Assessing accessibility and challenging ableism in Unit Operations Laboratories

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ABSTRACT

Unit operations (UO) lab courses prepare chemical engineering students for their careers through hands-on experience and are an essential component of any baccalaureate chemical engineering program. These courses typically involve engagement with pilot-scale and/or lab-scale chemical process equipment to help students connect the theory learned in the prior courses to related experiments and methods they'll see in industry. Student engagement with these labs typically involves navigating the physical environment of the lab and course policies, such as reading lab manuals, required attendance, and inflexible assignment and oral presentation deadlines due to the nature of group work and lab rotations. Most laboratory spaces, course policies, and course materials are created with non-disabled individuals in mind. Creating an equitable and accessible learning environment requires proactively designing the space and course policies for students with physical and mental disabilities and chronic illnesses, enabling them to fully engage with this important experiential learning opportunity. By modeling accessibility through the lab design and course policies, as well as intentionally discussing workplace accessibility, laboratory instructors can teach students the importance of designing and maintaining accessible spaces and the skills to achieve these goals in their future work. In this study, we surveyed UO lab instructors to understand how, or if, accessible design is implemented in existing chemical engineering lab courses to understand how our institutions and programs are supporting disabled and chronically ill students. We draw on our experience and the survey responses to provide both short-term and long-term changes that instructors can implement to move toward an accessibly designed UO lab space and course.

POSITIONALITY STATEMENT

We acknowledge that the authors represent faculty, staff, and students from a range of backgrounds, identities, and disability status. Those disabilities represented by the authors are far from representative of the entire community, and we recognize the need for many more voices in this type of work.

FORMATTING CHOICE STATEMENT

Deviations from the ASEE author's kit formatting requirements were chosen to more closely align with Web Content Accessibility Guidelines (WCAG) 2.1 [1] as well as best practices for varying disabilities. For example, we chose to use Arial instead of Times New Roman, as sans serif fonts are generally considered more accessible. We used Headers and avoided using carriage returns to create space between paragraphs to better align with screen reader usage. Spacing that is at least 1.5 between lines and spacing between paragraphs that is double the font size increases readability.

GLOSSARY

- **Ableism:** A bias that disfavors people with disabilities leading to exclusion of or discrimination against them in favor of non-disabled people.
- **Accessibility:** The capability of being easily reached, entered, used, or understood by a person regardless of ability status.
- **Accommodation:** An accessibility support required to make an environment, information, or service usable by a person. For example, sign language interpretation is an accessibility support that makes audible information obtainable by a deaf person.
- **Disability:** A physical, mental, cognitive, or developmental condition that interferes with or limits a person's ability to engage in certain tasks or actions or participate in typical daily activities and interactions that have been designed for non-disabled individuals. There are many types of disability, including but not limited to sensory (such as blindness, low vision, deafness, or hard of hearing), mobility, dexterity, cognitive and behavioral (such as attention deficit hyperactivity disorder), developmental (such as autism), learning (such as dyslexia), mental (such as anxiety or post-traumatic stress disorder), and communication disability (such as stuttering or aphasia). In this paper and in many of the cited works, statistics presented on the presence of disability in a population often lump all types of disability together.
- **Equity:** An application of fairness or justice to the way people are treated, ensuring all have access to what they need to be able to fully function in society without discrimination.
- **Inclusion:** The provision of equal access to opportunities and resources without discrimination.

INTRODUCTION

STEM disciplines, particularly engineering, are essential for addressing global challenges and fostering innovation. Creating equitable solutions to global challenges requires collaboration between diverse individuals. However, STEM careers remain inaccessible to individuals with disabilities, who make up 29% of the U.S. population but account for only 3% of employed scientists and engineers [2], [3]. Unequal access to and satisfaction in STEM jobs for disabled people are worse for those also holding intersecting minoritized identities such as gender, race, ethnicity, and LGBTQ+ status when compared to white, non-disabled, heterosexual men [4]. Inequalities in access to STEM jobs can be caused by systemic barriers–such as the absence of accessible facilities and curriculum adaptations, and the presence of societal biases–that exclude people with disabilities from training needed for STEM fields [5]. This is particularly apparent in laboratory settings, which are central to hands-on learning and research. Addressing these barriers is critical to fostering equal participation and ensuring that STEM disciplines fully benefit from the diverse perspectives and problem-solving skills of individuals with disabilities.

Historically, exclusion in STEM has been shaped by societal mindsets, physical barriers, and institutional practices. The moral model of disability stigmatizes disabilities as character flaws, while the medical model of disability frames them as conditions that need to be "fixed," reinforcing systemic ableism [6]. These perspectives marginalize individuals with disabilities, often viewing them as beneficiaries of solutions rather than equal contributors [7]. The human rights model of disability offers a framework for supporting the inclusion and upholding the dignity of disabled persons [8]. In accord with the human rights model, society must address physical, procedural, and cultural barriers of exclusion in institutions. Physical barriers, such as inaccessible workstations, narrow aisles, and inadequate safety measures, along with a lack of mentors and representation in leadership, further exclude disabled individuals from fully engaging in STEM [9], [10]. Furthermore, creating accessible laboratory spaces can be costly, which deters institutions from investing in inclusive designs. This financial barrier is exacerbated by a lack of recognition of the value, importance, and contributions of disabled individuals and accessible spaces for them, as many institutions fail to prioritize these efforts due to perceived limited impact on their immediate goals. Additionally, institutional practices often focus on compliance with minimum legal requirements, such as accessibility of the physical environment, like ramps, bathrooms, and elevators, rather than truly fostering inclusive classroom practices and environments [11].

Creating accessible laboratories requires an approach that combines Universal Design for Learning (UDL) principles with individualized accommodations. Accessible spaces include features such as adjustable-height workstations, assistive technologies, and tactile safety measures, ensuring that individuals with disabilities can engage fully and safely in laboratory work [12]. Furthermore, institutional support structures are vital. Collaboration between faculty, laboratory staff, students, and disability support services are necessary to design and implement tailored accommodations for diverse needs [13]. Proactive strategies, such as integrating accessibility into safety protocols and offering training on accessible design for faculty and staff, contribute to fostering inclusive laboratory environments [14].

Resources to support accessible lab design are increasingly available. UDL principles provide a foundational approach for creating inclusive environments by ensuring spaces accommodate diverse needs from the beginning, minimizing the need for future adjustments. Frameworks like the Americans with Disability Act (ADA) Accessibility Guidelines establish standards for physical accessibility, while online resources, such as those provided by the University of Washington's Disability, Opportunities, Internetworking, and Technology (DO-IT) Center, offer strategies for institutions seeking to create inclusive spaces [12]. Additionally, the Accessible Biomedical Immersion Laboratory (ABIL) at Purdue University, serves as a resource and blueprint for accessible lab design, as well as being a model for how thoughtful design can empower researchers with disabilities to work independently and effectively in laboratory settings [10]. These resources collectively provide institutions, and specifically instructors, with tools and models to create labs that are not only compliant but truly inclusive.

Despite these advancements, the literature on accessibility in STEM, particularly lab spaces, shows constant challenges, requiring action on both physical facility access and cultural change to combat ableism [5]. Early studies identified systemic barriers to STEM education for students with disabilities [15], while more recent efforts focused on implementing inclusive design principles and assistive technologies [16]. Recently, the COVID-19 pandemic highlighted the importance of accommodations and increased the attention to accessibility in STEM environments [13]. Unfortunately, the inconsistent adoption of these practices across institutions highlights the need for scalable and sustainable solutions. While the pandemic spurred progress, much work remains to ensure accessibility becomes a standard feature of STEM education and lab environments.

This paper explores the barriers and opportunities for creating accessible STEM laboratory environments, focusing on Unit Operations (UO) lab courses in undergraduate chemical engineering. These courses are essential for combining theory and practice but can exclude students with disabilities or chronic illnesses due to inflexible policies, inaccessible spaces, and materials designed for non-disabled individuals. Through a survey of UO lab instructors, staff, or other knowledgeable department individuals, and insights from our own experience, we assess the current state of accessibility of these courses and propose actionable strategies for designing inclusive lab spaces and policies that can empower all students to engage fully. By proposing strategies to make labs and course more accessible, we aim to equip instructors with the skills to design accessible laboratory environments, thus empowering individuals with disabilities, educating students about disability equity, fostering innovation, and promoting inclusion/diversity in STEM education.

While this paper focuses on the undergraduate student experience in the chemical engineering laboratory setting, the principles and design suggestions in this paper could be applied to STEM labs beyond chemical engineering. Additional work is needed to improve the experience for other stakeholders, including faculty and staff with disabilities who teach or work in the laboratory setting, graduate students whose research is performed in a laboratory setting, students and teachers with disabilities in the K-12 laboratory setting, and employees engaged in other workplace laboratory settings outside of academia.

METHODS

Faculty in chemical engineering departments across the world were surveyed to determine the current state of accessibility in unit operations lab spaces and courses.

To assess the current state of unit operations lab space and course accessibility across chemical engineering departments, we developed a survey, shown in Table 1, based on the University of Washington (UW) Disabilities, Opportunities, Internetworking, and Technology (DO-IT) Checklist for Making Science Labs Accessible to Students with Disabilities [17]. The survey was sent to chemical engineering faculty networks, including to members of the American Institute of Chemical Engineers (AIChE) Virtual Community of Practice for Lab and a national listserv of chemical engineering department chairs, to be shared with and completed by current or past instructors of unit operations or others with knowledge of the lab space and courses. The study was submitted for IRB determination and was determined to be exempt by the University of Washington Human Subjects Division (HSD) per classification as an educational test, surveys, interviews, observations of public behavior. The survey was fully anonymous, and quantitative and qualitative data from the survey was analyzed in aggregate. While the survey asked about take-home labs, the great majority of respondents (n=40/43, 93.0%) indicated that their department does not offer take home labs, and thus we do not have sufficient data to report these results.

Table 1. Assessing accessibility of unit operations laboratories survey.

Table 1a: Survey Description, Purpose, and Consent

QUESTION	RESPONSE OPTION(S)/TYPE
Do you consent to participate in this study by taking this anonymous survey?	● Yes, I consent. ● No, I do not consent.

Table 1b: General Institution and Unit Operations (UO) Lab Course Information
Please fill out the following information about your institution and your lab course(s).

