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Implementing Universal Design for Learning Principles in a Graduate-level Environmental Engineering Course

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ABSTRACT

Universal design for learning (UDL) is a pedagogical framework intended to promote accessibility and equity in learning environments, especially for students with disabilities. In UDL, instructors provide optionality and flexibility in the learning environment for representation, engagement, and expression, rather than expecting the learner to conform to a fixed structure of teaching and assessment. Examples of implementation of UDL are limited in engineering and in higher education. We assessed implementation of UDL-inspired course attributes in a graduate-level environmental engineering course by: (i) Quantifying student utilization of optional course attributes; (ii) Surveying student experiences with UDL-inspired course attributes; and (iii) Gauging overall student experience with inclusion, belonging, and accessibility. Student experiences and utilization of course attributes were assessed through mid-semester and end-of-semester surveys, interviews, and by tracking assignment submissions, and then analyzed using mixed methods data analysis. Students found the course to be inclusive and found UDL-inspired course attributes highly beneficial, regardless of disability status. Students differentially utilized the presented options for learning. For instructors seeking to increase the accessibility of their courses, the most widely beneficial course attributes introduced here were the stretch break, open-resource exams, optional assignments to reduce the weight of exams (e.g., study guide, redoing missed exam questions), and posted notes and summary slides. This manuscript includes concrete examples of successful implementation of UDL principles in a higher education engineering course. The outcomes and course attributes described here can be more widely adapted to other disciplines and education levels.

INTRODUCTION

Defining Universal Design for Learning (UDL)

Higher education classrooms are becoming increasingly diverse with growing variability across age, gender, socioeconomic background, and cultural and linguistic background (American Council on Education 2018). Furthermore, students with disabilities are attending higher education at higher rates in the United States (Newman et al. 2010; U. S. Government Accountability Office 2009; National Center for Education Statistics 2015) and often have different learning needs and preferences than students without disabilities (Amos et al. 2021). While enhanced diversity in the classroom has been associated with enriched learning environments as a result of a wide variety of student perspectives (Maruyama et al. 2000), students from minoritized backgrounds in higher education have had less success than their peers from majority backgrounds in completing undergraduate and graduate programs (Lee et al. 2015; Newman et al. 2010).

Given the noted increase in classroom diversity and the documented benefits of diversity in higher education (Tierney and Lanford 2016), it is imperative to implement instruction that takes into account the diverse learning needs of students. Universal design for learning (UDL) is a pedagogical framework that aims to address this need. UDL focuses on making teaching more accessible and equitable through modifications to the learning environment, rather than the learner (Kumar and Wideman 2014). Application of UDL can help make learning accessible to all learners so that all students may have an equal opportunity to succeed (Rose and Meyer 2002).

UDL is based on Universal Design concepts originally developed in the field of architecture, in which physical spaces were designed proactively to be accessible to the widest number of patrons, including those with disabilities (Wilkoff, Abed, and Brady 1994). For example, the incorporation of curb cuts in sidewalks helps those in wheelchairs cross the street but can also be beneficial for people with suitcases or strollers. In 1998, Universal Design was proposed as a valuable framework for the field of education (Orkwis and McLane 1998). In 2002, the U.S. non-profit organization Center for Applied Special Technology (CAST) published their guidelines for Universal Design for Learning (Rose and Meyer 2002). Because accessibility is a somewhat subjective variable (i.e., what is accessible to one student may not be accessible to another), the crux of UDL is optionality. To this end, application of the Universal Design framework to education holds much promise in helping educators design learning environments that are maximally accessible for diverse learner populations.

Although UDL often emphasizes inclusion of those with disabilities, the UDL framework is compatible with ongoing diversity, equity, and inclusion initiatives that aim to include learners from diverse backgrounds. Inclusion of all learners is fundamental to the UDL framework because of its emphasis on removing barriers in the learning environment to ensure all students all supported (Fovet 2020).

Barriers that students with disabilities face in the design of instruction and assessment may, for example, be similar to those faced by non-native English speakers, who have likewise been viewed through a deficit lens in higher education settings. Because UDL emphasizes regulation of the affective network to increase learning engagement, application of UDL has previously been shown to improve belonging in learning environments (Nelson 2021). There was also a resurgence of interest in UDL more generally in higher education in the aftermath of the COVID-19 pandemic as educational barriers increased for all students during remote and hybrid teaching.

To implement UDL, the CAST guidelines recommend providing multiple means of engagement, representation, and action and expression. "Engagement" refers to how learners become interested in and engaged with course material through various means, such as interaction with the instructor, social presence, and background material. Keeping students engaged also requires an optimal level of emotional activation, such that students are neither too bored nor too anxious to effectively take in material (Posey 2018). "Representation" refers to how course materials are presented to learners. For example, subtitles in an oral presentation allow the audience to either listen to or read the delivered content. Reading subtitles can be beneficial for those with impaired hearing, but also those with auditory processing disorders, those sitting far from the speaker, or in the case of lots of background noise. "Expression" refers to how students can demonstrate their knowledge, such as in the form of exams, papers, participation, or presentations.

The aim of this work is to make graduate-level courses in engineering more accessible using the Universal Design for Learning (UDL) framework. Herein, we illustrate practical examples of UDL course elements, assess course attributes using student feedback, and discuss how to remove systemic barriers to UDL implementation.

Prior Implementation of UDL into STEM Higher Education

In the literature, UDL is most commonly discussed in the context of K-12 education (Rao, Wook Ok, and Bryant 2014), but application of UDL in post-secondary settings has undergone exponential growth over the past two decades (Tarconish et al. 2023). In a study of a first-year undergraduate course (Kumar and Wideman 2014), the instructors incorporated multiple means of engagement, representation, and expression by incorporating course elements like online discussion forums, materials presented as slides and study guides, and variety in the types of graded assignments, respectively. A meta-analysis conducted with 18 independent studies from 2013 and 2016 concluded that UDL is an effective teaching methodology for improving the learning process for all students (Capp 2017). Over the last decade, the scholarship on UDL has remained distinctly fragmented between the K-12 and the post-secondary sector. There is urgent pressure on educators to acknowledge this and consider UDL scholarship and practice as a broad spectrum that should include both K-12 and post-secondary education (Fovet 2020).

