? What should the lecture content be to inspire the most critical thoughts? How do we ensure students are thinking critically about lecture material? Professors without a rigorous background in education are not well equipped to answer these questions.

Discussion sections may seem to invoke critical thought in students (Soden, 2000), but they may not be effective right off the bat. This may come as a surprise, but students are not predisposed as experts in discussion (Lappalainen, 2008). Just as lecturers need to hone their craft to lecture effectively, students need to practice and develop discussion skills so that they may think critically together. Critical thinking between students can be done effectively in discussion (Soden, 2000), but the quality of that discussion is not guaranteed. Communication skills are not explicitly required by engineering curriculum (Lappalainen, 2008) and discussions, a communication intensive activity, are hard to get right.

There are parts of the lecture model that have empirically benefitted students but also parts that have limited them. The limitations addressed have been the dynamic of student-teacher interaction, how it could be more developed and student focused, and critical thinking, how students should be given the opportunity to learn to think critically with their peers and explore course material independently. To improve the outlook of student success in these aspects of education, we introduce two alternative learning models. One is the Oxford Tutorial method, a learning method primarily focused on teacher guidance and support of individual students. The other is the Harkness method, focused on students' individual ability to think and learn material.

Oxford Tutorial Method

First implemented at Oxford but adapted within a few institutions in the UK such as Cambridge and Oxford, the Oxford Tutorial is also known as the tutorial. The tutorial method is focalized around one-on-one student and teacher tutorials where assignments and study material are set on a tutorial basis (Ashwin, 2005). However, tutorials are not the place where students first interact with knowledge; students have lectures, labs, projects, and study halls to introduce them to information for the first time. The tutorials are the places to review assignments, discuss points of weakness, and drive forward the depth or breadth of knowledge a student can harness through discussion or instruction (Ashwin, 2005). Notably, lectures still exist in the Tutorial method. Despite this overlap, the principles of the lecture model and tutorial method are very different. The primary difference between the tutorial method and lecture model is where students receive the most guidance on what they *should* learn. In the lecture model, the information presented in lecture is what students should learn. In the tutorial method, even though lectures still provide information, the professor a student is paired with determines what information is important.

Benefits of Oxford

The professor – student relationship takes center stage in the tutorial method. Students in an Oxford tutorial receive individual attention from professors. Unlike in a lecture hall, students can ask any question they want to further their own understanding because both the student and professor have joint ownership over a tutorial's time. "[T]he individual nature of the tutorial allows each student to learn at their own pace and to ask any questions they may have. It also allows the tutor to adapt the process to the student's learning needs and to give students immediate feedback on their performance" (Ashwin, 2005). If a student needs help understanding or exploring a topic, the tutor is an expert who can help. Unlike in the lecture model where interaction with the professor is not required, students have a constant, required feedback loop with their professor to make sure they are on the right track.

Oxford has a flexible philosophy when it comes to pedagogy which varies from professor to professor. There is no one experience that students can rely on aside from the fact that they have access to a field expert. This means that students have much more control over their education through discussion with their tutor than they would under a lecture model. Since professors are ultimately in control of what content students will cover, the format of the tutorial allows students to discuss and explore content with their professor even though it is not strictly within the curriculum.

Difficulties of Oxford

Given the nature of the tutorial, there is a direct reliance on the professor for each student's individual success. Whether it is the student-to-professor ratio or the quality of a professor's pedagogy, students' experiences are going to vary dramatically between institutions and professors. If there are an insufficient number of professors compared to the number of students, it may be difficult to host tutorials. The Oxford tutorial increases the number of students in each tutorial as they reach closer to graduation (Oxford Engineering Science, 2021) and has a 15:1 student to faculty ratio (Oxford Engineering Science, 2021). The result of a tutorial that is too large is that students will receive less guidance which is especially valuable in the beginning of their academic career (Walker et. al, 2017). In the lecture model, a class can vary dramatically between professors, so is the same with the Oxford Tutorial.