QUESTION	RESPONSE OPTION(S)/TYPE
What role do you have with respect to the unit operations course and/or lab space in your department? Check all that apply.	● Current Instructor or Co-Instructor ● Current Lab Manager ● Past Instructor or Co-Instructor ● Past Lab Manager ● None of the Above ● Other…
Is your institution within the US?	● Yes, it is within the United States. ● No, it is outside of the United States.
Is your institution public or private?	● Public Institution ● Private Institution ● Not sure
What kind of institution are you at?	● R1 ● R2 ● M (Master's as Highest Degree) ● PUI (Primarily Undergraduate Institution) ● Other…
How many courses is the chemical engineering undergraduate unit operations course sequence?	● None ● One Course ● Two Courses ● Other…
Do you have any lecture courses with lab experiments integrated (as opposed to a separate lab only course)?	● Yes, for 1 or more courses in the curriculum. ● No, UO lab and all other lab experiments are part of an explicit laboratory course.

Table 1b: General Institution and Unit Operations (UO) Lab Course Information – Continued

QUESTION	RESPONSE OPTION(S)/TYPE
Across your chemical engineering unit operations course sequence (one or more courses, or labs integrated into other courses), what experiments does your lab currently use in the course? Check all that apply.	● Fluid Flow ● Pump(s) ● Compressor(s) ● Turbine(s) ● Heat Exchanger(s) ● Drying ● Evaporation ● Refrigeration ● Cooling Tower(s) ● Mixing Tank(s)/Mixer(s) ● Boiling ● General Heat Transfer ● General Mass Transfer ● General Momentum Transfer (ex: Viscosity Experiment) ● Kinetics ● Reactor(s) ● Tray Distillation ● Batch Distillation ● Other Distillation ● Packed Column Absorption ● Adsorption ● Membrane Separation ● Liquid-Liquid Extraction ● Filtration ● Other Separation Unit ● Fluidized Bed ● Process Control ● Ion Exchange ● Fuel Cells ● 3D Printing ● Biochemistry/Biological Engineering ● Simulations and/or Computational Modeling ● Other…

Table 1b: General Institution and Unit Operations (UO) Lab Course Information – Continued

QUESTION	RESPONSE OPTION(S)/TYPE
Please rate to what extent the following statements are true about your lab. In this context, accessible means that labs/content can be equally engaged with by those with and without mental/physical disabilities and/or chronic illnesses. ● The UO lab space is currently accessible to individuals with disabilities. ● The UO lab course policies are currently accessible for those with disabilities.	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A
Does your department intend to redesign the UO lab in the next ~10 years?	● Yes ● No ● Maybe ● I don't know

Table 1c: Unit Operations Lab Space Accessibility Assessment

Please answer each of the questions below to the best of your ability about the accessibility of your lab space. These questions are based on the [institution] Disabilities, Opportunities, Internetworking, and Technology (DO-IT) [18].

QUESTION	RESPONSE OPTION(S)/TYPE
Please rate to what extent the following statements are true about **strategy, planning, policies, and evaluation of your physical lab space**. ● People with disabilities were included in the planning and selection of lab equipment and services. ● Considering accessibility is a requirement of the procurement process for lab products. ● There is a procedure to ensure timely response to required disability related accommodations. ● Disability-related access issues are addressed in your equipment procurement and evaluation. ● Disability-related access issues are addressed in your evaluation of student work.	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A – Not relevant to the lab

Table 1c: Unit Operations Lab Space Accessibility Assessment – Continued

QUESTION	RESPONSE OPTION(S)/TYPE
Please rate to what extent the following statements are true about the **physical lab environment**. ● Aisles are (36") wide and clear of obstructions for wheelchair users as well as people with mobility or visual impairments. ● Parking areas, pathways, and entrances to the building/room are wheelchair accessible (36" wide along continuous path) and clearly marked. ● All levels of the facility are connected via an accessible route of travel. ● There are high-contrast, large-print signs to and throughout the lab. ● At least part of a service counter, desk, and/or lab bench is at a height accessible from a seated position. ● There are quiet work or meeting areas where noise and other distractions are minimized. ● Safety procedures have been addressed for students with hearing impairments (e.g., instructions in print and visual lab warning signals). ● Safety procedures have been addressed for students with visual impairments (e.g., large print signage, audible alarms). ● Safety procedures have been addressed for students with mobility impairments (e.g., fire extinguisher that can be reached from a seated position).	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A – Not relevant to the lab
Please rate to what extent the following statements are true about the **lab staff**. ● Staff members are familiar with the availability and use of assistive technology and alternative documentation formats. ● Staff members know how to respond to requests for disability-related accommodations such as sign language interpreters.	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A – Not relevant to the lab

Table 1c: Unit Operations Lab Space Accessibility Assessment – Continued

QUESTION	RESPONSE OPTION(S)/TYPE
Please rate to what extent the following statements are true about the **information resources** associated with the lab/course. ● Pictures/visuals in your documents and/or course website include people with disabilities. ● Key documents include statements about procedures for requesting disability-related accommodations. ● All printed publications are available (immediately or in a timely manner) in alternate formats such as Braille, large print, and electronic text. ● Lab documents can be reached from a seated position. ● Electronic resources, including web pages, adhere to accessibility guidelines or standards.	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A – Not relevant to the lab
Please rate to what extent the following statements are true about the lab **equipment**. ● An adjustable-height table is available for each type of workstation in the lab. ● Adjustable-height tables in the lab can be adjusted from a seated position. ● Equipment is marked with large-print and/or Braille labels. ● Plastic products are purchased instead of glass when available and chemically compatible. ● Non-slip mats, beaker and object clamps/stands, beakers and equipment with handles, and/or surgical gloves are provided to handle slippery items. ● Controls on lab equipment can be reached from a seated position. ● Adequate work areas are available for both right- and left-handed users.	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A – Not relevant to the lab
Do you have any current lab equipment in place that are accessible, but that were not included in any of the questions that we asked in the survey so far?	Open-ended response
Does your unit operations course require or provide take home labs?	● Yes ● No

Table 1c: Unit Operations Lab Space Accessibility Assessment – Continued

QUESTION	RESPONSE OPTION(S)/TYPE
Please rate to what extent the following statements are true about the **institutional policies** that affect courses. ● Institution-level disability accommodations apply for group assignments. ● The institution provides the necessary resources to address disability accommodations in the lab course.	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A – Not relevant to the lab
Do you have any current lab practices in place that are accessible, but that were not included in any of the questions that we asked in the survey so far?	Open-ended response

Table 1d: Unit Operations Take Home Lab Accessibility Assessment.
Please answer each of the questions below to the best of your ability about the accessibility of your take home labs.

Note: this section was only available to individuals who answered "Yes" to the previous question.

QUESTION	RESPONSE OPTION(S)/TYPE
Please rate to what extent the following statements are true about the **take home lab experiments.** ● The size/weight of the take-home components are suitable for tabletop use. ● Multiple options for transportation to student's location are provided. ● Lab documents are screen reader accessible. ● Equipment is accessible for blind/low vision students. ● Equipment is accessible for deaf/hard of hearing students.	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A – Not relevant to the lab
Do you have any current take home lab equipment in use that are accessible, but that were not included in any of the questions that we asked in the survey so far?	Open-ended response

Table 1e: Unit Operations Lab Course Structure and Policy Accessibility Assessment
Please answer each of the questions below to the best of your ability about the accessibility of your lab space.

QUESTION	RESPONSE OPTION(S)/TYPES
Please rate to what extent the following statements are true about the **course policies**. ● Assignment extensions are available for students. ● Make-up labs are available to students that miss class due to disability or illness for extended periods of time. ● Experiments do not require students to come into lab outside of normal class time. ● Lectures are recorded. ● Teams are created with accessibility in mind. ● Teams fill out a team contract. ● Teams complete peer evaluations. ● Accessible lab design is actively taught in the course. ● Disability equity is actively taught in the course.	Rating scale with options: ● Not at all ● Somewhat ● Mostly ● Completely ● Unknown/Not Sure ● N/A – Not relevant to the course

RESULTS

Survey data captures responses from primarily a mixture of public and private R1 institutions in the United States.

The majority of the survey respondents were current or past lab instructors, co-instructors, or managers (Fig. 1A), indicating that survey respondents would be knowledgeable about the lab experiments and spaces. Questions about institution demographics indicated that all but one response came from an institution within the United States (Fig. 1B), more than two-thirds (n=30/43, 69.8%) of responses came from public institutions (Fig. 1C) with the rest being private institutions, and almost three-quarters (n=32/43, 74.4%) of responses came from R1 institutions with small numbers from R2 and primarily undergraduate institutions (PUIs). Overall, with only 43 responses and uneven distributions of responses within each category, we analyzed the data in aggregate. Due to the anonymous nature of the survey and lack of identifiable data collected, it is possible that one institution is represented multiple times within the survey data. However, we believe this is unlikely as the survey was sent out broadly and with instructions for lab instructors to fill it out on behalf of their institution, including collaborative efforts amongst multiple instructors if desired.