Furthermore, presence of UDL in graduate education is rare (Rose et al. 2006). There seems to be a perception that UDL is more suited to undergraduate than graduate education because (i) Generally smaller class sizes are assumed have more interaction between students and instructors and more capacity for addressing accessibility issues; (ii) Students are assumed to have already adapted to the demands of higher education through their completion of an undergraduate degree; and (iii) The graduate student population is assumed to be more homogenous and therefore no longer require differentiated instruction strategies (Fovet 2021). However, these assumptions generally do not hold true for graduate classrooms. Many graduate students struggle, and graduate programs continue to increase in diversity (Fovet 2020). Graduate students are more than six times as likely to experience depression and anxiety as compared to the general population (Evans et al. 2018). Therefore, it will be crucial for faculty to consider UDL from a perspective of reducing barriers, particularly barriers which create or exacerbate mental health issues among students.

UDL is not widely followed in STEM (science, technology, engineering, math) education (Schreffler et al. 2019). The number of empirical research studies exploring the efficacy of UDL for postsecondary STEM education remains too small to support success of the model and to provide examples for interested instructors (Schreffler et al. 2019). As more students with disabilities endeavor to enter STEM fields, STEM faculty need to be prepared to engage all students in their lessons (Newman et al. 2010). Nationally, fewer than 40% of undergraduates who intend to major in a STEM field complete a STEM degree (Olson and Riordan 2012). By making STEM content accessible to all students, colleges and universities may see an increase in STEM enrollment by underrepresented populations (Newman et al. 2010) as well as overall retention.

Summary and Goals

In this paper, a summary is provided of student uptake and experiences with course attributes that were implemented to provide learners with multiple means of engagement, representation, and expression. We aim to disseminate practical examples of successful implementation of UDL-inspired course components in a graduate-level engineering course. To the authors' knowledge, this is one of the first studies to document incorporation of UDL principles into a graduate-level STEM course. Most of the strategies used would also be appropriate for other disciplines and education levels.

This study has been guided by the following research questions:

1. To what extent did students utilize UDL-inspired course attributes when given the choice?
2. What were student experiences with UDL-inspired course components?
3. How did the incorporation of UDL-inspired components affect overall student experience with inclusion, belonging, and accessibility in the course?

METHODS

Course Context

The study was conducted in Fall 2022 at a large public university in the western United States in a graduate-level class hosted by the Department of Civil and Environmental Engineering titled Physical/Chemical Processes in Environmental Engineering. Course content included fundamental models and equations related to water treatment processes. The class was one of the core class options for environmental engineering MS and PhD degrees. The existing grade structure involved homework assignments (20% of final grade), two midterms (each contributing 20% of final grade), and a final exam (40% of final grade); therefore, 80% of the final grade comprised exams.

The class met in person every Tuesday and Thursday morning for 1.5 hours for a lecture presented by the lead instructor, with a one-hour discussion section each Monday led by the Graduate Student Instructor (GSI). The course utilized a university-hosted website, where course materials and grades were posted (referred to as the bCourses site). Lecture sessions consisted of an oral lecture from the instructor that incorporated visuals (e.g., slides, notes) and occasional partner or group exercises. During class sessions, there were multiple live demonstrations (e.g., a gas transfer demonstration with a dissolved oxygen probe) or use of hands-on materials (e.g., a membrane filter) for students to see physical examples of topics being discussed. Both the instructor and GSI held weekly office hours. The goal of the discussion section was to reinforce concepts from the lecture and give students an opportunity to complete example problems prior to the homework. Graduate student instructors were on strike for the final weeks of the semester, during which time there was no discussion section or graduate student instructor office hours.

Participants

34 students were originally enrolled, with 33 students completing the course. Previously, the students completed their undergraduate degrees at 22 universities across four countries. Students held citizenship across 14 countries. According to self-reporting (where categories representative of fewer than three students are not reported here such that data are not identifiable), the class was 58% female and 42% male. Students were 36% White and 24% Asian, with the remainder of students identifying as another category or not reported. 15% of students identified their ethnicity as Latin American/ Mexican American/ Other Hispanic, Latin American or Spanish Origin. Three students disclosed that they were registered to receive accommodations with the university disabled students program (DSP). The majority of students (79%) intended to complete their MS as a terminal degree, while 21% intended to earn their Ph.D..

UDL-Inspired Course Attributes

Ten course attributes that align with the UDL framework are highlighted below. Five major modifications were introduced to the course for the first time during the study semester (Attributes 1, 2, 5, 8, and 9) with the explicit purpose of alignment with the UDL framework. The remaining attributes had been previously incorporated into the course to improve accessibility.

Multiple Means of Engagement

1. Stretch Break

   A "stretch break" was introduced midway through the lecture. The break lasted one to three minutes and occurred about one hour into the 1.5 hour lecture, with slightly variable timing such that it fell at a natural break in the lecture. During the stretch break, students were encouraged to stand or walk about the classroom but not to leave the room, and the instructor always requested questions from students at the end of the break. The UDL motivation for the stretch break was to increase engagement with course content by: (i) Providing a physical opportunity for resting/stretching, (ii) Providing a mental opportunity to process information and refocus, (iii) Providing dedicated time for questions.

2. Anonymous Polling in Discussion

   Anonymous polling was utilized during the discussion section using the free version of Mentimeter (mentimeter.com), which allows two questions per presentation in various forms, such as multiple choice, word clouds, and short answer questions. Students could respond using their personal internet-enabled devices using a short link and code. Polling questions began as conceptual and intentionally basic to increase student confidence and make sure they understood core concepts at the start of the lesson. After the mid-semester feedback survey, student feedback was incorporated, and poll questions were modified to be more challenging. The UDL motivation for the anonymous polling was to: (i) Increase participation and engagement with formative assessment without inducing anxiety and (ii) Allow the instructor to gauge understanding without grading emphasis.

3. Connections to Real-World Applications

   Supplemental resources were provided on the class website that connected course materials to real-world applications, such as virtual tours of full-scale water treatment facilities. Demonstrations were conducted during lecture, and physical examples were passed around. Instructors emphasized the connection of class concepts to engineering practice and research. These resources, demonstrations, and examples were intended to increase student engagement by making connections to real-world applications, thus providing motivation beyond grading and aligning with the UDL framework.

4. Flexible Homework Deadlines

   Deadlines for homework assignments were stated in the syllabus. However, deadlines were flexible, and no points were deducted for late assignments. The goal was to reduce stress, accommodate personal situations, and give students more flexibility and autonomy with course pace. These actions could increase student engagement with the course by removing barriers.

