Centering Teachers' Voices: Design Guidelines for High School Laboratory Technologies

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High school science laboratories serve as critical spaces for developing scientific reasoning inquiry skills, yet educational technology often struggles to support these practices. Through engaging with science teachers via school visits (n=7), surveys (n=58), and interviews (n=18) spanning diverse socioeconomic contexts, we investigate how teachers envision technology's role in science labs. We identify mismatches between existing technologies and classroom realities. Many technologies focus on showing abstract concepts and "perfect" simulations, while teachers favored students learning the "ways of science" (e.g., lab skills, designing experimental methods) and grappling messiness of empirical data. Typically, teachers modify traditional labs to meet diverse student needs. However, todays technologies but lack this flexibility. We therefore argue for moving beyond pure technical sophistication towards pedagogy-based technologies that empower teachers and promote equitable science education. In this work, we contribute actionable design guidelines towards laboratory teaching technologies emphasizing customization, preservation of hands-on experiences, and real-world knowledge transfer.

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1 Introduction

When computers became mainstream and provided access to educators around the world, technology was projected to revolutionize education. That did not occur as expected [**?**]. When extended reality entered consumer markets, again, student learning stayed roughly the same [54, 77]. Recently, with the advent of generative AI, promising learning gains resurfaces to the headlines. What steps must designers take to ensure the technology designed today benefits the learners of tomorrow?

There are a myriad of ways well-designed, well-intentioned, and well-researched educational tools can fail after they move into classroom settings [24, 52, 55]. Tools that produce statistically significant learning gains in controlled lab settings fail to explain concepts in a way that relates to specific students [52]. Simulations that boast a quick and easy set-up take away the benefits of hands-on learning [55]. Even government-supported, resource-backed initiatives can fail to adapt to specific classroom structures [24]. While educators have similar learning objectives, they work with vastly different student populations and classroom landscapes. These examples highlight the all-too-common blind spot in educational technology: we are designing education technology largely in isolation from the very contexts that determine their success or failure.

In this paper, we present a mixed-method analysis of teachers' technological perspectives for high school science laboratories. High school science represents a compelling and dynamic area for HCI research, where educational landscapes shift drastically from district to district, teacher to teacher, and even classroom to classroom [38, 46]. Through labs learn to think with evidence, question assumptions, interpret messy data, and collaborate with peers [28]. This embodied engagement relies on numerous artifacts (e.g., notebooks, scientific equipment, simulations) that not only mediate scientific practice but also highlight areas where technology can extend or transform learning. At the front-lines are the science teachers themselves: they regularly adapt labs for their specific classrooms, adjusting for resource constraints and connecting to student interests.

Co-desiging education technologies with high school science teachers is easier said than done. Despite prior efforts to include teacher voices [53, 56], many commercial solutions still relegate teachers to the role of end-users rather than co-designers [48]. This "design, build, test" approach has produced a graveyard of educational technologies that work brilliantly in demonstration videos but fail in actual classrooms [22]. Therefore, establishing guidelines rooted in teachers' perspectives is essential for deploying systems that support the realities of high school laboratories.

Prior HCI research has demonstrated that technology can successfully support students in grasping abstract concepts [30], making connections to real-world phenomena [55], and developing scientific reasoning [16, 43]. Despite these advances, students still falter on inquiry [42] and disciplinary proficiency [1], suggesting a persistent gap between research prototypes and everyday classroom use. Previous work highlights that the limited adoption of new educational technologies often stems from systemic constraints: teachers face pressure to adhere to existing curricula and testing requirements, while schools lack the structural adaptability to support technological instructional approaches [57]. On top of this, most teachers are interested in adding technology into their classrooms only when it fits their needs [51].

We conducted a mixed-methods study via school visits, a survey, and interviews to investigate teachers' perspectives on technology in science labs (**RQ1**), aiming to understand barriers to adoption (**RQ2**), and contribute design guidelines to inform more effective design strategies for classroom-ready tools (**RQ3**). We first completed school visits (*n*=6) in [anonymized] across various socioeconomic demographics, conducting semi-structured interviews with high school science teachers and an observation in a biology lab to inform survey development. Second, we developed a survey to capture the desired learning outcomes, common challenges, and necessary adaptations in educational laboratories, which was deployed in the United States (*n*=58). Finally, we conducted semi-structured follow-up interviews (*n*=18) with teachers in [anonymized] to explore their perspectives on both the use of existing technologies and their aspirations for future educational technology science lab classroom integration.