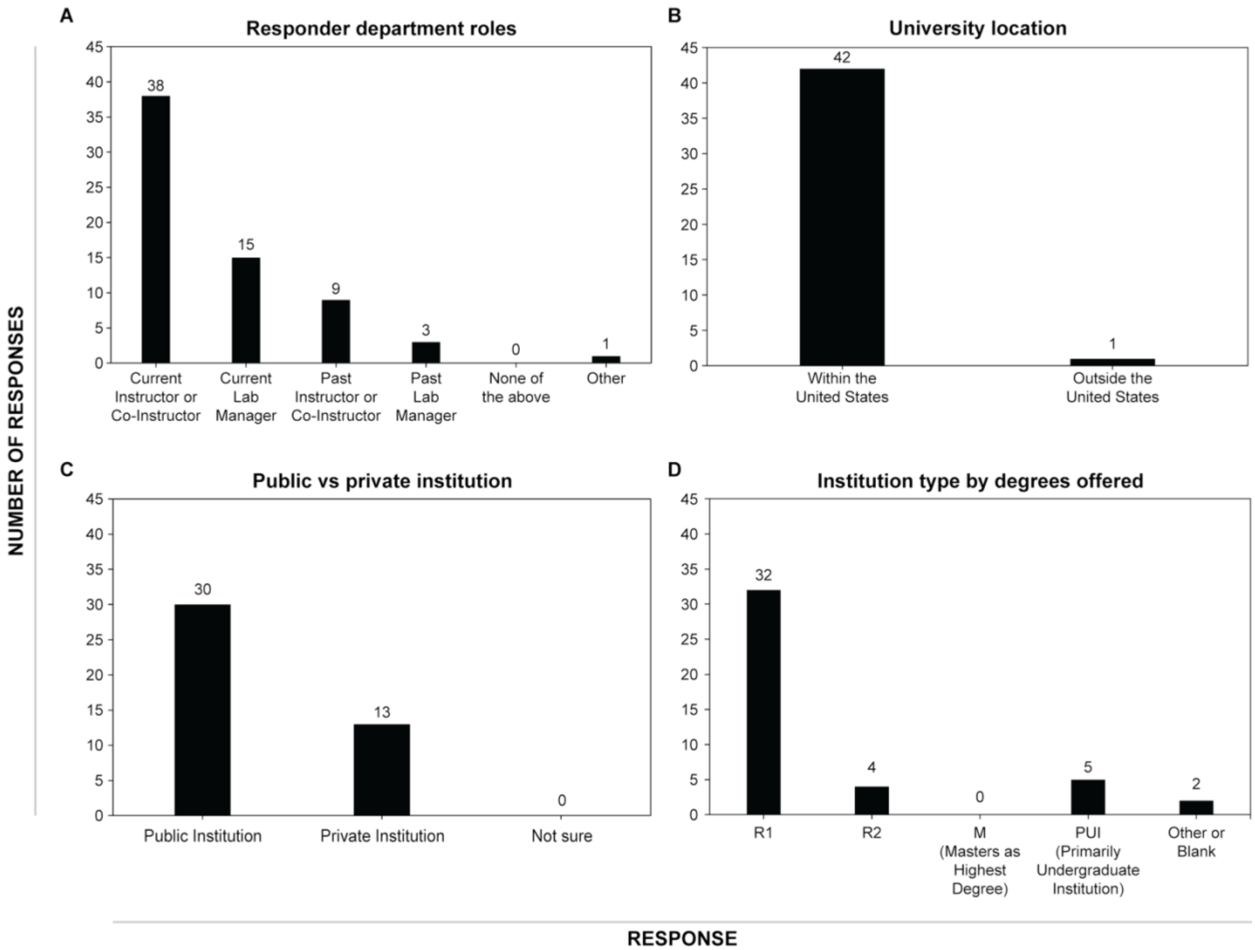

Figure 1. Responder and institution demographics. A) Survey responder positions with relevance to their unit operations labs within their departments/institutions. **B)** Institution location as within or outside of the United States. **C)** Institution classification as public or private. **D)** Institution type by research and degree awarding status.

Most chemical engineering departments provide more than one unit operations lab course with a range of common experiments.

Respondents were asked to indicate information about their chemical engineering laboratory course(s), including the number of courses offered and types of experiments included in the course(s) (Fig. 2). More than half of the respondents (n=26/41, 60.5%) indicated that their department offered two unit operations lab courses, while the 20.9% (n=9/43) that answered "other" specified that they either offered 3 courses, 4 courses, or 1-2 courses with additional use of the lab space/experiments integrated into traditional lectures courses (Fig. 2A).

We sought information about the types of experiments offered in unit operations lab courses, as different types of experiments may be easier to make accessible than others depending on scale and resource requirements. Nearly all respondents indicated that their institutions offered experiments on fluid flow (n=39/43, 90.7%) and heat exchangers (n=39/43, 90.7%) (Fig. 2B). The next most common types of experiments included reactors (n=30/43, 69.8%), kinetics (n=28/43, 65.1%), pumps (n=28/43, 65.1%), tray distillation (n=27/43, 62.8%), membrane separation (n=26/43, 60.5%), and general heat transfer (n=25/43, 58.1%). All other unit operations were offered at less than half the institutions. However, if responses were filled out by an instructor who teaches one of the possibly two or more unit operations courses in their department, they may have only accounted for units within their course or that they are aware of.

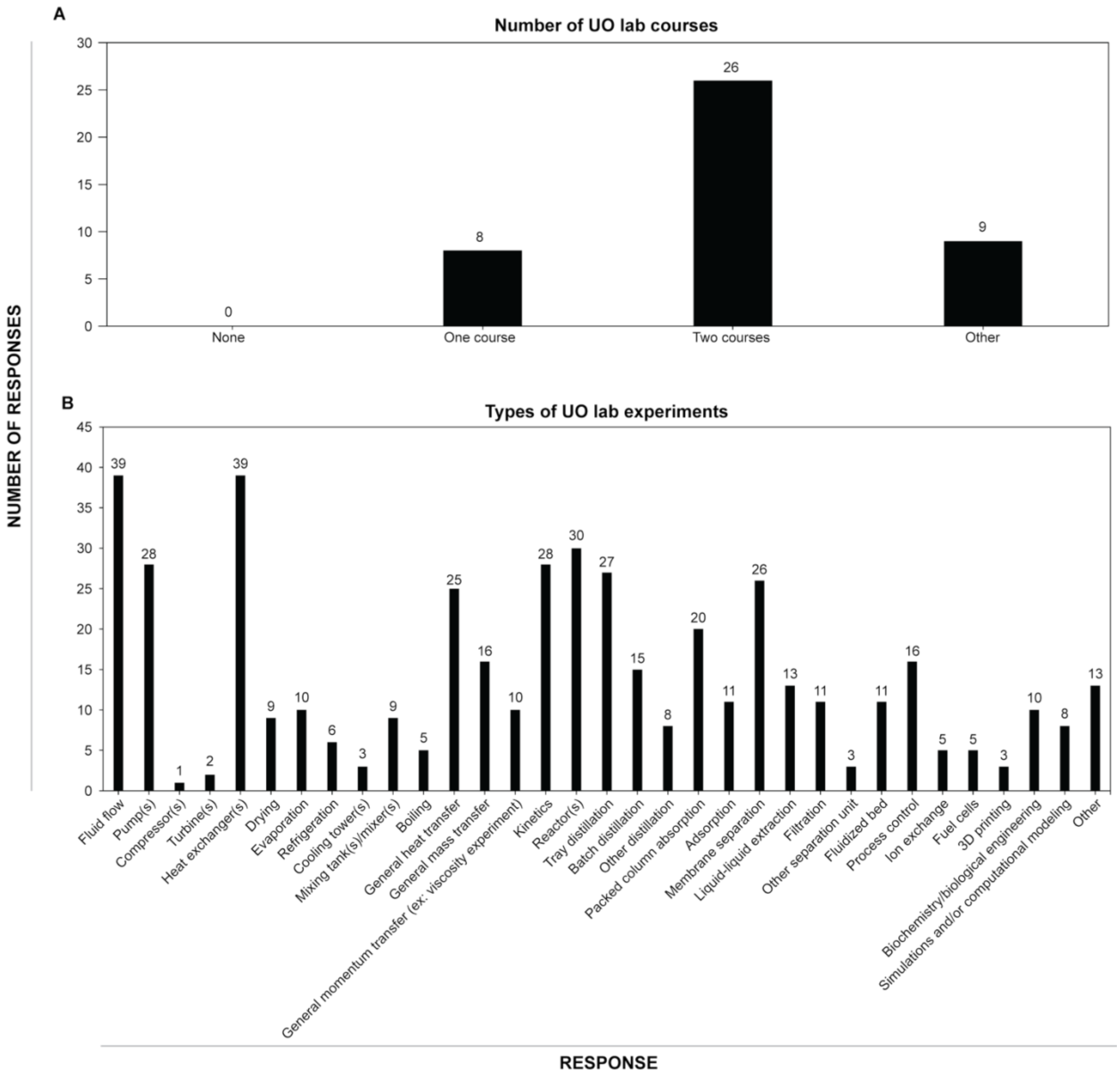

Figure 2. Unit operations lab course structure and experiments. A) Number of unit operations lab courses offered in the department. **B)** Experiments offered as part of unit operations lab course(s).

Many institutions are planning to redesign their lab in the next 10 years and acknowledge the lack of accessibility of their lab spaces.

Instructors were asked to comment on their perceived degree of accessibility of their unit operations lab spaces and courses to those with disabilities (Fig 3A). Interestingly, 20.9% (n=9/43) of survey respondents indicated that their physical lab space was “completely” accessible and another 25.6% (n=11/43) indicated it was “mostly” accessible to individuals with disabilities, demonstrating that nearly half of the laboratories have some level of accessibility infrastructure, modifications, or accommodations. On the other hand, just over half of respondents fell below that threshold, with 51.2% (n=22/43) of respondents indicating that their lab was only “somewhat” accessible to those with disabilities and 2.3% (n=1/43) indicating it was “not at all” accessible. Meanwhile, respondents indicated that their course policies were accessible to a higher degree, with 32.6% (n=14/43) indicating they were “completely” accessible, 34.9% (n=15/43) indicating they were “mostly” accessible, 23.3% (n=10/43) indicating they were “somewhat” accessible, 2.3% (n=1/43) indicating they are “not accessible at all,” and 6.7% (n=3/43) indicating they were unsure or did not know the level of accessibility of the course policies. It is unsurprising that course policies were largely perceived to be more accessible than the physical lab space, as implementing accessible course policies is often either free or requires fewer resources or is more easily supported by the department or institution. However, there is room for improvement in both the accessibility of the lab space and the course policies to support students with disabilities.

When asked whether institutions planned to implement future changes in unit operations labs (Fig. 3B), 41.9% of the respondents (n=18/43) indicated that their department intends to redesign the UO lab in the next ~10 years, with another quarter (n=11/43, 25.6%) indicating a redesign was a possibility. With so many institutions planning a redesign and acknowledging the lack of accessibility of their lab spaces, we believe this further motivates our work in providing suggestions for incorporating accessibility into lab redesigns. Though redesigns of laboratory facilities may require large sums of money, which all departments may not immediately have access to, some designs that increase accessibility are free or inexpensive.

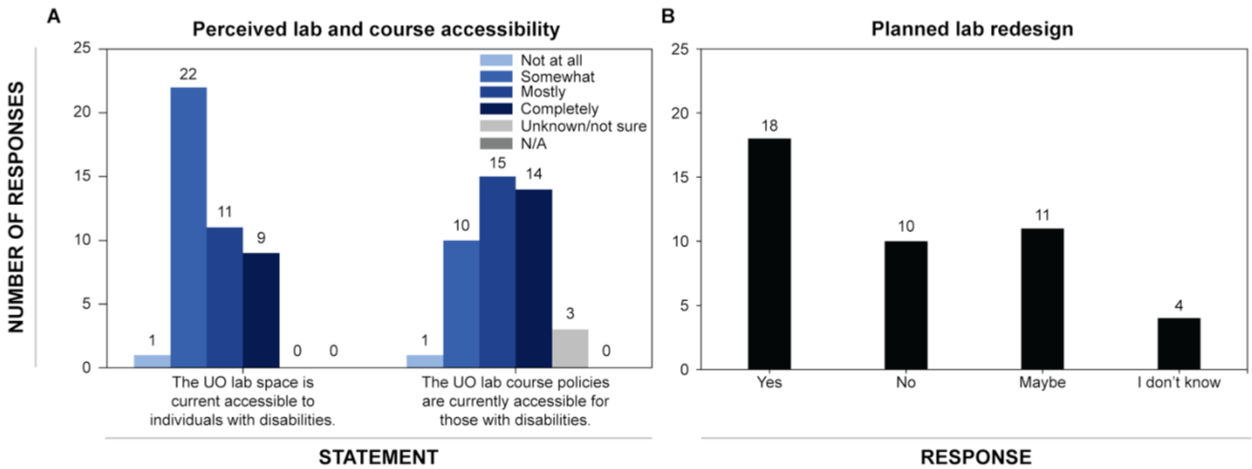

Figure 3. Current space accessibility and plans for lab redesigns. A) Perceived current lab space and course accessibility. **B)** Department plans to redesign the unit operations lab in the next ~10 years.