Multiple Means of Representation

5. Automated Captions

   Automated captions via Microsoft PowerPoint were utilized in discussion so that the instructor's speech was automatically transcribed in real-time and projected onto the screen. The UDL-motivated goal was to provide a visual representation of the material that was delivered verbally.

6. Posting of Recorded Class Sessions

   During the COVID-19 pandemic, remote and hybrid instruction became common (Manierre et al. 2022), and many classrooms were equipped with course capture technology. Although all students were physically on campus and instruction had returned to in-person during the study semester, the instructors continued utilizing course capture and promptly posted recorded lectures and discussions for students. The intent behind this additional representation of course material was to (i) Increase course accessibility for students who could not attend every class session due to an ailment or personal life event and (ii) Enable students who attended lecture to rewatch them to reinforce material or to rewatch portions they missed during the live lecture, thereby reducing the stress of taking complete notes during live lectures. If students consistently missed class sessions, instructors reached out personally to discuss their circumstances.

7. Posting of Class Notes/Slides

   Instructors utilized the course website to host documents. During most lectures, the instructor wrote material in real-time on a tablet, and the written notes were posted immediately after class. The goal was to provide students with multiple means of representation of course material and give them optionality in how they engaged with the material during lectures. During class sessions, students could still take notes in real-time if it benefitted their learning, but they also had the option to just listen with the knowledge that written materials would be available to them later. Any slides used were posted to the website prior to class sessions. Students could choose to take notes directly on class slides, especially through the use of tablets, and access to slides in advance of class sessions provided students with an additional opportunity to prepare for class. Although instructors aimed to upload slides more than 24 hours prior to class sessions, this was not always achieved.

Multiple Means of Action and Expression

8. Choice of Optional Project or Higher-Weight Exams (Pre-exam optional assignments)

   In engineering courses, such as the one in this study, it is fairly common for a high proportion of final grades to be derived from exams alone, providing limited variety in how students may demonstrate gained knowledge. One of the goals of the teaching interventions was to reduce the considerable impact of exams on the final grade. To this end, students were given the option to submit a study guide that effectively captured important exam concepts prior to each exam. The grade on the project, if submitted, replaced 25% of the exam grade. To create the study guide, students were provided with a project prompt that included four stylistic examples and a rubric. The project rubric is provided in **Appendix A**. The project was explained to students via an in-class announcement more than one week before the first exam. The UDL motivation for the optional assignment was to: (i) Present an additional option to demonstrate knowledge, (ii) Reduce testing anxiety by reducing weight on examinations, and (iii) Help students develop good study habits and synthesize material independently.

9. Points for Redoing Missed Exam Questions (Post-exam optional assignments)

   Students had the option to submit write-ups after both midterms explaining incorrect answers and providing a correct solution. Students received up to 50% of the points lost back in return for each question answered correctly in the post-exam optional assignment. The UDL motivation for the exam points-back assignments was to reduce testing anxiety and to emphasize goals-based learning, ensuring students understand concepts and that their grade is not dependent on performance in a single examination period.

10. Open-Book and Open-Note Exams

    Students were permitted to use textbooks (including devices with PDF versions) and notes as support during exams. The UDL-inspired motivation was to emphasize goals-based learning, rather than memorization of course materials, and to reduce testing anxiety.

Data Collection

Student engagement with optional assignments and materials was analyzed through submission and grading data. Students also responded to mid-semester and final course surveys with questions related to course modifications, existing course attributes, and overall accessibility. Students were given the option to also share their experiences through interviews, and two students shared feedback via this option. All procedures of the study were approved by the Institutional Review Board at the study university (Protocol ID 2022-11-15823).

The mid-semester feedback survey (**Appendix B**) was conducted via a Google Form that was sent to students through an announcement on the class bCourses website. Students were encouraged to

fill out the survey during lecture and discussion, and class time was allotted to complete the survey.

The final course evaluations (**Appendices C** and **D**) were conducted via a survey sent out about each lecture course and discussion section by the university. Instructors were given the option to add custom questions to the surveys. Custom questions were added regarding the UDL-inspired course modifications. Students were encouraged to fill out the surveys during lecture, but no additional incentives were provided for doing so. Instructors received anonymized responses to the surveys.

Interviews were conducted remotely after the submission of final grades by an author who was not affiliated with the course and were anonymized prior to analysis by authors affiliated with the course. Interviews were advertised in lecture using a flier and through the bCourses page. Interviews were semi-structured, loosely following the script provided in **Appendix E**.

Qualitative Data Analysis

Qualitative data analysis was performed by the first and second authors. Responses to open-ended questions on the mid-semester and end-of-semester surveys for both the graduate student instructor and faculty instructor of the course were aggregated, and meaning was assigned to smaller units of the data (Miles and Huberman 1994). The coding process involved two phases: etic and emic. The theoretical framework guiding etic coding comprised the three principles of UDL developed by CAST (i.e., multiple means of representation, engagement, and action and expression). The authors also used emic coding, creating codes grounded in what participants described as their meaning-making about their specific experiences in the course (Headland, Pike, and Harris 1990). Emic coding assumes there may be gaps in the theoretical framework that are best fit by analyzing respondents' statements. After using both etic and emic coding approaches, the authors collapsed codes with the same theme into categories and identified emerging patterns (Miles and Huberman 1994). The authors triangulated responses from the surveys with data from the two semi-structured interviews to solidify the codebook. Example codes can be found in **Figure 1**.

Author Positionality Statements

At the time of the study, the authors included a doctoral student in environmental engineering, a doctoral student in school psychology, and a tenured professor of environmental engineering, all at the study university. One of the authors identifies as having learning disabilities, and one of the authors has a sensory disability. One of the authors identifies as South Asian, and two identify as white. All authors are participants in higher education and seek to make classrooms more inclusive, including through the use of UDL. Two of the authors were the lead and student instructors of the study course. Because affiliation with the course could bias the interpretation of the data, the author who was not affiliated with the course played a large role in data analysis and oversaw interpretation.