Because a one-on-one tutorial is very intimate, students and professors can have a wide range of experiences. One of the limitations of the lecture model is the ability to engage students to think critically. Although this is not a direct limitation of the Oxford Tutorial method, it is not a guarantee. Because professors are not explicitly required to engage students in critical discussion, it may not happen. In an analysis of students' experiences in the Oxford Tutorial, Ashwin developed 4 hierarchically ordered perspectives of the tutorial and the role it played in their education (Ashwin, 2010). This hierarchy is not expressly ordered by its emphasis on students' critical thought but does end up being so. The amount of quality critical thinking increases according to the numbering of each student perspective of Oxford tutorial.

1. Tutorials as the tutor explaining to the student what the student does not understand

2. Tutorials as the tutor showing the student how to see the subject in the way that the tutor does

3. Tutorials as the tutor bringing things into relation to each other to help the student develop a new perspective in the wider context of the discipline

4. Tutorials as the tutor and the student exchanging different points of view on the topic and both coming to a new understanding. (Ashwin, 2010)

The topmost perspective (1) does not require any level of critical thinking from the student on assignments let alone about subject matter as a whole. The bottommost perspective (4) is where both students and professors have their horizons broadened through critical thought. A more reasonable outcome for engineering students is perspective 3, where students alone have their horizons broadened. The probability that a student from the sciences experiences any one of these perspectives decreases as they rise through the levels of critical thinking quality. In fact, out of a sample of 14 students in the Sciences, not one experienced the highest level. Despite the opportunity for critical thought in and about the sciences, according to this study, not many students experience it. This difficulty is addressed in the Harkness method. The Harkness method explicitly requires students to develop new perspectives and understandings about a topic, as we will describe in the next section.

Harkness Method

The Harkness method is a discussion-based learning method focused on student interaction and critical thought separate from teacher inculcated 'fact'. Harkness is a lesser-known learning method in university education but is becoming more widely used in elite secondary schools in the United States. The technical function of a Harkness classroom acts in the same way as a flipped classroom. Students conduct readings and work on homework to prepare to complete activities or discuss in class (Kerr, 2015). Classically, Harkness has been used for literature and social studies, but has also been adapted for mathematics, primarily through the Exeter Math curriculum. The format is very similar: students work problems ahead of class, write them up on boards around the classroom in the first few minutes of class, then present and discuss each of the assigned problems (Phillips Exeter Mathematics, 2021). It is likely that a Harkness engineering classroom would look at lot like one for Exeter Math. Should students get stuck, or a conversation hits a dead end, teachers can prompt new questions, or maybe even give a small amount of information, with the intention of reinvigorating conversation. However, Harkness is moreso a culture than it is a technical framework for classroom operations. "Harkness is found in forms of education that are committed to maximal student preparation, problem solving, discussion, enquiry, and a diminished role for the teacher's authority or ego" (Williams, 2010). This means that even if a discussion is not done at a round table, it could still be considered Harkness.

Figure 2 Modern Harkness Classroom – Students sit around a table designed to promote discussion. A teacher is helping a student present a problem in an Exeter Math classroom.

A useful tool to use in a Harkness discussion is a discussion map. These are used to map the flow of discussions and track individual students' contributions. Students can be notated with initiations - starting a conversation, interruptions, or supports - helping a student contribute to a discussion if they are having difficulty (Caldwell, 2021). These metrics along with qualitative instructor observations are contributing factors toward a student's evaluation for a class. Overall, Harkness in its philosophy, execution, and assessment is fundamentally different from the lecture model, and these differences propagate dramatically in the student experience.