Accessibility related access issues are likely being addressed in a reactionary, rather than proactive, manner.

The survey results provide insights into the development, procurement, and evaluation of physical lab equipment and space and whether these aspects of lab design include or consider people with disabilities (Fig. 4). Survey respondents were asked to what degree ("completely," "mostly," "somewhat," or "not at all") various statements about lab accessibility were true. The results indicate that accessibility issues were not often considered in the design of the lab. When asked if people with disabilities were included in the lab planning and equipment selection, only 11.7% of respondents indicated that statement was completely true (n=3/43) or mostly true (n=2/43). When asked if considering accessibility is a requirement in the procurement process for lab products, only 23.3% indicated that was completely true (n=3/43) or mostly true (n=7/43). Additionally, when asked if accessibility issues are addressed when procuring and evaluating equipment, only 20.9% indicated that was completely true (n=3/41) or mostly true (n=6/41). These results show that people with disabilities are not often included in the development of the lab space. Neither are their needs considered by their non-disabled counterparts when decisions about the laboratory spaces are made. By far the most accessible aspect of lab design was found to be that there are "procedures to ensure a timely response to required disability related accommodations," with nearly half (n=18/43, 41.9%) of respondents indicating this was "completely" true. This is likely the result of support from university disability resource centers for students, which help instructors respond reactively to disability-related access issues in classes as needs arise and are voiced, and legal requirements to respond to accommodation requests. Less encouragingly, only about a quarter of respondents (n=10/43, 23.3%) indicated that it was "completely" true that "disability-related access issues are addressed in your evaluation of student work," with almost equal proportions of respondents indicating that statement to be "not at all," "somewhat," and "mostly" true. This finding indicates that some instructors are successful in accounting for disability-related access issues, which could range from disability- or chronic illness-related absences to the inability to perform certain tasks in the lab, when evaluating assignments.

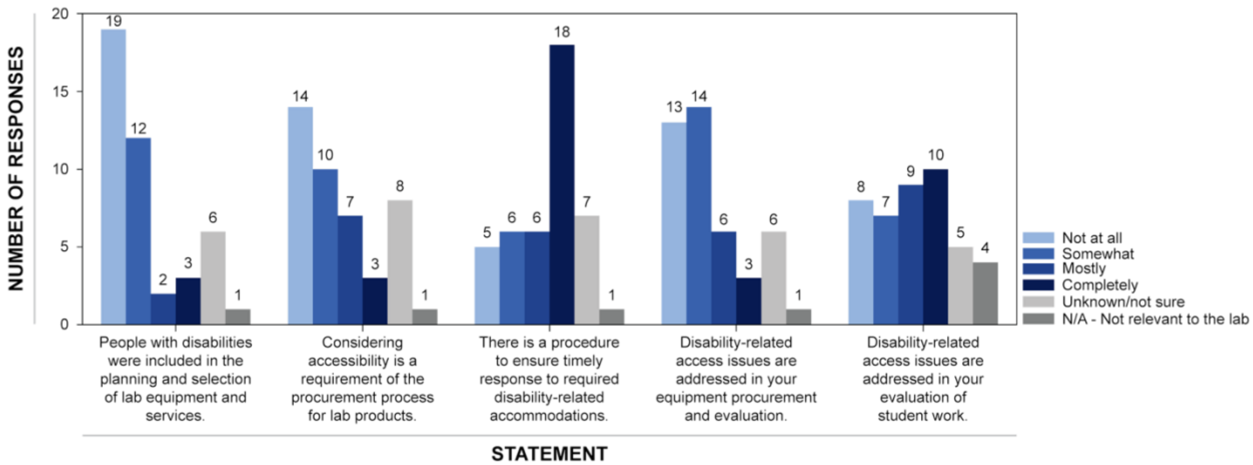

Figure 4. Accessibility of the strategy, planning, policies, and evaluation of the physical lab space.

External building facilities are more accessible than physical lab environments.

Figure 5 shows details of the current state of accessibility of the physical lab environment. While external building structures–such as parking areas, pathways, and entrances to the building being wheelchair accessible and clearly marked and all facility levels being connected via an accessible route of travel–were found to be nearly "completely" accessible (n=34/43, 79.1%), likely due to ADA requirements, the environment inside the lab was considerably less accessible. Though almost half of respondents (n=19/43, 44.2%) indicated that aisles are wide enough and clear of obstructions to accommodate wheelchair users and other individuals with mobility or visual impairments, far fewer noted agreement with the statement that "at least part of a service counter, desk, and/or lab bench was at a height accessible for a seated position." This indicates partial, but not full, consideration of access to lab space and equipment for those with mobility impairments that necessitate the use of a wheelchair and/or available seating.

Lab environments were also assessed for hearing and visual function accessibility. There was close to even distribution across all degrees of agreement with the statement that “there are quiet work or meeting areas where noise and other distraction are minimized,” such as for students with hearing impairments or students who need quieter or less distracting areas to work. Lab spaces can often be loud, particularly with all equipment and stations running simultaneously–but finding areas within the lab, or even close to but outside the lab, can help students be productive during lab when not actively engaging with equipment or to take brief breaks as needed. Unfortunately, when it comes to providing accommodations to individuals with visual impairments through high-contrast and large-print signs to and throughout the lab, most respondents indicated that these accommodations were only “somewhat” (n=21/43, 48.8%) or “not at all” (n=10/43, 23.3%) present. Providing this accessible signage is a relatively low-cost way to address visual accessibility challenges. Overall, both accommodations–finding quieter spaces within or close to the lab and accessible signage–can be done at a relatively low or no cost to the department but can increase accessibility of the lab.

Lab safety procedures should be addressed for individuals with disabilities. Survey results indicate roughly equal distribution of agreement with the statement that “safety procedures have been addressed for students with mobility impairments (e.g., fire extinguisher that can be reached from a seated position).” However, higher fractions of respondents indicated safety procedures had been only “somewhat” or “not at all” “addressed for students with hearing impairments (e.g. instructions in print and visual lab warning signals)” and “addressed for student with visual impairments (e.g. large print signage, audible alarms).” This finding indicates a need to make sure safety equipment–including fire extinguishers, eyewash stations, safety showers, spill kits, and personal protective equipment (PPE)–can be located easily and reached from a seated position. Additionally, signage and safety alarms with both visual and audible indicators of safety issues need to be added to equipment, though this adjustment may require a significant financial investment. Inclusion of clear written instructions, accessible with a screen reader, and detailed videos with captions for how to deal with various safety issues are important components of a thorough training process to ensure these instructions are understood prior to operation of lab equipment.

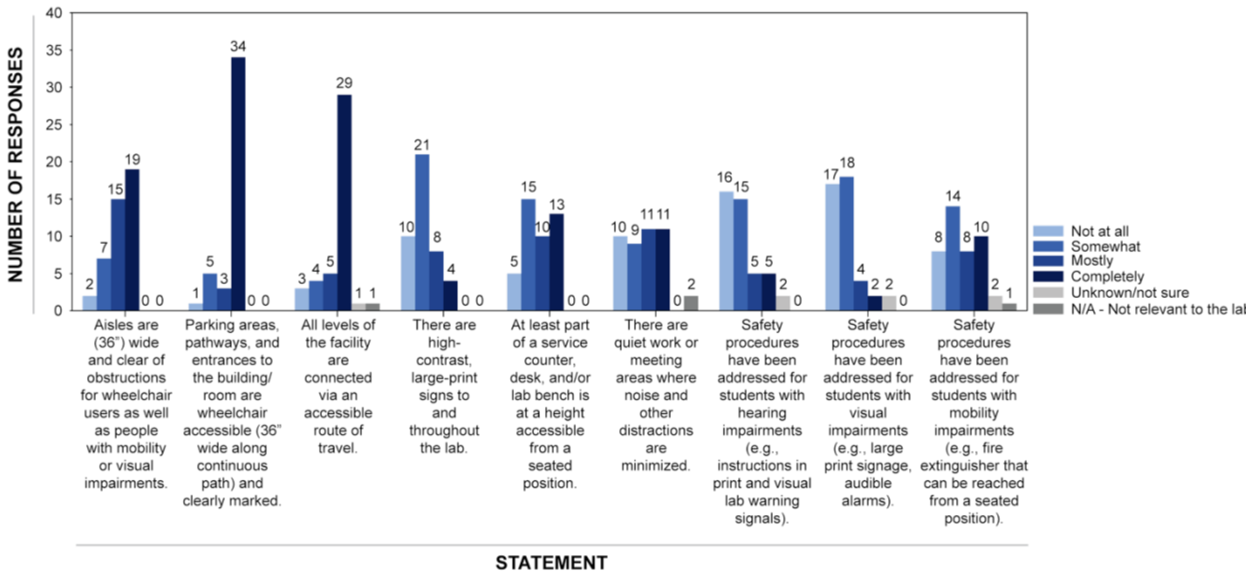

Figure 5. Accessibility of the physical lab environment.

Lab staff require more training on accessible technologies and responding to requests for accommodations.

Survey respondents were asked to assess the familiarity of lab staff with technologies and procedures that support students with disabilities. The largest fraction of respondents reported that lab staff were “somewhat” (n=20/43, 46.5%) or “mostly” (n=15/43, 34.9%) “familiar with the availability and use of assistive technology and alternative documentation formats.” Meanwhile, a more even distribution of agreement ranging from “somewhat” to “completely” was found with the statement “staff members know how to respond to requests for disability-related accommodations such as sign language interpreters.” We suspect it is likely that there is generally more familiarity with responding to requests for accommodations, as institutions typically instruct lab staff and instructors to direct such requests through an office or center for students with disabilities on campus. However, both can be addressed and improved through additional training for lab staff and faculty, which can be found either through any disability related office or center on campus or online resources.