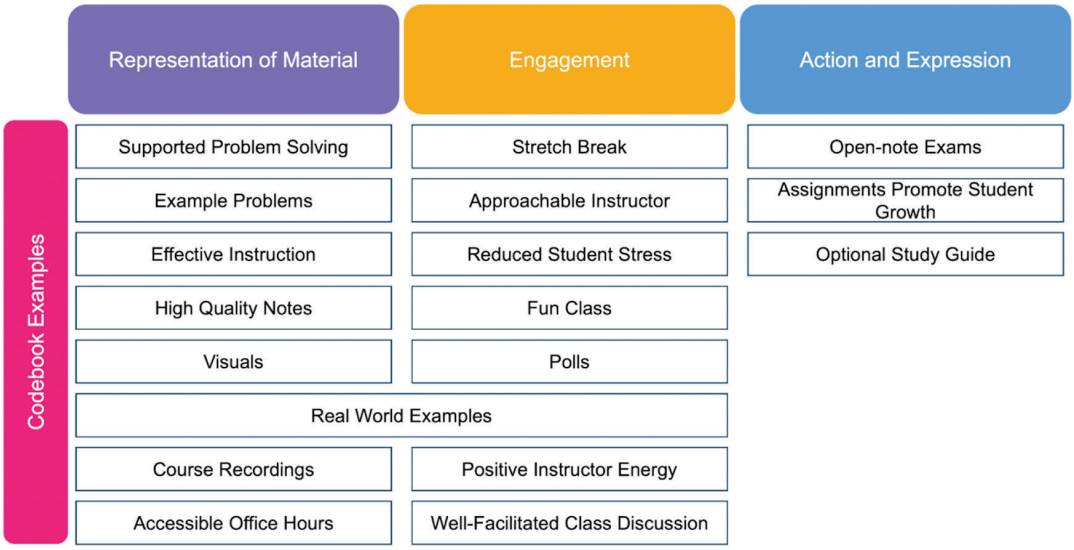

Figure 1. Example codes from the qualitative data analysis codebook categorized according to the UDL framework based on CAST (2018) UDL guidelines.

RESULTS

Analysis of course components was conducted using: (i) Student Responses to Mid-semester Survey (completed by 27 students), (ii) Student engagement with optional submissions, (iii) Student Responses to Final Surveys for both lecture and discussion (completed by 22 and 21 students, respectively), and (iv) Student interviews (completed by 2 students). Throughout the results section, terms included in the code book are underlined.

At what level did students utilize UDL-inspired Course Attributes?

Student completion of the optional assignments was high. All students in the class submitted the optional assignment connected to Midterm 1 (n=34). The project was graded using a rubric that was given to students prior to submission. The average score was 98.7%, with seven students scoring below 100% but none scoring below 90%. The students with the bottom three test scores on the midterm also had project scores below 100%, potentially indicating shortcomings in exam preparation. All students received higher scores on the optional project than on the exam, with the exception of one student who scored 99% on the midterm and 97% on the project. Submissions of the optional assignment remained high for the remaining exams. All but one student (n=32 out of 33) submitted an optional assignment for midterm 2, and all but two students (n=31 out of 33)

submitted an optional assignment for the final. The average scores for the midterm 2 and final optional assignments were 100%.

Student utilization was also high, but not as high, with the post-exam optional assignments, in which students could receive partial credit for redoing missed exam questions. Twenty-two students submitted corrections for the first midterm, and nineteen students submitted corrections for the second midterm. For the first midterm, 35% of high-scoring students (original exam score of 90% or higher) submitted corrections, while 94% of lower-scoring students (original exam score below 90%) submitted corrections. For the second midterm, 26% of high-scoring students and 100% of lower-scoring students submitted corrections. The single student that scored below 90% on the first midterm but did not submit corrections later submitted corrections for midterm 2. There was no option to submit a post-exam assignment for the final exam due to the short deadline for grading at the end of the semester.

Finally, students were asked whether and how they used recordings of class sessions that were posted to the class website. The majority of students used the recordings at least once during the course (n=13 of 22 respondents). Of the students who accessed the recordings, most students only used the recordings as a backup if they needed to miss lecture (n=8), but several students (n=5) used the recordings as a consistent supplement to lecture. From the instructors' observations, only one student relied almost exclusively on the recordings, choosing to stop attending class in person except for exam days.

What were student experiences with UDL-inspired course components?

Overall, student experiences with the UDL-inspired course components were strongly positive. On a scale of 1 (no benefit at all) to 7 (very beneficial), all students responded to five course attributes with scores greater than or equal to 5: (i) Stretch break, (ii) Choice of project or higher weight exam, (iii) Points for redoing missed exam questions, (iv) Open-note/book exams, and (v) Posting of class notes/slides (**Figure 2**). Notably, all students gave the highest score to the class feature of open-note, open-book exams. The posting of recorded class sessions received slightly lower scores than the posting of class notes/slides, which could be due to the technical difficulties in recordings mentioned in some of the student free-responses. For the remaining course components (automated captions, anonymous polling, and flexible homework deadlines), more students responded that these course attributes were only "somewhat" beneficial, with some students indicating that the automated captions were "not at all" beneficial. Although larger portions of the class scored these components lower, a majority of the class still gave the highest scores (5-7), showing that they helped many students. A shortcoming of the scaled survey questions (**Figure 2**) was the lack of an option to say that the course attribute hindered their learning; instead, the lowest score could