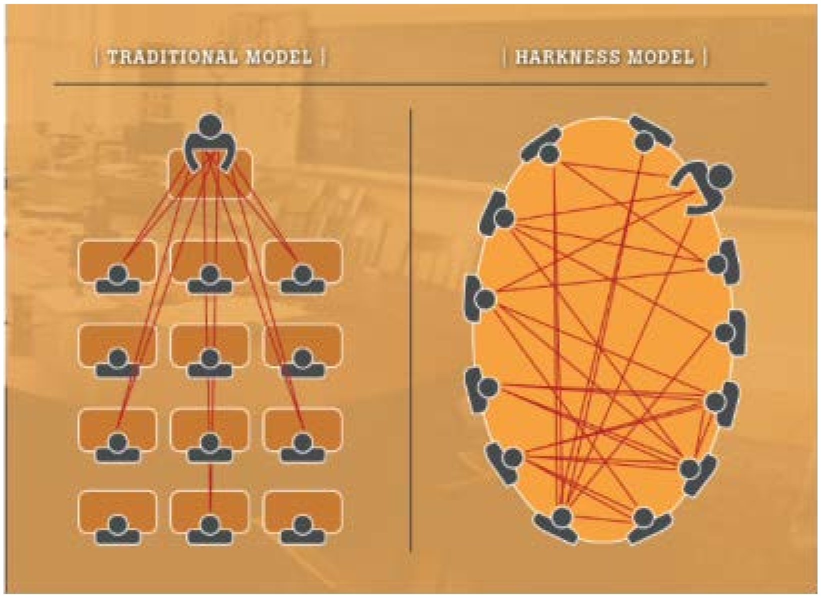

Figure 3 Discussion maps of Lecture Model vs Harkness Model – Comparing the discussion patterns in a lecture model versus a Harkness model classroom. Within the Harkness model, there is a more distributed conversation whereas in the traditional model, focus is primarily center around the teacher.

Benefits of Harkness

According to Williams, the most important goal of education is to "provide [students] with the cognitive skills to be able to determine truths for themselves" (Williams, 2010). One of the limitations of the lecture model is its difficulty in inspiring critical thought in students; Similarly, in the Oxford Tutorial, there is no guarantee that students will think critically with their professors. Within Harkness, critical thought and discovery of truth is more than a requirement and is instead a culture. There is no enforced fear in speaking falsely because through discussion, sometimes with the guiding touch of the teacher, students will be guided toward the truth (Williams, 2010). The teacher can assign readings or provide mini lectures to give students new tools to use in discussion. The ability to discern fact and fiction and think critically at a generic level is a skill necessary as engineers, now more than ever in becoming ambassadors of their field to society.

Given that Harkness is inherently a "social model" of learning, students will be required to develop their communication skills. Interpersonal skills and emotional intelligence have become a standard for engineers who work with non-engineering teams, enter management, or even working within their own team (Lappalainen, 2011). In its essence, a Harkness discussion is measured by the evolution of participant students. How they interact with each other continues to evolve to give birth to more insightful and deep discussions. Developing communication skills and developing a mastery of discussion is not usually an explicit goal of engineering education, but due to modern demands of the workplace, these are skills that have become increasingly valuable.

Difficulty of Harkness

In Harkness, there is a lesser emphasis on content knowledge and greater on the skill of acquiring that knowledge. Despite the high standards placed on students to learn content, there is a time constraint to learn all the necessary material, especially within an engineering curriculum. Discussion between peers will be less effective as a 'content distribution tool' than laser focused lectures. Discussions can branch into a direction that escapes the intended scope of a class's curriculum. Because of how generalized student discussion may be, teachers' jobs as educators become more sophisticated. It becomes necessary for teachers to predict and be prepared for student discussion, especially in trying to fulfill the content demands of the class.