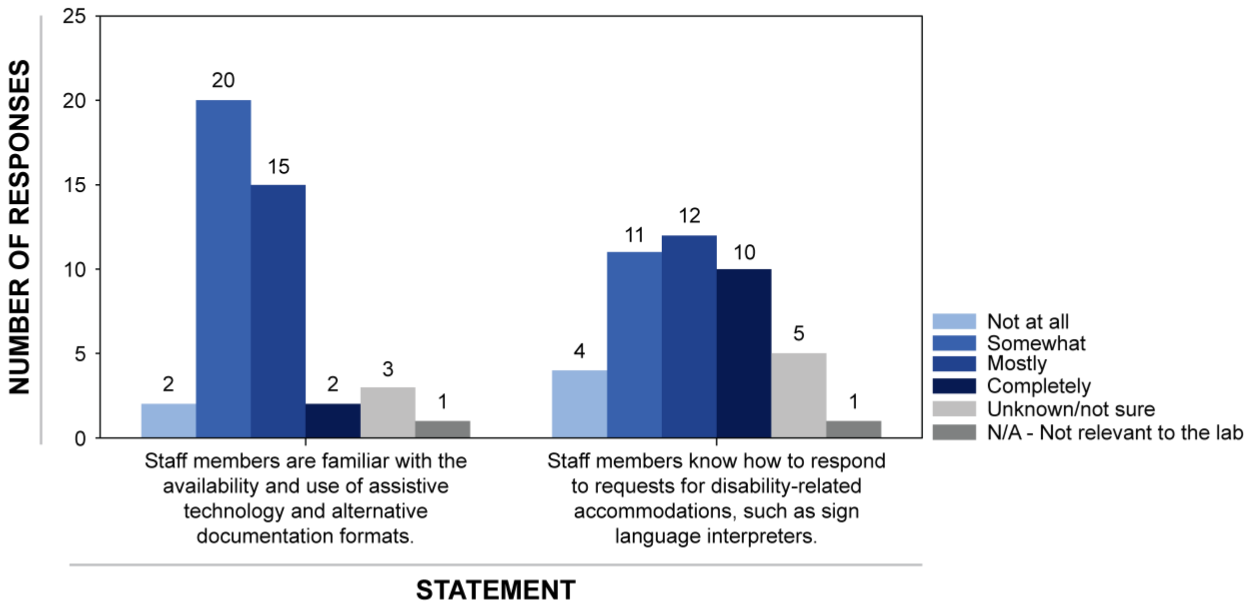

Figure 6. Lab staff familiarity with accessible technologies and responses to requests for accommodations.

Lab information resources are more accessible than internal physical lab environments but still show room for improvement.

The survey asked respondents to indicate the level of accessibility of informational resources, including lab and other course documents, web pages, and other electronic resources (Fig. 7). Roughly half of respondents indicated strong agreement with the statements that “key documents include statements about procedures for requesting disability-related accommodations” and that “lab documents can be reached from a seated position,” with 51.2% (n=22/43) and 44.2% (n=19/43) of respondents responding “completely” true, respectively. Many universities require statements about requesting disability-related accommodations can be found in course syllabi, and that lab documents are often in electronic formats and can be accessed via a laptop, and thus from a seated position. These can be further improved by ensuring that statements about requesting accessibility-related accommodations can be found in multiple documents–including lab procedures, syllabi, and course websites–and ensuring any lab document can be accessed online using the internet, such as on a course website or learning management system, and that they are screen-reader accessible. There is further evidence for the need to make sure these online resources adhere to accessibility guidelines, such as the Web Content Accessibility Guidelines (WCAG) 2.1, per the survey results indicating that most respondents marked the statement “electronic resources, including webpages, adhere to accessibility guidelines or standards" as primarily "somewhat" (n=15/43, 34.9%) or "mostly" (n=14/43, 32.6%) true. Increasing the accessibility of these documents to match these guidelines will require increased training on document accessibility, particularly given the Department of Justice's Final Rule to Improve Web and Mobile App Access for People with Disabilities impacting Title II and Title III of the ADA with respect to public and private institutions [19], [20], and can potentially be supported by offices on campus dedicated to enhancing accessibility for courses, as some may provide services in document formatting.

Meanwhile, making documents that are accessible in alternate formats may require additional work. The largest fraction of respondents indicated that "all printed publications are available (immediately or in a timely manner) in alternative formats such as Braille, large print, and electronic text" was "somewhat" true (n=16/43, 37.2%). While large print and electronic text can be addressed with the availability of editable electronic documents, making documents accessible in Braille will likely require external support. Though online documents can be made screen reader accessible, printed signs and other hard-copy documents for which no electronic alternative exists need to be accessible via Braille, which requires Braille-specific printers or labelers that can be purchased at a wide range of price points.

The least accessible aspect of the information resources was found to be that "pictures/visuals in your documents and/or course website include people with disabilities," with 46.5% (n=20/43) and 27.9% (n=12/43) respondents indicating that this was "not at all" or only "somewhat" true, respectively. While this may be the result of images in these documents having no pictures with any people in them at all, this may also be the result of lack of representation of students with visible disabilities in department cohorts if photographs from former years are included in documentation. If visuals with individuals are required, such as in videos or pictures demonstrating equipment usage, it would be most accessible to include individuals with varying disabilities in these documents and discuss or outline accessibility of the equipment directly.

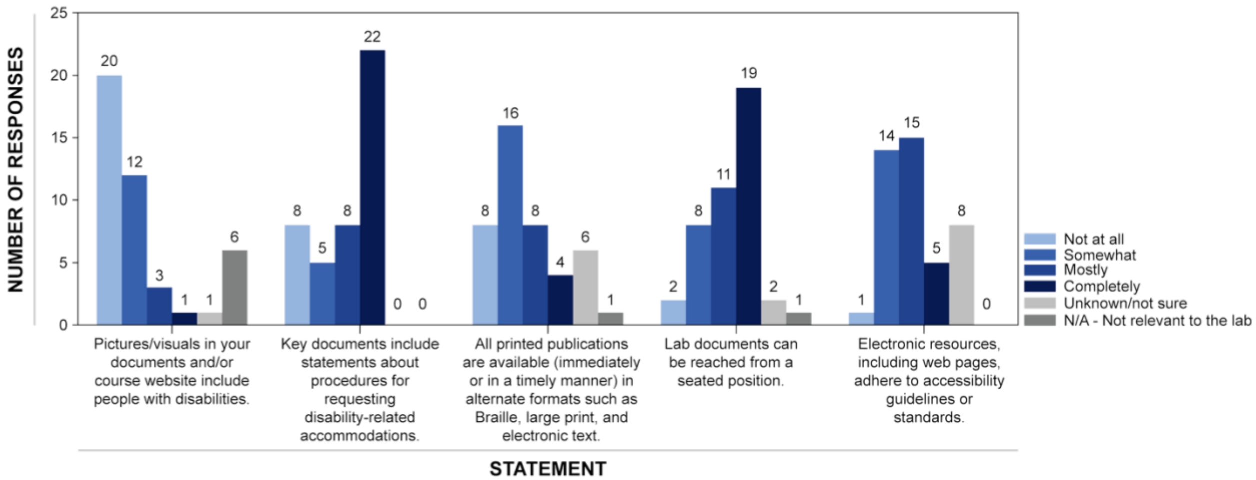

Figure 7. Accessibility of information resources, including lab documents, websites, and electronic resources.

Larger pieces of equipment, workstations, and labels were found to be less accessible than small, portable equipment.

The survey asked respondents to indicate the level of accessibility of lab equipment, ranging from tables at workstations to beakers (Fig. 8). Unsurprisingly, most respondents (n=31/43, 72.1%) indicated a lack of adjustable height benches and accessible marking of equipment, such as with large-print and/or Braille labels. Traditional lab benches or workstations can be attached to walls as counters above storage cabinets, while adjustable height benches require more flexibility in the space and are high-price items. Large equipment and lab benches are some of the most difficult items to make accessible either due to facility limitations or lack of funding. Similarly, most respondents (n=31/43, 72.1%) indicated that controls on lab equipment either could not or could only somewhat be adjusted from a seated position. Though in some cases, handles can be retrofitted to extend the reach of some controls, others cannot be adjusted without adjusting the experimental equipment entirely. When purchasing new workstations during lab re-designs, these types of design elements can be considered prior to purchase.

Though larger pieces of equipment were found to be relatively inaccessible, respondents indicated a higher degree of accessibility when it comes to smaller pieces of equipment, such as beakers, non-slip mats, object clamps, and handles. These are some of the least expensive adjustments to make to quickly improve accessibility in lab spaces and can be changed relatively quickly without requiring a lab re-design. Additionally, work areas were found to be relatively accessible for both left- and right-handed users, which we suspect is a result of the scale of lab equipment providing sufficient room to operate in the orientation of choice.

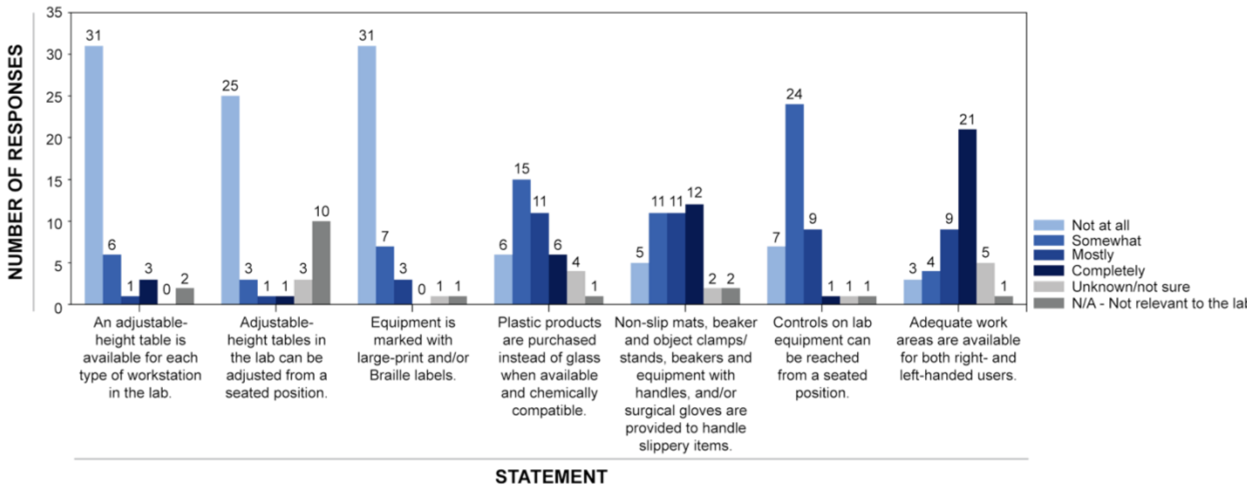

Figure 8. Accessibility of lab equipment.

Courses tend to be more accessible on an individual-student basis rather than to teams of students, and accessibility is rarely actively taught.