In this work, we contribute the following:

(1) A representative survey informed by site visits and qualitative interviews, that captures teachers' perspectives on science labs and the role of educational technologies.
(2) A mixed-methods analysis of survey responses and follow-up interviews surfacing gaps between current technology and teachers' needs in laboratory education.
(3) Design guidelines for educational science laboratory technologies that foreground teacher practices, classroom contexts, and the realities of experimental learning.

Our findings point toward a fundamentally different approach to educational technology design: one that prioritizes adaptability over sophistication, contextual responsiveness over technical advancement, and teacher agency over automated solutions. These insights are valuable not just for industry educational companies, but also researchers designing technology for learners in real-world educational settings.

2 Related Work

Our works builds on previous work in participatory design, teachers past perspectives on technology, and previous work in educational technologies.

2.1 Participatory Design with Teachers

Participatory design with educators has emerged as a productive approach for aligning educational technologies with classroom realities. In HCI, co-design has been shown to increase teacher agency, improve adoption, and foster professional development by positioning educators as active collaborators rather than passive end-users [19, 31, 50, 53, 56]. For example, Nicholson et al. introduced "co-teaching" as a model of participatory design, embedding researchers in classrooms alongside teachers to iteratively develop and test digital tools, demonstrating how this process surfaces practical constraints such as curricular integration and assessment demands [53]. Similarly, Ravi et al. conducted interviews and workshops with K–12 educators to co-design large language model tools for project-based learning, yielding guidelines that emphasized transparency, adaptability, and alignment with instructional goals [56]. Other work, such as VIVID, has extended participatory practices into the authoring of interactive lecture dialogues, highlighting how design workshops with instructors can inform the creation of technologies that support active learning [19]. Together, these studies illustrate how participatory approaches with educators not only generate contextually relevant tools but also empower teachers to shape how emerging technologies are integrated into their practice.

Beyond instructors, participatory methods have also engaged students and professionals as co-designers in educational contexts. Building on traditions such as Cooperative Inquiry, researchers have documented how involving young learners in low-fidelity prototyping and design workshops surfaces new metaphors and representations that better align with student understanding [29, 76]. In apprenticeship and training settings, participatory design has been used to reconcile mismatches between instructional practices and learner needs, as in studies of medical residencies where interviews and workshops with mentors and trainees produced guidelines for timely, artifact-centered feedback [75]. Taken together, these strands reinforce the potential of participatory approaches to generate design insights across levels of education, from K–12 classrooms to professional training, and underscore the value of involving teachers, students, and practitioners as domain experts in the design of educational technologies. This study expands prior work by integrating teachers' perspectives on science laboratories with

2.2 Teacher Perspectives on Technology and Classroom Adoption

As technology evolves, it's important to evaluate teachers' evolving perspectives. Czerniac et. al evaluated teachers' perspectives in 1999 and discussed the importance of technical infrastructure, internet access, and administrative support [20]. Then in 2010, when technology became more developed and more widely accessible, Ng and Gunstone conducted another likert survey in 2010, and found teachers had positive views on technology and technology use was more widespread in schools, typically as dedicated computer rooms [51]. Now, with over 90% of schools having 1 to 1 use of computers for each student since 2021 [13], there is a need to reassess teachers' views and visions for technology.

2.2.1 Personalization for Education. Every school, classroom, and student is contextually different. Curricula have different foci, classrooms have different structures, and students live in different environments that can affect their academic progress. Therefore technology has helped teachers adapt curricula to their diverse classrooms by offering personalizable and customizable learning experiences. Personalized tutors [45], lessons [27], and learning plans [71] can help learners with specific needs. However, aside from building their own systems via low-code technology authoring

[23], teachers are unable to customize current technologies. Our work looks into how teachers want to customize current technology they use or desire in their classrooms, and provide guidelines to make new technologies more customizable.