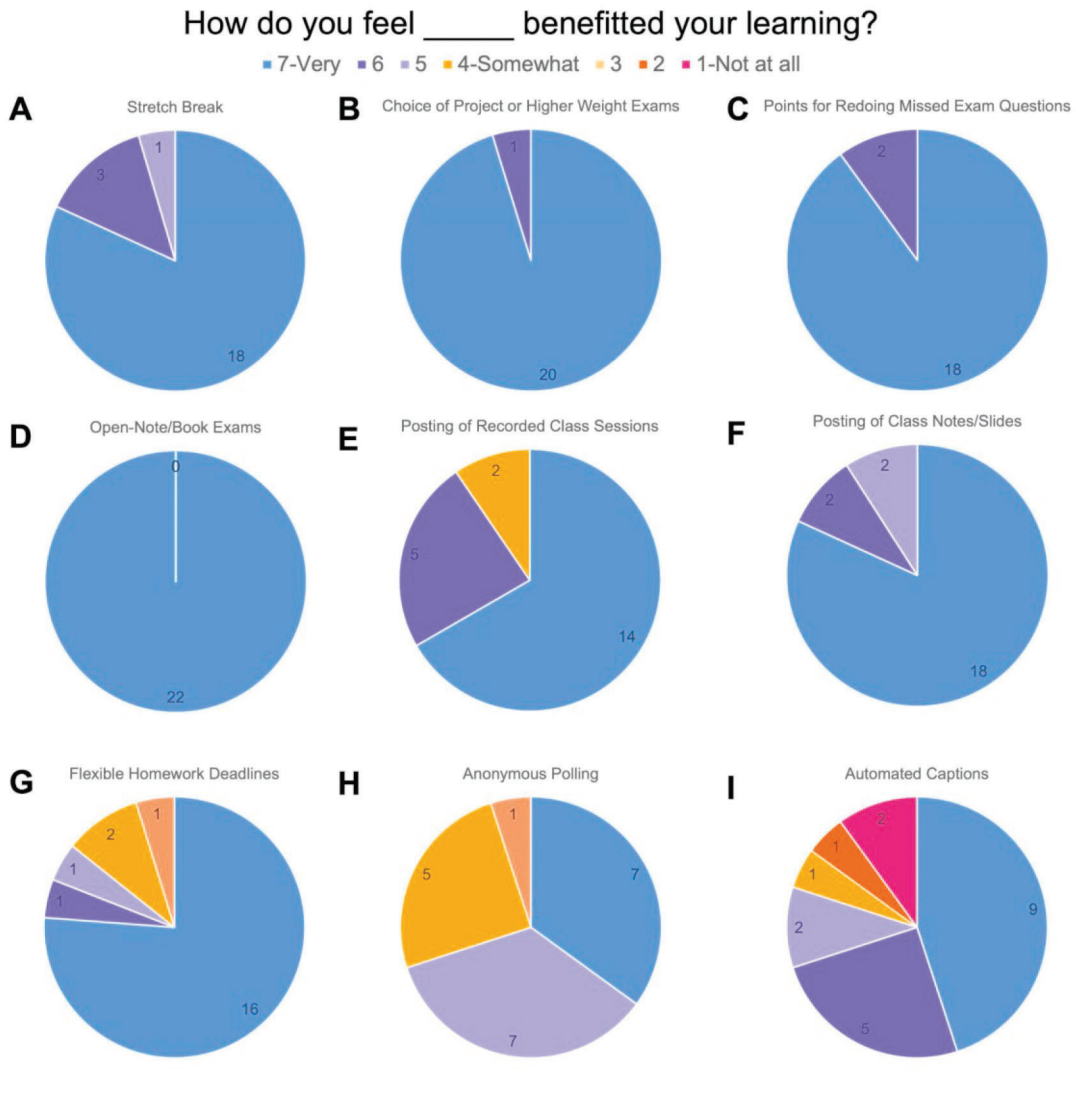

Figure 2. Pie charts of student experiences with nine of the UDL-inspired course attributes.

mean the attribute was neutral for their learning. In the free responses, no student offered negative comments about automated captions, but some suggestions were offered for anonymous polling and flexible homework deadlines (see **Section 3.3**).

In their free responses, students often commented on the benefits of multiple means of representation of course material. For example, one student mentioned that they disliked the textbook and chose instead to only use lecture notes and the discussion summaries. Providing optionality enabled students to choose which redundant representation of material worked best for them.

Students emphasized how the flexibility of assignment deadlines and optional assignments gave them more autonomy in their action and expression. Students mentioned that flexible homework deadlines were beneficial when they needed more time for challenging topics or needed to arrange their schedule around personal circumstances. The flexibility of assignment deadlines also enabled students to feel in control of the pace of their learning. For example, one student stated:

> I think the flexible system in this course has given me a chance to better arrange the pace of my studying process as it allows me to adjust the plan for each week. Sometimes this allows me to use more time to fully understand the content.

Under the engagement principle, students also emphasized how these course features helped with emotional regulation by reducing stress. For example, flexible deadlines on the homework assignments reduced stress during particularly busy weeks. Multiple students mentioned that the optional assignment reduced their stress over the exams by reducing the grading emphasis placed on the exam. Students also felt less stressed about the exams knowing that they could earn back some of their missed points by completing the post-exam optional project. One student shared:

> I really appreciated having flexible deadlines for the homework assignments. Some weeks were too stressful with other assignments to get everything done, so it was very helpful to have additional time! I also felt less stressed about the midterms with the optional project and corrections assignments. When I didn't do well on the first midterm, it was a relief that I could make up half of my missing points.

In addition to reducing stress, the optional assignments aided in student learning by scaffolding the learning process, encouraging students to reexamine missed concepts, and reinforcing course content. Students mentioned that because the optional assignments involved creating study guides, the exercise itself helped them perform better on the exam. The assignment encourages students to practice good study habits through summarizing information from the course. Students also mentioned that they might not have looked over their exams to see which questions they missed and figure out why if it were not for the post-exam optional assignments.

> I appreciate how the instructors (professor + graduate student instructor) have provided us with opportunities to make grades of assignments and exams less of a burden for us. The optional study guide project also encourages me to summarize information learned in

> lectures and that contributes greatly to my exam performance. I am confident I understand the material a lot better because of it.

Students also commented on the success of the course in engagement in reference to approachable instructors, instructor energy, class discussions, real-world examples, inclusion of learning styles, and the stretch break. Notably, the stretch break received highly positive feedback and seemed to enable students to maintain focus throughout the end of the lecture period as intended. One student commented:

> I truly think [the stretch break] is helpful. Allows me to take a pause and "wring out the sponge of excess water" and get to absorb more info in the second half. Basically, I can take a break and give myself a minute to prepare to learn more.

Similar to the sidewalk cut-outs from architecture, some course attributes that may be thought of as helpful only for students with a specific disability can end up helping a wider population. For example, the automated course captioning was appreciated by some students who are not hearing impaired. For example, one student stated:

> Loved the course captures, and my hearing is pretty good, so for people who actually need the accommodation, I can only imagine how helpful it is.

Many comments related to the strong benefits of the course summaries created and presented by the graduate student instructor. Students appreciated the review of material and the clear presentation of course material. Lectures provided time to introduce concepts and delve into context and derivations, while discussion sections provided time to reinforce key concepts in the context of problem-solving. The positive response to summary content created by the graduate student instructor also points to the benefit of representation of information from multiple instructors in multiple formats.

Numbers in each slice represent the number of students who chose that response. Colors indicate the response option, which was a scale from 1 to 7 (see legend). Colorblind-friendly palette was selected based on the IBM palette (Nichols, n.d.).

Student Suggestions for Course Attributes

When asked in short answers if any of the course attributes were not helpful or hindered their success in the course, only three students (n=3 of 21) responded yes. These students commented

on the technical difficulties encountered in course recordings, ineffective use of anonymous polling, and the potential for students to take advantage of flexible homework deadlines. One student commented on the neutral impact of automated captions.