Courses can be made accessible through implementation of a combination of universal design for learning principles and course policies that proactively accommodate students with disabilities and chronic illnesses. Some course designs and policies impact individual students, while others affect teams of students. Survey results indicate that course policies that impact individual students were generally more accessible than those impacting teams (Fig. 9A). For example, more than 50% of respondents indicated that statements “assignment extensions are available for students,” “make-up labs are available to students that miss class due to disability or illness for extended periods of time,” and “experiments do not require students to come into lab outside of normal class time” were “completely” true. Meanwhile, availability of lecture recordings was mixed despite evidence that this resource supports students with varying types of disabilities [21]. Students do not appear to need time outside of class to complete labs, which respects students’ ability to use non-class time as needed–whether it be for school or paid work, care-taking duties, or disability- or chronic illness-related care–and plan ahead for scheduled class periods. Finally, while students with disabilities or chronic illnesses appear to be given extensions or make-up assignments for missing class, they are not necessarily provided with the opportunity to review missed lectures. Each of these can be further improved by ensuring these accommodations are available and plans exist for when students need to miss lab due to disability or illness.

While individual accommodations appear to be available, considerations for disabilities and accommodations are less available when it comes to student teams (Fig. 9A). While the majority of respondents (n=36/43, 83.7%) indicated that it was “completely” true that “teams complete peer evaluations,” which can help illuminate to instructors if workload distributions are equal or if teams or individuals experience discrimination on the basis of their disability or chronic illness, slightly less than half (n=19/43, 44.2%) “completely” agreed that “teams fill out a team contract,” which can help create open dialogue and equitable agreements that teams can follow and enable individuals with disabilities to advocate for themselves and their schedules as needed [22]. Worse, the largest fraction of respondents (n=18/43, 41.9%) indicated it was “not at all” true that “teams are created with accessibility in mind.” Even the use of team-making programs like CATME [23] can help account for accessibility without directly asking about student disability status by accounting for their schedules and ability to work on weekends, as students with disabilities or chronic illnesses may have periods of the day or week when they are more able to work or meet up with teammates.

When asked whether accessibility and disability equity were features of the course content, nearly all respondents indicated that accessible lab design and disability equity were not actively or only somewhat taught as part of the course (Fig. 9A). Inclusion of small discussions or assignments regarding these topics, such as discussing accessible lab design and having students assess where it is or is not implemented in the lab space during the lab orientation or lectures on disability equity in the workplace, can provide proactive learning opportunities on accessibility for students. These assignments, discussions, and lectures can originate from instructors, but many could feel unsure about creating content to address these sensitive topics. Resources that address these topics may already exist through online modules or resources, or instructors can call in support from institution staff working at the disability support office or center.

Universities can do more to support instructors in supporting students with disabilities (Fig. 9B). Survey results indicated mixed agreement, including higher levels of unsure responses, with statements that “institution-level disability accommodations apply for group assignments” and “the institution provides the necessary resources to address disability accommodations in the lab course.” Instructors are either unaware of these policies and resources, or they are not entirely required or provided by institutions. While instructors should seek support from relevant campus offices and resources to address accessibility issues and accommodations proactively, universities should provide increased support and clarity about how to support students with disabilities.

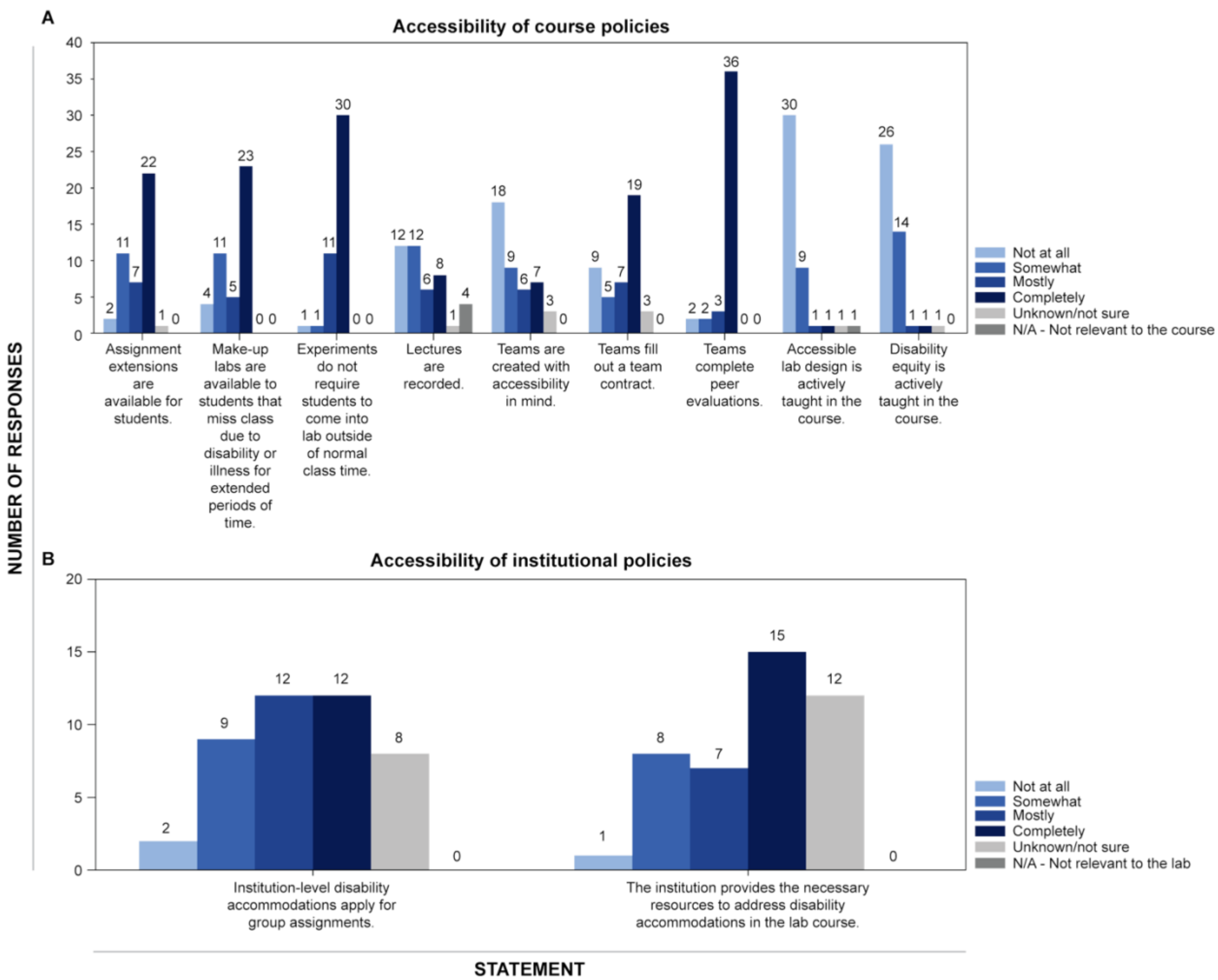

Figure 9. Accessibility of and accommodations provided by course and institutional policies. A) Accessibility of course policies. **B)** Institutional support for accommodations for students with disabilities.

DISCUSSION

Lab policies and documents were found to be more accessible than lab spaces.

Overall, and perhaps unsurprisingly, the data suggests that digital documentation and course policies tend to be more accessible than internal physical lab spaces. While external physical spaces are typically required to be ADA compliant–including parking locations, building access, and floor/hallway navigation–internal lab spaces require department support and individual knowledge to make these spaces accessible.

It is possible that the lack of inclusion of or considerations for people with disabilities when designing laboratory spaces could result from a lack of representation of disabled people in positions within the university that make decisions on facilities. This could be further compounded by lack of representation in positions that run, maintain, and develop laboratories. Additionally, funding limitations could impact an institution's proactivity on accessibility issues because large-scale equipment is infrequently purchased, due to its expense and is typically based on need due to disrepair. Overall, these issues combine to maintain lab spaces that do not include and accommodate disabled individuals.

Proactive changes that consider accessibility issues are needed to evaluate student work.

We found that instructors, with the support of university disability resources centers for students, were able to respond reactively to disability related access issues in classes. However, disability-related access issues were less often considered in the evaluation of student work. Disability- or chronic illness-related absences from the lab impact student work as well as the inability to perform certain tasks in the lab because the equipment is inaccessible. Accounting for these access issues in the evaluation student work currently arises from reactionary accommodations resulting from lack of accessible lab design in the first place. We recommend instructors be provided with better strategies for accounting for accessibility issues when evaluating student work so that they may develop thoughtful evaluation policies that successfully account for unexpected disability related challenges. However, with proactive accessible design of the laboratory space and course assessments, these existing accessibility related challenges may no longer be apparent, and reactionary policies may be prevented.

Updating labs to be more accessible requires increased knowledge of accessibility practices and funds, but not all updates are costly.

We suspect there are two primary limitations to the lack of accessibility are knowledge and financial resources. While increased knowledge of accessibility practices can help increase accessibility of free-to-update aspects of the lab, such as documents and course policies, funding is also needed to increase the accessibility of physical lab environments. However, not all updates are costly. To aid departments and instructors in both increasing their knowledge of accessible lab design and understanding changes that can be made with and without large amounts of funds, we created a list of accessibility tips sorted by (estimated) cost and disability type, including: blind, low vision, or other vision- related function (Table 2); deaf and hard of hearing (Table 3); mobility and dexterity (Table 4); cognitive, behavioral, and learning (Table 5); mental and physical health and chronic illnesses (Table 6); and all types of disabilities (Table 7). We will discuss some of these tips in detail in the following sections.

Table 2. Tips for improving lab accessibility for blind, low vision, or other vision- related disabilities. Suggestions from various sources [9], [12], [24], [25]. Costs estimated from online searches.

COST	TIPS FOR IMPROVING ACCESSIBILITY FOR BLIND, LOW VISION, OR OTHER VISION-RELATED DISABILITIES
FREE ($0)	● Providing screen reader-accessible versions of lab documents and lecture materials. ● Provide verbal descriptions, demonstrations, and visual aids. ● Provide preferential seating for visual access to demonstrations and lectures. ● Provide additional time for setup and completion. ● Use high-contrast, larger icons and fonts on computers. ● Request lectures be in rooms with large display screens. ● Ensure all documents, signage, and safety equipment is prepared for color blind individuals.
LOW COST ($1-500)	● Provide high contrast, large signage. ● Make sure all labels include Braille. ● Purchase Braille/tactile instruments (e.g. ruler, caliper, syringes with stops or notches, etc.). ● Purchase large print calculators. ● Use different textures to label areas on items (e.g. sandpaper). ● Provide utility/equipment controls within easy reach (price varies depending on what equipment) ● Use a camera to enlarge microscope images on computers/monitors
MEDIUM COST ($500-1500)	● Purchase signage with Braille. ● Purchase audible/talking scales, thermometers, and probes.
HIGH COST ($1500+)	● Connect instruments to screen readers (e.g. use Window-Eyes screen reader to navigate the data displayed in Vernier Equipment LoggerPro software collected from a connected instrument such as the Vernier GC [26]). ● Translate all course materials to Braille.