2.3 Technology for Supporting Science Education

Much research in supporting science education has focused on teaching science concepts. Education technology, and in particular augmented reality (AR) [47] has been able to show abstract science concepts over real observations, allowing for a stronger connection between science explanations and their respective physical results. Prior work typically removes the physical observations from the studied phenomena to have better control over the learning activity [14, 36, 58, 66], or focuses on overlaying informative information on static physical objects [68, 74]. Further research stresses the importance of providing teachers the ability to adapt and customize these tools for their needs. However, students fail to transfer what they learn in class to laboratory observations [44] and broader scientific impacts. Our work investigates how students are trying to help students improve in knowledge transfer and scientific literacy, and articulate ways technology can assist.

Starting in 2013, multiple states began adopting the Next Generation Science Standards (NGSS) [4] standards as the new curricula for science education. In addition to adding learning concepts such as explicitly teaching the effect of science on society and the world, NGSS hones in on core practice of science, such as planning and carrying out investigations, analyzing/interpreting data, and constructing models and explanations from evidence. Many of these practices are taught through science labs. While some work has also started to support these skills [2, 9, 16, 43], the primary use of education technology in science has been on teaching content and engagement [11]. Currently, many students still struggle to obtain and apply NGSS skills [10, 42]. Our work focuses on teachers' needs from technology to help teach these skills.

3 Survey Development

This section details the development of an online survey to understand teachers' perspectives on laboratories in their classrooms. We conducted in-person semi-structured interviews with six teachers and a biology lab observation, using the findings to design a large scale survey.

3.1 Participants

We aimed to select high schools of a range of different socioeconomic backgrounds across [location anonymized] to capture a representative distribution of schools in the area. Therefore, we classified schools using reported economic disadvantage (e.g., low–high) according to the percentage of the student body receiving Free/Reduced price lunch (FRPL) [6]. For our final list of schools, two were classified as low poverty (with 0–25% of the student body receiving FRPL), one medium-low (25–50% FRPL), two medium-high (50–75% FRPL), and one high (75–100% FRPL). We recruited teachers via IRB approved recruitment emails either to science teachers or school leaders at selected schools.

We observed students performing a microscope lab in the high economically disadvantaged school. The teachers visited had an average of 12.2 ± 9 years of experience teaching various levels of biology, chemistry, environmental science, and biomedicine. Please see (tab: 1) for the school demographics of participants.

3.2 Procedure

For each school visit, we conducted semi-structured interviews in the participants' laboratory classrooms to understand their process for creating new labs, criteria for successful/unsuccessful labs, desired outcome for labs, as well as their perspectives on areas of difficulty for students, resource constraints, and virtual labs. By engaging with teachers in their classrooms, we gained first-hand knowledge of the current laboratory experience. For example, participants showed us the specific equipment and materials underlying learning outcomes and challenges. See Appendix A for the semi-structured interview questions.

3.3 Survey Design

Through these visits, we recorded teachers desired for labs, ways teachers needed to adapt labs to fit their classroom environments, challenges students have conducting labs (unrelated to subject content), as well as teacher's views on virtual labs. The first author then conducted a content analysis for lab outcomes, lab design challenges, student challenges, and virtual labs likes/dislikes. The most frequent responses became answer choices for our subsequent survey. For example, many teachers stressed the importance of collaboration and engagement when doing labs. These were coded under lab outcomes, and then became answer choices for which teachers picked for their top lab outcomes in the survey (Appendix A). Additionally, some teachers adapt labs often, while others implemented the exact same labs as the previous year with little change. We therefore asked survey participants to both detail how often they adapt labs, as well as in what ways they were adapting their labs.

4 Methods

We conducted a mixed-methods approach using two complementary methods: online surveys and in-person, semi-structured interviews. The interviews gave deeper analysis into the quantitative data, as well as insights on how teachers use and envision technology for their students in the laboratory.

4.1 Survey

4.1.1 Participants. We recruited a total of 58 US high school teachers in 16 states. 16% of teachers came from low poverty schools , 16% from medium-low poverty schools, 25% from medium-high poverty schools, and 44% from high poverty schools. Teachers had an average of 8 (s.d. 7) years of experience across 12 science subjects.

4.1.2 Procedure. We deployed our developed survey on both Prolific as well as via ads on Reddit and Google with a screener for science teachers. Please see Appendix B materials for the detailed survey questions. After collecting demographic data, consenting participants, and screening participants to ensure they currently taught a high school science class in the US, they were able to complete the 5 minute survey. Participants who completed the survey or referred another teacher who also completed the survey were entered into a raffle for a $100 Amazon gift card.