Students gave mixed feedback about the anonymous polling. While it was generally appreciated, some students requested that the poll questions be made more challenging, while others wanted to spend less time on them. Students seemed to agree that poll responses should not be shown in real-time while some students were still working on responding.

Only two out of 22 students gave suggestions when asked, "What gaps do you see in addressing classroom accessibility, inclusion, and support? Do you have any suggestions for improvement in these areas?" One student noted the accessibility imbalance of being able to take notes on lecture slides using an iPad. The student suggested that the instructors print out lecture slides and distribute them to students at the start of class. Alternatively, instructors could ensure that lecture notes were always available online at least 24 hours prior to class so that students could print them if that is their preference for note-taking. The second student noted the technical difficulties surrounding recording classes and ensuring all material is captured in recordings.

How did the incorporation of UDL-inspired components affect overall student experience with inclusion, belonging, and accessibility in the course?

Overall, students overwhelmingly perceived the course to be inclusive and accessible. In the final surveys for both lecture and discussion, all students (100%) either agreed or strongly agreed that "the instructor created an environment in which I could feel included (for example, encouraged multiple voices/perspectives, welcomed questions and critiques, responded to student feedback)." Students gave an average rating of 6.73 for the question, "Uses a grading system that is clearly defined and equitable," compared to a department average of 6.17 (scale from 0 to 7). In an interview, one student commented that this was the first higher education class where they did not feel the need to ask for additional accommodations through a university office for disability services for their Attention-Deficit / Hyperactivity Disorder (ADHD) because their needs were already being met by the course design. This student reflected:

> I have accommodations through the testing center...I would say in nearly every course since undergrad I have requested accommodations, and they've all been met. Because I don't think that professors have any ability to go against the Office for Disability Services. But they've all been mad...And this class was the first time I never had to really ask for explicit accommodations that weren't already being met with the general structure of the course. (*transcript edited for clarity*)

This student's experience is not intended to suggest that implementing interventions to a course in line with UDL should serve as a replacement for legally-mandated accommodations for students with disabilities. However, it is promising to find evidence that barriers students with and without disabilities face in completing a course can be removed through effective implementation of UDL-inspired course modifications.

DISCUSSION

Overall, students found the course to be very inclusive and found UDL-inspired course attributes highly beneficial. Although only a few students identified as having a disability, the vast majority of students in the class appreciated the UDL-inspired attributes to make the learning environment more flexible and accessible. For example, most students appreciated having the option to use recorded lecture videos with transcripts and posted instructor notes/slides, course features that have previously been shown to be preferred by students with disabilities (Amos et al. 2021). For instructors seeking to increase the accessibility of their courses using UDL guidelines, the course attributes introduced here that students found most beneficial were the stretch break, optional assignments, open-resource exams, and organized summary slides.

Providing more options to students gave them autonomy over their learning. Flexible deadlines allowed them to set their own learning pace and have previously been ranked by students as a highly useful UDL feature (Varadhan 2023). While many students never accessed the posted recordings of class sessions, multiple students reported using them consistently as an additional learning tool. While several students said that automated captions did not help them, many students appreciated the transcribed representation of course content, especially when it was difficult to hear. One student, who had access to accommodations through the Office of Disability Services, chose not to use these campus resources and instead chose to utilize the flexibility and resources woven into the course. Classrooms are full of diverse learners, and presenting options allows students to pick a path that works best for their needs. It should be noted that this was a graduate-level course, where students may have been more attuned to which learning styles worked best for them than students earlier in their education.

Many students commented on how course attributes, especially the optional assignments surrounding exams, reduced their anxiety and therefore increased their engagement. UDL may therefore be compatible with ongoing student mental health initiatives. Only one comment referred to how course components may diminish engagement: the student commented that flexible homework deadlines diminished needed pressure to actually complete the assignments in pace with the course.

Because the optimal point of emotional activation varies by learner, providing clear learning targets and then maximizing flexibility in achieving those targets may be the best approach for each learner to optimize their learning.

In addition to increasing autonomy and reducing anxiety, optional assignments before and after exams gave students the ability to earn higher grades if they were willing to invest the time and effort to complete them. This approach to grading is moving closer towards the "A's for All (as time and interest allow)" position, which asserts it is increasingly possible for all students to achieve a high grade (high level of mastery) if they invest the necessary effort, even if some students take longer than others or require more practice to get there (Garcia et al. 2023). In this model, a grade is a flexible starting point, which students have the ability to improve through regrades and optional assignments, performed at their own pace with flexible deadlines.

Although development of pedagogy is less emphasized in graduate education, UDL was shown here to be an effective framework that was well-received by learners in a graduate-level context. Optionality could potentially be even more effective for graduate students, who have the educational experience and self-awareness to choose the course elements that work best for them. Furthermore, the mental health benefits of UDL-inspired course attributes reported by students in this study supports the expansive use of UDL in graduate education, where students experience high rates of anxiety and depression (Evans et al. 2018). Finally, as graduate programs become increasingly diverse, it is exceptional that 100% of students either agreed or strongly agreed that the class environment felt inclusive, supporting the synergies of the UDL framework with ongoing diversity, inclusion, and belonging efforts.

The outcomes and course attributes described here can be more widely adapted to other subjects and grade levels, but course attributes found to be beneficial in this study are not guaranteed to work in other contexts. Requesting student feedback through multiple means, such as mid-semester feedback surveys and conversations with the instructor, are essential to assessing whether course attributes are successful for students. Requesting feedback and modifying the course should be an ongoing process, as no group of students is identical. Future studies should continue developing and trialing UDL-inspired strategies and documenting their impact on student learning to enable uptake by the broader teaching community. This study was limited in that there was no control group in which UDL components were not intentionally incorporated. Future studies could conduct surveys in consecutive years surrounding course redevelopment to better isolate the impact of the UDL-inspired course components. Future studies with an increased number of students would lend further insight into the efficacy of course components for students with a broader set of learning backgrounds and disability statuses.