Being a teacher in a Harkness classroom may seem like the job of a chaperone, but it is usually much more involved. "Teachers have the expertise to demand the right processes and frameworks, but the discussion does not belong to them" (Williams, 2010). Teachers are responsible for charting discussion possibilities and being prepared to guide student thought in a productive direction (Williams, 2010). The issue of asking "how can I inspire creative thought" in the lecture model is one that teachers are required to approach every day. “The teacher is present to coordinate truth seeking in the conversation, and to ensure that the knowledge is brought out from the students through intelligent questions” (Williams, 2010). Harkness requires professors to be teachers and mediators more so than field-experts while in the classroom. This requires a different skill set, with a greater emphasis on education than what may be expected of engineering professors as they get hired.

Teachers need to be field experts to understand discussion pathways. In fact, this requires an even stronger grasp on knowledge than a field-expert lecturer would. The lecturer is an expert of the presentation they give, whereas the teacher is an expert of the realm a discussion may progress in. The possibilities of the discussion are a superset of what a lecture may contain, necessitating greater preparation on the part of the Harkness teacher.

There have not been many examples of flipped classrooms at the university level and thus not enough research has been done to measure their effectiveness (Kerr, 2015). Harkness, similarly, is in untested waters in engineering pedagogy. Part of this reason is the perception that discussion-based learning is not feasible in engineering curriculum because of the value proposition of content knowledge over skill proficiency.

The argument remains that engineering students need to have a strong grasp on specific *content* to be successful in the workforce or as a field expert. A contrary argument exists where if students do not hone their personal skills independent of what knowledge they grasp, their ability to learn more content and approach foreign situations will be limited (Bowden et. Al, 2007). The question then is as follows: Should universities prioritize what skills students graduate their program with, or maximize knowledge as they enter the workforce? The reality is that most programs exist within some middle ground. But if we consider the lecture model versus the

Harkness method, the lecture model vests great importance on content whereas Harkness on skills.

Conclusion

There are many professors who are satisfied with how students are being taught within the lecture model, though this can vary depending on the values vested by institutions and professors alike. The decision to choose one education model over another should reflect these values rather than being subject to norm or tradition. Within the lecture model, we have addressed its limitations in fostering student-teacher interaction and teaching students how to think critically. These limitations are addressed in the narrowly used, but successful, Oxford Tutorial method and more fully in the Harkness method. By focusing more on the student experience and less on the content being disseminated, the tutorial and Harkness both set explicit requirements for student interaction with professors or other students.

To frame the above limitations, we introduced a framework for models defined by a focalizing experience for students. These experiences are the lecture, tutorial, and discussion section for the lecture model, Oxford tutorial method, and Harkness discussion methods, respectively. Other models can be generated by using different focalizing experiences such as a lab, for research-oriented curriculum, or a project, for more deliverable oriented classes. To further hone these models and create more standardized experiences for students, they should be driven by guiding principles. A culture, driven by a philosophy, can be used to model the behavior of both students and professors. There is no one clear philosophy on how professors should run Oxford Tutorials leading to inconsistent student experiences whereas Harkness describes a clear culture it intends to be implemented with.

Transitioning from the lecture model to any other model is radical and should be taken in stride. Running a pilot program to determine feasibility and explore different teaching/learning principles is a first step. These can be used in developing metrics to compare student outcomes and experiences. It may turn out the lecture model is the best fit, but this should be informed by an understanding of its limitations and the limitations of alternatives. In short, if you feel like a class is hitting the edge of the lecture model, it may be time to consider an alternative, whether it be the Oxford Tutorial, Harkness, or something else altogether.

Amin, A. M., Corebima, A. D., Zubaidah, S., & Mahanal, S. (2020). The Correlation between Metacognitive Skills and Critical Thinking Skills at the Implementation of Four Different Learning Strategies in Animal Physiology Lectures. *European Journal of Educational Research*, *9*(1), 143–163.

Ashwin, P. (2005). Variation in Students' Experiences of the 'Oxford Tutorial.' *Higher Education*, *50*(4), 631–644. https://doi.org/10.1007/s10734-004-6369-6

Bligh, D., & Cameron, B. J. (2000). [What's the use of lectures?]. *The Canadian Journal of Higher Education*, *30*(1), 192–196.