4.2 Interview

4.2.1 Participants. We spoke with 3 teachers from the site visits and invited 15 more teachers from schools across [anonymized] to take part in online interviews (we also viewed a recording of a biology lab at one school and observed one chemistry lab). 20% came from low poverty schools , 50% from medium-low poverty schools, 25% from medium-high poverty schools, and 5% from high poverty schools. The teachers interviewed had 12 (s.d. 10) years of experience, across 10 different science subjects. Please see (tab: 1) for the school demographics of participants.

4.2.2 Procedure. For each participant, we conducted 1+ hour online interviews to better understand how technology plays a role in their classroom's labs. Teachers first chose one of their top lab outcomes, such as laboratory skills. If teachers could not think of a lab outcome, we suggested samples from our survey (Appendix: B) for them to pick from. They then listed a lab from their classroom that achieves that outcome, and details the labs objectives. Teachers were then shown an example of how technology can connect to real data and showing abstract concepts during labs. Afterwards, we walked through each objective and discussed how they currently use technology (if at all) to help students achieve that objective, as well as how they would envision technology (if at all) to help students to achieve that objective. Lastly, we discussed any prior knowledge struggles students had that made the lab difficult. See (fig: 1) for an overview of our interview structure. Although the survey gathered data on material constraints and logistical challenges, due to limitations of teachers time, we were unable to discuss these during the interview, and details for diving into these challenges are discussed in future work.

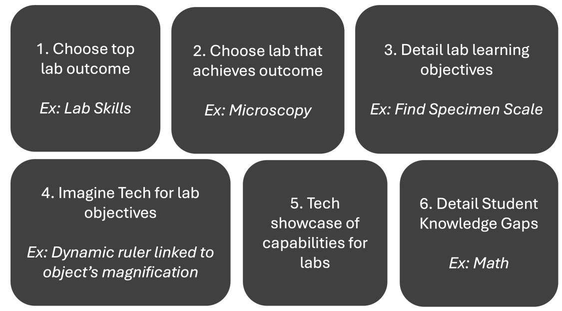

Fig. 1. Procedure for Teacher Interviews: We interviewed 18 teachers to determine their views on and desires for technology for science labs. For a given lab, teachers talked about how they currently use technology, and if they had their own technologist, how they would redesign technology to better serve their classroom.

4.3 Data Analysis

Survey responses were analyzed to provide the quantitative data on teachers laboratory educational outcomes, student struggles, and lab adaptations. We analyzed the qualitative data through a two-stage coding process. First, we conducted deductive coding using a codebook derived from survey responses about laboratory outcomes and design challenges. This provided an analytic lens for mapping interview excerpts onto known categories of teacher concerns. Next, we applied inductive coding to capture emergent themes around student struggles and teachers' desires for technology support. To synthesize these findings, we used an affinity diagramming approach: transcripts and field notes were segmented into excerpts, grouped into clusters of related ideas, and iteratively reorganized. The resulting clusters were refined into the thematic categories that structure our results, combining insights from site visits and interviews to provide a holistic account of teachers' perspectives on science labs. In total, we analyzed 24 transcripts from 21 total participants (3 participants took part in the site visit and interview), which are numbered randomly from P1 to P21. The differentiation between the site visit or interview is indicated via an s or i in parentheses (i.e., P1(s) indicates Participant 1's words during a site visit whereas P2(i) indicates Participant 2's words during an interview). Within our results, unless explicitly stated all qualitative results (percentages) come from are site visits and interviews, whereas quantitative results came from the survey.

5 Findings

Overall, we present our findings in the following themes: teachers emphasized (1) a focus on NGSS practices such as lab skills, and designing procedures, (2) a desire to support students who are struggling with data and English literacy,

[1]These participants teach multiple subjects and are listed twice

Table 1. Participant Demographics. FRPL indicates the percentage of students at the school who receive Free or Reduced-Priced Lunch. Teachers were recruited across various different subjects and schools to ensure our insights reflect a representative sample of teacher insights.