In addition to student experience, available resources, the workload of instructors, and instructor interest must be considered when sustainably designing a course. Introducing a stretch

break into lectures and allowing students the use of notes, a study guide, or a textbook during the exam required little effort to introduce in this course. However, it is noted that for other subjects/courses, a switch from closed-book to open-book exams might require significant effort. Incorporating optional assignments (i.e., study guides, exam regrades) and presenting course content in different formats (such as through summary slides) required more effort but with large returns for the students. Institutional resources allowed for the incorporation of some course elements (e.g., posting of recorded lectures) with minimal instructor effort. Creation of the new course elements was moderately time-consuming, but materials such as the optional project rubric and polling questions could be reused in subsequent semesters. However, the additional assignments and options for regrades could significantly increase the instructor's grading workload for future semesters. Instructors are more likely to invest in UDL when they believe UDL can improve student engagement and when community-based UDL workshops are available (Xie and Rice 2020).

For the widespread implementation of UDL to become a reality, there must be a commitment of the learning organization, not solely individual instructors, to systemic change (Pace and Schwartz 2008). Faculty have previously reported lack of training on accessibility features and supportive technologies to be a key barrier to UDL implementation (Varadhan et al. 2023). Universities can support instructors in implementing UDL by providing supportive technology (e.g., automatic lecture recording, assistive listening systems, automated grading platforms, supportive course websites), instructor training workshops, teaching support centers and coordinated peer groups, and policies that are dedicated to UDL. For example, universities could pay for additional work hours of faculty or student instructors to support a course redesign and the first semester of implementation. For the course redesign in this study, support was offered through the Working Group on UDL, hosted by the university's teaching center for graduate students, which offered training, peer discussions, and a modest stipend for participants.

CONCLUSION

This study presented concrete examples of successful incorporation of the UDL framework into a mid-sized graduate-level engineering course. Previously, strategies to incorporate UDL had been presented for other subject areas, class sizes, and grade levels, so this study appends the literature base of UDL case studies by providing examples in a graduate STEM environment. Overall, students found the course to be very inclusive and found UDL-inspired course attributes highly beneficial, regardless of disability status. These findings support that implementation of

UDL will not only help increase retention of students from underrepresented groups, but may increase overall retention in higher education STEM programs, by catering toward the differences that abound in students of all backgrounds. Different groups of students took advantage of different options for learning, such as consistently viewing recorded lectures as a supplement to attending class sessions. For instructors seeking to increase the accessibility of their courses using UDL guidelines, the course attributes introduced here that were most widely beneficial were the stretch break, optional assignments, open-resource exams, and organized summary slides. Many course components required additional work hours from the instructors, especially during the first semester of a course redesign. Findings from this study point to the promise of investing in UDL at an institutional level.

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APPENDIX A. OPTIONAL PROJECT PROMPT AND RUBRIC

Quality criteria	Not Sufficient		Excellent	Score
Usefulness and Synthesis	The study guide is disorganized or hard to read. Includes lengthy class notes, copies of the textbook, or materials that are not summarized/ synthesized by the student. (8 pts)	Quality and organization of content is inconsistent. (9 pts)	Summarizes/synthesizes key material and presents concepts in way that is clear, organized, and easy to understand. Material is annotated with helpful comments, colors, visuals, or memory tools. (10 pts)	10 pts max
Breadth	The study guide is brief and missing some material or is extraordinarily long such that every detail presented in class is included making it difficult to pull out key concepts. (8pts)	Some important concepts are excluded. (9pts)	The study guide contains all major unit concepts, important equations, etc. (10 pts)	10 pts max
Accuracy	Some concepts are presented in an inaccurate way. Many errors. (8 pts))	Some small errors. (9 pts)	Information presented appears correct. (10 pts)	10 pts max
Total score				30 pts max

Figure A1. ***Pre-exam study guide optional assignment rubric.***

APPENDIX B. MID-SEMESTER FEEDBACK SURVEY QUESTIONS

- What are some of the aspects of lecture (led by Kara) that you like / are useful to you?
  - [short answer]
- Do you have any suggestions for how to make lecture more effective?
  - [short answer]
- How do you like the stretch break midway through lecture?
  - [Option 1] I like it. It helps me focus, process information, and think of questions.
  - [Option 2] I do not like it. It wastes time or introduces distractions.
  - [Option 3] No preference
  - [short answer]
- What are some of the aspects of discussion (led by Hannah) that you like / are useful to you?
  - [short answer]
- Do you have any suggestions for how to make discussion more effective?
  - [short answer]
- Do you like the conceptual polls using Mentimeter at the beginning of discussion?
  - [Option 1] Yes

- [Option 2] No
- [short answer]

- Did you find creating the study guide for the optional project useful for understanding/retaining course content and preparing/taking the exam?
  - [Option 1] Very useful
  - [Option 2] Somewhat useful
  - [Option 3] Not useful
- Do you have other comments on the optional study guide or ways we can improve the optional project for future exams?
  - [short answer]
- Do you think we need to add additional office hours?
  - [Option 1] Yes
  - [Option 2] No
  - [short answer]
- Is there any other feedback you'd like to give us?
  - [short answer]

APPENDIX C. END-OF-SEMESTER FEEDBACK SURVEY FOR LECTURE

1. Course Ratings_Required course material is sufficiently covered in lecture
2. Course Ratings_The required text/notes are beneficial
3. Please provide comments or suggestions about the organization of the course and the text/notes
4. Please provide additional comments or suggestions about the course (eg. pace or workload of the course)
5. The assignments were well designed to help me understand the course material and gain a deeper perspective on the subject._The assignments were well designed to help me understand the course material and gain a deeper perspective on the subject.
6. Classroom Presentation_Gives lectures that are well organized
7. Classroom Presentation_Is enthusiastic about the subject matter
8. Classroom Presentation_Identifies what the instructor considers important
9. Classroom Presentation_Has an interesting style of presentation
10. Classroom Presentation_Uses visual aids and blackboards effectively
11. Please comment on the strengths and weaknesses of the instructor in classroom presentation and provide suggestions, if any, for improvement.