Charlton, B. G. (2006). Lectures are such an effective teaching method because they exploit evolved human psychology to improve learning. *Medical Hypotheses*, *67*(6), 1261–1265. https://doi.org/10.1016/j.mehy.2006.08.001

Chaudhury, S. R. (2011). The lecture. *New Directions for Teaching and Learning*, *2011*(128), 13–20. https://doi.org/10.1002/tl.464

Engineering Science | University of Oxford. (n.d.). Retrieved April 9, 2021, from https://www.ox.ac.uk/admissions/undergraduate/courses-listing/engineering-science

Full Text PDF. (n.d.). Retrieved April 9, 2021, from http://files.eric.ed.gov/fulltext/EJ1152098.pdf

Kerr, B. (2015). The flipped classroom in engineering education: A survey of the research. *2015 International Conference on Interactive Collaborative Learning (ICL)*, 815–818. https://doi.org/10.1109/ICL.2015.7318133

Lappalainen, P. (2009). Communication as part of the engineering skills set. *European Journal of Engineering Education*, *34*(2), 123–129. https://doi.org/10.1080/03043790902752038

Lesson learned? Massive study finds lectures still dominate STEM ed. (n.d.). EurekAlert! Retrieved April 9, 2021, from https://www.eurekalert.org/pub_releases/2018-03/uon-llm032818.php

Mathematics Department at Phillips Exeter Academy. (n.d.). Phillips Exeter Academy. Retrieved April 9, 2021, from https://www.exeter.edu/academics/departments/mathematics

Matheson, C. (2008). The educational value and effectiveness of lectures. *The Clinical Teacher*, *5*(4), 218–221. https://doi.org/10.1111/j.1743-498X.2008.00238.x

Michael Bernard. (2017). Impact of Teaching Attitudes and Behaviors for Learning on the Reading Achievement of Students Falling Behind. *International Journal of Learning, Teaching and Educational Research*, *16*(8), 51–64.

Pithers, R. T., & Soden, R. (2000). Critical thinking in education: A review. *Educational Research*, *42*(3), 237–249. https://doi.org/10.1080/001318800440579

Scheele, N., Wessels, A., Effelsberg, W., Hofer, M., & Fries, S. (2005). *Experiences with Interactive Lectures – Considerations from the Perspective of Educational Psychology and Computer Science*. https://repository.isls.org//handle/1/3733

Schmidt, H. G., Wagener, S. L., Smeets, G. A. C. M., Keemink, L. M., & van der Molen, H. T. (2015). On the Use and Misuse of Lectures in Higher Education. *Health Professions Education*, *1*(1), 12–18. https://doi.org/10.1016/j.hpe.2015.11.010

Smith, M., Chen, Y., Berndtson, R., Burson, K. M., & Griffin, W. (2017). “Office Hours Are Kind of Weird”: Reclaiming a Resource to Foster Student-Faculty Interaction. *InSight: A Journal of Scholarly Teaching*, *12*, 14–29.

Snapshot. (n.d.-a). Retrieved April 9, 2021, from https://psycnet.apa.org/record/1999-03660-011

Snapshot. (n.d.-b). Retrieved April 9, 2021, from https://eric.ed.gov/?id=EJ1152098

Tracking the Discussion. (n.d.). Strategies for Classroom Dialogue. Retrieved April 9, 2021, from https://www.katherinecadwell.com/tracking-the-discussion

Wiley, J., & Voss, J. F. (1999). Constructing arguments from multiple sources: Tasks that promote understanding and not just memory for text. *Journal of Educational Psychology*, *91*(2), 301–311. https://doi.org/10.1037/0022-0663.91.2.301

Williams, G. (2014). *Harkness learning: Principles of a radical American pedagogy*. https://uobrep.openrepository.com/handle/10547/335887