Table 3. Tips for improving lab accessibility for deaf and hard of hearing disabilities.

Suggestions from various sources [9], [12], [24], [25]. Costs estimated from online searches.

COST	TIPS FOR IMPROVING ACCESSIBILITY FOR DEAF AND HARD OF HEARING DISABILITIES
FREE ($0)	● Provide preferential seating for demonstrations and lectures. ● Provide written instructions, including on/near equipment. ● Provide additional time for setup and completion. ● Request lectures be in rooms with large display screens. ● Encourage a culture of group communication where only one person speaks at a time and faces the listeners.
LOW COST ($1-500)	● Install/purchase visual timers. ● Install visual signage. ● Have whiteboards, notebooks, or smart devices available to aid in team communication. ● Caption videos related to course materials and lab safety.
MEDIUM COST ($500-1500)	● Install visual complements to auditory alarms, such as those containing flashing lights. ● Use speech-to-text software options for verbal instructions that are not included in the written materials.
HIGH COST ($1500+)	● Hire interpreters or sign language translators and ensure they understand the instructional material prior to the arrival of the student.

Table 4. Tips for improving lab accessibility for mobility- and dexterity-related disabilities. Suggestions from various sources [9], [12], [24], [25]. Costs estimated from online searches.

COST	TIPS FOR IMPROVING ACCESSIBILITY FOR DISABILITIES RELATED TO MOBILITY AND DEXTERITY
FREE ($0)	● Ensure space is well organized, and that walkways are clear. ● Ensure small equipment (e.g. rulers, timers, beakers, etc.) can be accessed from the height of a seated position. ● Ensure the route to the lab location is accessible (i.e. elevator access and unobstructed pathway to entrance). ● Ensure all walkways enable wheelchair access (36" wide minimum). ● Provide preferential seating for visual access to demonstrations and lectures. ● Use modified procedures that utilize larger weights/volumes (to avoid needing precision with very small volumes). ● Provide additional time for setup and completion. ● Request lectures be in rooms with large display screens.
LOW COST ($1-500)	● Purchase grip assistive devices and typing aids to aid those with hand mobility limitations in using computers and gripping lab equipment, such as beakers or turning valves, safely. (Alternatively, purchase equipment, such as beakers, with handles). ● Ensure equipment controls are within easy reach (price varies for equipment). ● Place larger equipment or facility features at height accessible from seated position (price varies depending on equipment and mobility, ex: sink, eye wash, electrical outlets, emergency shower, fire extinguisher, beakers, etc.). ● Place mirrors above the instructor during demonstrations. ● Use an enlarged screen for displays during the lab. ● Purchase an electric stirrer and container filler. ● Purchase equipment support stands (e.g. beaker/object clamp, test tube rack) ● Purchase an extended eyepiece for microscopes. ● Use a camera to enlarge microscope images on computers/monitors. ● Utilize alternative lab storage methods (e.g. lazy Susan, rotary storage, storage with wheels attached). ● Consider plastic equipment (e.g. beakers) when chemically compatible. ● Include lever or paddle controls instead of knobs. ● Utilize non-slip mats.
MEDIUM COST ($500-1500)	● Provide flexible connections to water, electricity, and gas lines (e.g. extended tubing). ● Install door handles that are levers instead of knobs, or purchase removable handle covers for round doorknobs (a cheaper option).
HIGH COST ($1500+)	● Purchase adjustable height benches and fume hoods for at least one station (height between 28-34 inches with at least 27 inches of knee clearance). ● Remove any requirement/need to use stairs within any experimental setup and purchase equipment that can be accessed without stairs. ● Install an automatic door opener or doors that can easily be opened and that are sufficiently wide.

Table 5. Tips for improving lab accessibility for cognitive, behavioral, and learning disabilities. Suggestions from various sources [9], [12], [24], [25]. Costs estimated from online searches.

COST	TIPS FOR IMPROVING ACCESSIBILITY FOR COGNITIVE, BEHAVIORAL, AND LEARNING DISABILITIES
FREE ($0)	● Ensure instructions can be accessed in a combination of written, verbal, and pictorial formats. ● Repeat demonstrations or provide videos of demonstrations for repeated watch. ● Provide or enable students to take frequent and/or brief breaks. ● Provide preferential seating during lectures and demonstrations to avoid distractions. ● Provide flexible schedule/time allocation when possible.
LOW COST ($1-500)	● Provide quiet spaces within or nearby the lab for focused work or short breaks. ● Provide simulations/virtual labs or accessible take-home labs as alternatives when needed for periods of long absences.

Table 6. Tips for improving lab accessibility for mental and physical health-related disabilities and chronic illnesses. Suggestions from various sources [9], [12], [24], [25]. Costs estimated from online searches.

COST	TIPS FOR IMPROVING ACCESSIBILITY FOR MENTAL AND PHYSICAL HEALTH-RELATED DISABILITIES AND CHRONIC ILLNESSES
FREE ($0)	● Provide preferential seating for demonstrations and lectures. ● Enable students to request assignment extensions as needed or with limitations. ● Enable zoom participation for students who need to stay home but feel well enough to engage with teammates during lab time. ● Require or encourage mask wearing in class and lab spaces and provide masks in the lab. ● Provide flexible schedule/time allocation when possible.
LOW COST ($1-500)	● Create teams with accessibility in mind, such as using CATME to account for student schedules. ● Provide simulations/ virtual labs or accessible take-home labs as alternatives when needed for periods of long absences.

Table 7. Tips for improving lab accessibility for all types of disabilities. Suggestions from various sources [9], [12], [24], [25]. Costs estimated from online searches.

COST	TIPS FOR IMPROVING ACCESSIBILITY FOR ALL TYPES OF DISABILITIES
FREE ($0)	● Record lectures with high-quality audio and captions. ● Provide a copy of lecture notes, instructors, lab manuals, and other written documents in screen-reader accessible format. ● Cover accessible design and disability equity as part of the curriculum.

Equipment, facilities, and curricular updates at a range of costs can increase lab and course accessibility in both the short and long term.

Curricular changes made to lab and lecture courses, such as course documents like syllabi and lab safety procedures and policies like homework extensions can be made freely and with low instructor effort to increase accessibility. Recording lectures not only supports student learning by enabling students to review content and fill in missed notes but also supports students with a wide variety of disabilities [21]. Similarly, providing lecture notes and other course documents, particularly those that adhere to digital accessibility guidelines (discussed in detail below) can enable students with many types of disabilities to engage with course content. Flexible but limited assignment extension policies like free no-questions-asked 24-hour extensions applied to any or a subset of assignments of choice can enable students with and without disabilities to have additional time on assignments when needed. For students with disabilities that require absences from lab the opportunity for extensions, make up periods, or virtual labs may accommodate these absences.

Curricular changes around teamwork, such as discussions around empathy, adaptability, and communication can go a long way towards creating a supportive team environment. Coupled with team-building programs like CATME, teams can be established with accessibility in mind, such as by factoring in student schedules and preferred working times. Additionally, teams can be encouraged to have an open dialogue about their goals, availability and preferred working times, strengths, and challenges when creating team contracts or filling out peer evaluations. However, students must be educated on how to engage in these discussions respectfully and constructively. For example, students with cognitive, neurological, or behavioral disabilities may need specific strategies and more structured support to thrive in a team setting [27], [28]. Clear communication with direct language, written directions or visuals, predictable routines and timelines, and agreement on regular communication schedules and methods (face-to-face, online, text) help provide structure. However, individual needs may require additional supports such as explicit instructions on group expectations and social cues, awareness of sensory triggers or needs, and adaptation of tasks based on ability. As another example, students with chronic illness may have more frequent or longer-term absences that may require additional flexibility and more open communication on limitations and challenges that lead to clearer expectations of team role, responsibilities, tasks, and timelines and internal deadlines. In many cases, regular check-ins with teammates and instructors to discuss feedback, progress, challenges, and adjustments may be useful in supporting students with disabilities, educating their peers, and promoting effective teamwork. Policies and processes for requesting disability accommodations should be clearly outlined on course syllabi.

Small, low-cost modifications to lab space organization or equipment can make existing lab spaces more accessible. For example, organizing the lab such that walkways are clear and ensuring all small equipment items (ex; beakers, timers, rulers, etc.), and, if possible, equipment controls, can be reached from a seated position is a low-cost or free way to increase accessibility for those with mobility limitations. Additionally, these small items can either be purchased with accessibility in mind or adapted with assistive technology/devices to be made more accessible. For example, plastic beakers can be used in favor of glass when possible and chemically compatible, as plastic beakers are lighter, and thus easier to hold and carry, and do not break as easily if dropped. Beakers or other items can also be purchased with handles already attached or grip assistive devices/aids can be bought that removably attach to items to increase ease of handling these items for those with hand mobility limitations. Similarly, typing aids and detachable door handles can be purchased for those who need typing or gripping assistance, respectively. The lab space can be arranged such that there are quiet, low-distraction places to work or take short areas, or areas adjacent to the lab can be provided for this purpose. Large, high-contrast lab signage can be purchased from lab equipment suppliers or custom made. These changes are relatively inexpensive and can be additionally used to educate students about small changes they can make in their future work environments to increase accessibility.

If more funding is available, larger or more extensive changes to equipment and facilities can significantly increase lab accessibility when a large overhaul and/or redesign is possible or upcoming. For example, instructors can purchase equipment that does not require the use of stairs and where all controls and/or sampling can be accessible from a seated position and with easily graspable knobs and valves. Adjustable height benches can enable experiments to be conducted at a height comfortable for any individual. If facility updates can be made, safety devices such as fire extinguishers, safety showers, eye wash stations, and fume hoods should all be accessible from seated positions and ADA doors can be installed at doorways to or within the lab. These changes all require significant funds, and possibly an overhaul of large experimental equipment or of the lab space itself and thus may take significant amounts of time and planning. However, they are items worth considering for the next time the funding to redesign the lab is available.

Applying principles of digital accessibility offers a way for instructors to make “free” accessibility improvements to their lab spaces and courses, and soon implementation of these principles will be required by federal law.