12. Course Climate_Encourages questions from students
13. Course Climate_Is careful and precise in answering questions
14. Course Climate_Relates to students as individuals
15. Course Climate_Is accessible to students outside of class
16. Course Climate_Is friendly and helpful to students during office hours
17. If you have additional comments regarding your experience around climate and inclusion in the classroom, please share them here
18. Assignments and Exams_Gives interesting and stimulating assignments
19. Assignments and Exams_Gives exams that permit students to show their understanding
20. Assignments and Exams_Uses a grading system that is clearly defined and equitable
21. Please give your opinions on the nature and quality of the exams and assignments/projects
22. The instructor's lectures, facilitation of classes, and/or office hours and help sessions enhanced my learning. ("Learning" may include gaining mastery of course content and new skills, exposure to new methodologies and modes of critical thinking, and extending the ability to express oneself on the topics treated in the course).
23. The instructor created an environment in which I could feel included (for example, encouraged multiple voices/perspectives, welcomed questions and critiques, responded to student feedback).
24. Please provide additional comments or suggestions about the instructor
25. How do you feel the following course attribute benefited your learning? Posting of recorded class sessions
26. How do you feel the following course attribute benefited your learning? Discuss with your neighbor followed by polling via hand gestures in lecture
27. How do you feel the following course attribute benefited your learning? Posting of class notes/slides after sessions
28. How do you feel the following course attribute benefited your learning? Stretch break
29. How do you feel the following course attribute benefited your learning? Demonstrations (e.g., gas transfer beakers, adsorption GAC+dye) and passed around physical examples (membranes, brita filter, urine-derived fertilizer)
30. How do you feel the following course attribute benefited your learning? Ability to use notes and textbook during exams
31. Did you access recorded lectures and discussions? If so, were they your primary means of engagement with lecture, a consistent supplement, or a backup?
32. Do you have any comments on strategies used for course participation (e.g., discussions with your neighbor, polling via hand gestures, polling via Mentimeter, hand raising)

33. What gaps do you see in addressing classroom accessibility, inclusion, and support? Do you have any suggestions for improvement in these areas?
34. If you were to design a course that was completely accessible to you, what features would you include in the course design, materials, or assignments, and why?
35. Do you have any other comments on any of the other course attributes? (stretch break, demonstrations, ability to use notes and textbook during exams)

APPENDIX D. END-OF-SEMESTER FEEDBACK SURVEY FOR DISCUSSION

1. Helpful in understanding course material
2. Is well prepared
3. Communicates ideas effectively
4. Appears to have a good knowledge of the subject matter
5. Answers questions accurately
6. Encourages questions and/or classroom discussion
7. Is aware when students are having difficulty
8. Is accessible during office hours
9. The instructor fostered an open and inclusive learning environment
10. The GSI's instructional activities, contributions, and/or feedback enhanced my learning. ("Learning" may include gaining mastery of course content and new skills, exposure to new methodologies and modes of critical thinking, and extending the ability to express oneself on the topics treated in the course.)
11. The GSI created an environment in which I could feel included (for example, encouraged multiple voices/perspectives, welcomed questions and critiques, responded to student feedback).
12. If you have additional comments regarding your experience around climate and inclusion in the classroom, please share them here
13. Please provide comments or suggestions about the GSI
14. How do you feel the following course attribute benefited your learning? Automated captions in discussion
15. How do you feel the following course attribute benefited your learning? Anonymous polling in discussion
16. How do you feel the following course attribute benefited your learning? Flexible homework deadlines
17. How do you feel the following course attribute benefited your learning? Ability to choose whether to complete optional project or have exams worth more weight

18. How do you feel the following course attribute benefited your learning? Partial points back for re-answering exam questions
19. What comments do you have on any of the course attributes from the above rating questions?
20. Do you feel that any course attributes were not helpful or may even have hindered your success in the course?
21. One way to define an accessible course is as a course where all students have the ability to access the content and the potential to perceive and understand the content. Based on this definition of accessibility, did this course feel accessible to you?

APPENDIX E. INTERVIEW PROTOCOL

Adapted from Kumar et al, 2014:

Semi-Structured Interview Protocol: Thank you for agreeing to be interviewed for this study. It will be very helpful to learn from you about what course attributes were beneficial to your learning and what may help to make a course more accessible for students. We aim to generalize results from this interview into themes that can help instructors more broadly. Your participation in and responses to this survey will not impact your grade in any way.

I'm going to ask you a few questions about your experiences and preferences with respect to the way that courses are designed. There are not any right or wrong answers—it's your experiences and opinion that the questions are related to. You are free to decline to answer any questions if you choose, and if you wish to stop the interview at any time, simply let me know.

Part I: General Questions The first section of questions are general questions about your opinions and experiences with course accessibility

1. One way to define an accessible course is as a course where all students have the ability to access the content and the potential to perceive and understand the content. For example, if information is posted in bCourses, all students should be able to find and open or download the content, and also use the content (e.g., by reading or listening to it). It should also be possible for all students to have the ability to express their understanding of content, and therefore course assignments should also be accessible to all students. In general, accessible courses tend to be flexible. Based on this definition of accessibility, is accessibility of a course something that is important to you?
2. Have you ever had an experience when a more accessible (flexible) course would have benefitted or detracted from your learning? Tell me about that.

3. In general, what features do you associate with an accessible course? For example, what aspects of a bCourses site, course materials, grading, or assignments make them accessible to you?
4. In general, what features do you associate with an inaccessible course? For example, what aspects of a bCourses site, course materials, grading, or assignments make them accessible to you?
5. Have you ever requested that changes be made to a course to make it more accessible? How did you do that? What was the response?
6. If you were to design a course that was completely accessible to you, what features would you include in the course design, materials, or assignments, and why?
7. Please describe your preferred method of learning
8. Please describe your preferred method of assessment
9. Is there anything else about course accessibility that you'd like to tell me about?

Part II: Course-Specific Questions The last section of questions are related to your experience in CE211A in Fall 2022.

The following list contains course modifications that were made for the first time this semester:

- Optional study guide assignments to reduce the weight of exams
- Option to solve missed exam questions for partial credit
- Anonymous polling in discussion using mentimeter
- Stretch break during lecture
- Automated captions/subtitles on discussion slides

The following list contains existing course attributes designed to increase course flexibility and accessibility:

- Flexible homework deadlines
- Homework graded for completion
- Recorded class sessions
- Posted notes/slides after class sessions
- Demonstrations and hands-on examples
- Supplemental materials posted on bCourses

1. As you look at these lists, which of the course attributes listed were most helpful to you and why?
2. Were there other materials or attributes of materials that you found helpful that you'd like to comment on?
3. Which of the course design aspects listed did you feel were not helpful or may even have hindered your success in the course?

4. Were there other course attributes that you'd like to comment on?
5. Is there anything else related to accessibility of this course that you'd like to tell me about?
6. What additional recommendations do you have for improving course accessibility in future semesters?

Conclude by asking the student for contact information and general demographic information (gender identity, racial/ethnic background).