Digital accessibility is becoming an important aspect of making all courses, including laboratories, more accessible. In the United States, the Americans with Disabilities Act (ADA) is a law aimed at protecting people with disabilities against discrimination. Recent work in the digital domain has focused primarily on websites; however, Final Rule 89 by the Civil Rights Division in April 2024 stated the following regarding digital accessibility for public schools [29].

> “*Public schools at all levels, including **public colleges and universities**, offer programs, reading material, and **classroom instruction through websites**. Most public colleges and universities rely heavily on websites and other online technologies in the application process… for course registration and **assignments**; and for a wide variety of administrative and logistical functions in which students must participate.*”

While improving digital accessibility in courses is considered a free way to improve accessibility, the knowledge needed, labor, and time required to implement certainly have a cost. While many other resources are available for creation of accessible documents [1], [30], [31], this section will focus on major tips to improve two major areas: laboratory documents and the accessibility of Learning Management Systems (LMS).

Accessible Laboratory Documents

Creating Word Documents

Documents (SOPs and Manuals, Assignment Memos with Experimental Objectives, etc.) are critical pieces of digital media in undergraduate laboratories. Students within these labs rely on these documents to build knowledge and meet learning objectives in a safe manner in a relatively short amount of time. Creating accessible documents will benefit all students, not only students with accessibility needs.

It is easiest to make documents accessible during the initial creation, rather than amending old documents. Here we will provide overall tips and some specifics to Microsoft Word, as Microsoft products combine text creation and typesetting. If using LaTeX for document creation, additional LaTeX packages need to be used to create more accessible documents [32].

- **Headings:** Headings are short descriptions of sections of text on a page. To be accessible, they should be descriptive, organized, and use proper hierarchy. Use of the correct heading "styles" with proper hierarchy in Word or Google Docs enables visually impaired users to understand where they are in a section and how those sections are related. Additionally, using proper heading styles and hierarchy enables the word processors to automatically build tables of contents using these styles, if needed.
- **Line Spacing:** When adding blank lines within a text document, avoid using multiple carriage returns. Screen readers will read each of these as the word "blank." It is better to use page breaks when attempting to shift lines to the next page or to use paragraph spacing to add a space after a paragraph or list items. Adding additional spacing makes it easier to read for users with visual-impairments or difficulty reading.
- **Hyperlinks:** One of the biggest impacts for accessible documents is avoiding links that are either solely web addresses or hyperlinked to non-link specific or descriptive words, such as the word "here." To make hyperlinks more accessible, give a title to the link. For instance, instead of "www.asee.org" give it a title like ASEE Homepage. This convention avoids an issue where screen readers will read multiple links named "here" (which isn't helpful) or read complete HTML addresses (which takes much longer and is harder to decipher).

- **Lists:** The best way to create a bulleted or numbered list is using the built-in list formatting (for bullets and numbered lists) instead of creating your own. Screen readers will read these as “bulleted list” or “numbered list” enabling visually impaired readers to understand that these items are grouped together.
- **Equations:** Over the last few years as technology and disability laws have improved, there has been a shift in recommendations [33] on how to input equations in accessible documents. Some slightly older sources recommended inputting equations as images. However, the alt text description can be lengthy to describe advanced equations. Recent articles promote use of built-in equation functions (such as Microsoft Office Equation Editor) [34], [35], [36] .
- **Images:** One of the biggest challenges in creating accessible documents are images including charts and graphs. Ideally, any image or figure should add context to the paper. These figures can be critical in assisting individuals with dyslexia or who are visual learners.
    - **Alternative (Alt) Text:** Alt text is critical for images that add context. Decorative elements can remain but should be identified in the alt text as such. Alt text should be concise and communicate the same information as the visual image. Specifically for graphs and charts, the alt text should give relevant content, such as data trends, and not describe the look of the image. A title should be included in addition to the alt text [37].
    - **Figure Caption:** While alt text of images assists people using screen readers, each image should be accompanied by a similar figure caption that includes the figure number and brief description to help readers understand the figure without referring to the main text. An easy way to do this is to right click on the figure and “insert caption” [38].
    - **Image Formatting:** To ensure the accessibility of non-text elements, the “wrapping style” should be set as “In line with text.” Do not overlay text on images. If needed, it is best to create an image with that text and capture the addition in the alt text.
- **Tables:** Like images, tables should add context and are for presenting data, not for content layout. Addition of a caption (by right-click then “insert caption”), is beneficial. When creating tables in Microsoft Word, keep them simple and include either a formatted Header Row or a formatted First Column (or both if appropriate). These formats can be found in Word under the Table Design Ribbon. Because the Header Row

cells correspond to specific cells below, do not merge or split cells. Due to the importance of Header Rows, a table should not split pages and should instead be broken down into two separate tables with their own respective Header Rows. [39], [40]

Checking Documents for Issues

Upon completion of the document creation, it is beneficial to run an accessibility checker to see if any improvements can be made. These checkers are not fail-proof tools but will give good recommendations for improvements. Within Microsoft Word, you can go to the Accessibility Checker (Review → Check Accessibility). This checker will create a report with recommendations including the ability to click on the necessary improvements and move to associated sections of the document. As of the authorship of this paper, Google Docs does not have a built-in accessibility checker. Recently, many universities have started allowing Grackle Docs, Sheets, and Slide through the Google Workspace [41], [42]. However, as this is an external extension to the Google Doc suite, another recommendation is to download the completed document as a Word document and use the Microsoft Word accessibility checker.

Document File Formats

Once your document is completed, the best practice is to save and share it with students as a Word Document. If modification by students is a concern, one way to do this is to protect your word document to "read-only" by encrypting with a password. However, if this password is lost, it is hard to recover documents. Alternatively, you can export as an accessible PDF. This can be accomplished by "save [File] as → File Format: PDF." Do not print documents as a PDF. Please note that a PDF is only as accessible as the document it is built upon.

Having both updated print and digital copies available on your learning management system as well as on computers at the lab station, if available, gives multiple ways to access the manuals and SOPs for the experiment. Remember that these print and digital versions should be kept updated to the same revision version.

Learning Management Systems

According to a list of 383 universities and community colleges from Follet Higher Education [43], Canvas and Blackboard are used by over 70% of the listed universities and community colleges. Therefore, recommendations within this section will focus on these LMS.

Clarity, conciseness, and consistency are key items to increasing accessibility within an LMS. Navigation by users is easier and more intuitive if the naming structure of pages, experimental names, and files are consistent. Rename files to have a descriptive title, especially when uploading papers downloaded from other journals or websites.

One major challenge in updating and maintaining a cohesive and accessible LMS is ensuring that links (both to external websites as well as internal documents) remain active. Canvas and Blackboard have link validation software. In Blackboard, this tool is called "Check Course Links" and appears in the Packages and Utilities section of the Control Panel [44]. For Canvas, this is the "Course Link Validator" and is located on the right-hand side of the Course Settings page [45].

Many of the accessibility recommendations for creating pages (including assignments and announcements) within LMS or documents within the LMS are the same as those above in the document accessibility section and thus will not be repeated here. Both Canvas and Blackboard have accessibility checkers in their Rich Text Editors. The symbol for these tools looks like a stick person and works like those in Microsoft Office.

Accessible design and disability equity can be actively taught in lab courses and engineering curriculum.

Engineers can either identify as, interact with, and/or build technology that impacts individuals with disabilities. It is important to train engineers to join the workforce prepared to engage with others and their work through an equity lens. One way to provide this training is to actively discuss and teach disability equity in the context of lab courses. Incorporating this into curriculum is a low-cost way to make a course more accessible and inclusive of those with disabilities. If needed, associated curriculum can be paired with now-common ethics lessons via association with the AIChE Code of Conduct, one point of which states "*Treat all colleagues and* *co-workers fairly and respectfully, recognizing their unique contributions and capabilities by fostering an environment of equity, diversity and inclusion*” [46].

Digital accessibility can be taught, or even required, for written or presented work submitted in lab courses. Students can be taught all principles and guidelines for digital accessibility discussed in this paper, required to implement these strategies in submitted reports, and a portion of their report grade can be assessed on accessibility by determining adherence to these guidelines. For example, one tool that exists for the purpose of understanding the experience of disabled individuals when interacting with online tools is the Google Chrome Add-On: Web Disability Simulator [47], which can be used as an in-class activity or demonstration. Instructors can also teach other aspects of accessibility associated with data presentation, including designing graphs to be readable to those with colorblindness by teaching principles of double encoding (ex: using both color and marker shape/line style to indicate different items in a plot) and demonstrating choosing colors compatible with different types of color blindness using online tools.

Another method of educating students about accessible design that does not require changes to the lab space is to teach students how to assess a lab for accessible design. Labs that are not accessible for disabled individuals may also present hazards or safety issues, and accessible lab design can be taught alongside lab safety. During the lab orientation, in addition to any standard safety training, students can be asked to complete the University of Washington’s Disabilities, Opportunities, Internetworking, and Technology (DO-IT) Checklist for Making Science Labs Accessible to Students with Disabilities [17]. This assignment will encourage students to consider what types of features make a lab accessible to individuals with disabilities and can help instructors identify features of the lab that do not currently match these criteria to use these as starting points for future changes.

Finally, instructors can develop curriculum on disability equity in the engineering workforce and field. Teaching this content requires discussing the broader principles of disability equity in a workplace and/or engineering design context, the current lived experiences of disabled engineers or engineering technologies that are not accessible, and the types of actions that can be taken by engineers to move toward equity and justice. Actions to improve accessibility in laboratory courses and discuss disability equity centers disabled students and disrupts ableist norms; it is one step toward changing the culture of STEM to inclusion. For those unsure of where to start in developing this curriculum, reading books like *Demystifying Disability: What to Know, What to Say, and How to Be an Ally* by Emily Ladau [48] or viewing the online posts in the #DisabledinSTEM hashtag can be helpful in beginning to understand the lived experiences of disabled individuals.

CONCLUSION

Though laboratory courses at present vary in their level of accessibility, and smaller equipment and course policies tend to be more accessible than broader facilities and larger equipment, the first step to creating a more accessible lab is increased understanding of accessibility. We hope this paper provided a starting point in this education as well as a roadmap with suggestions for increasing accessibility at all price points and through multiple avenues. Designing accessible labs will require time, iterative changes, and in some cases funding, but the changes will benefit all students through explicit support for students with disabilities and implicit education for all.

AUTHOR CONTRIBUTIONS

ANP and JLC conceived of the idea for the study, created the survey, and analyzed the data. JLC and JC conducted a literature review of existing assessments and studies of accessible lab design. ANP, JLC, CJB, and JC compiled suggestions for improving lab and course accessibility and wrote and edited the manuscript. ANP created the manuscript figures.

ANP and JLC are co-corresponding and co-first authors of this paper.

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