Subject	FRPL	Participants
Biology	Low (0–25%)	P1, P15
	Med-Low (25–50%)	P4, P5, P17[a]
	Med-High (50–75%)	P2, P18
	High (75–100%)	P20*
Chemistry	Low (0–25%)	P13[a]
	Med-Low (25–50%)	P7, P10, P17[a]
	Med-High (50–75%)	P8, P11, P19[a], P21
	High (75–100%)	P20[a]
Physics	Low (0–25%)	P3, P13[a]
	Med-Low (25–50%)	P6, P12, P14
Enviromental Science	Med-Low (25–50%)	P12
	Med-High (50–75%)	P16, P19[a]

[a] These participants teach multiple subjects and are listed twice

and (3) a preference to help students connect science to real world contexts, and (4) ways in which they adapt science labs and use them to support collaboration and engagement.

5.1 Teacher's goals for labs are to support Next Generation Science Standards

"Bottom line, very few of my students are actually going to go into the biology field. So to me, it's more about...being able to synthesize data into something meaningful...just more of the practices of science." P1(s)

While teachers wanted students to learn about various scientific phenomena, there was an overall focus on teaching the ways of doing science. Our survey respondents listed NGSS skills, such as lab skills (15%), understanding the ambiguity and data (11%), or creating procedures (6%) as one of their top outcomes for laboratories (fig: 2). Overall, teachers report a lack of technology in supporting students learning in these skills, and desire for a stronger link between NGSS activities and technological features.

5.1.1 Embracing Messy Data: Teaching Lab Skills and Scientific Practices. Physical experiments allow students to learn lab skills, such as how to collect and grapple with the ambiguity of data. Many teachers emphasized students' lack of lab skills when entering high school. In the survey, 12% cited a lack of lab skills as a top learning challenge. Students struggled not just in how to operate laboratory equipment, but also when and how to appropriately use equipment. Biology teachers in particular talked about microscopes or pipetting, and other scientific equipment. P2(i) noted: *"If I don't instruct them properly, they will all measure using a beaker. You know, they won't go and use a graduated cylinder."*

Table 2. Summary of Finding and Design Guidelines. Overall, technology should support authentic, hands-on laboratory practices, while also scaffolding prior knowledge to be accessible for students with differing math and language skills. Allowing teachers to customize technology is also important, as they can best adapt it to suit student, classroom, and societal context.

Category	Finding	Design Guideline
Supporting Next Generation Science Skills	Students struggle with lab skills and the ambiguity of empirical data.	Technology can augment lab skills by reflecting real tools and real errors.
	Students struggle to design experimental methods.	Technology can support experimental design through guided exploration.
Scaffolding Prior Knowledge	Students have limited prior knowledge in applying math and graphical analysis to lab data.	Dynamic visualizations can make math and data analysis accessible during labs.
	Students' English and reading abilities can hinder their ability to engage in laboratories.	Technology should support differentiated language instruction.
Supporting Real Experiences and Impacts	Personal relevance helps students find meaning in labs.	Technology should adapt to personal and classroom contexts to support every student.
	Teachers desire students to be able to connect science to broader societal impacts.	Technology can help show the broader impacts of science.
Collaboration	Current laboratory technology reduces opportunities for student collaboration.	Technology should support authentic discussions and scientific collaborations.
Adaptation	Teachers struggle to adapt technology to fit their classrooms.	Technology needs customizable representations to support teacher agency in classroom integration.
Engagement	Students value engaging in physical, hands-on laboratories.	Technology should augment, not replace hands-on experiences.

Lab skills involve not only carrying out procedures but also understanding why certain equipment is used and how to obtain precise, uncontaminated data. In wet labs, "rules of the lab" guide accuracy and safety (i.e., measuring volumes with a graduated cylinder rather than a beaker, using separate cylinders for different materials to avoid contamination).

Many teachers mentioned the need to instill that laboratory procedures rarely produce the exact same results as idealized simulations, and that experiments often do not work as planned. 9% of teachers found grappling with experimental ambiguity as a top learning challenge (fig: 3). P3(s) noted how students dislike when experiments don't work perfectly, making science feel less trustworthy. In turn the teacher desired to showcase *"that experimental error and like, faulty equipment… is a normal part of lab work… we have to be okay and comfortable with weird data, fuzzy data."* By having students practice these skills, they can gain an understanding of uncertainty and experimental ambiguity. While this touches on understanding empirical data, its relation to equipment and their limitations also tie these concepts into lab skills.

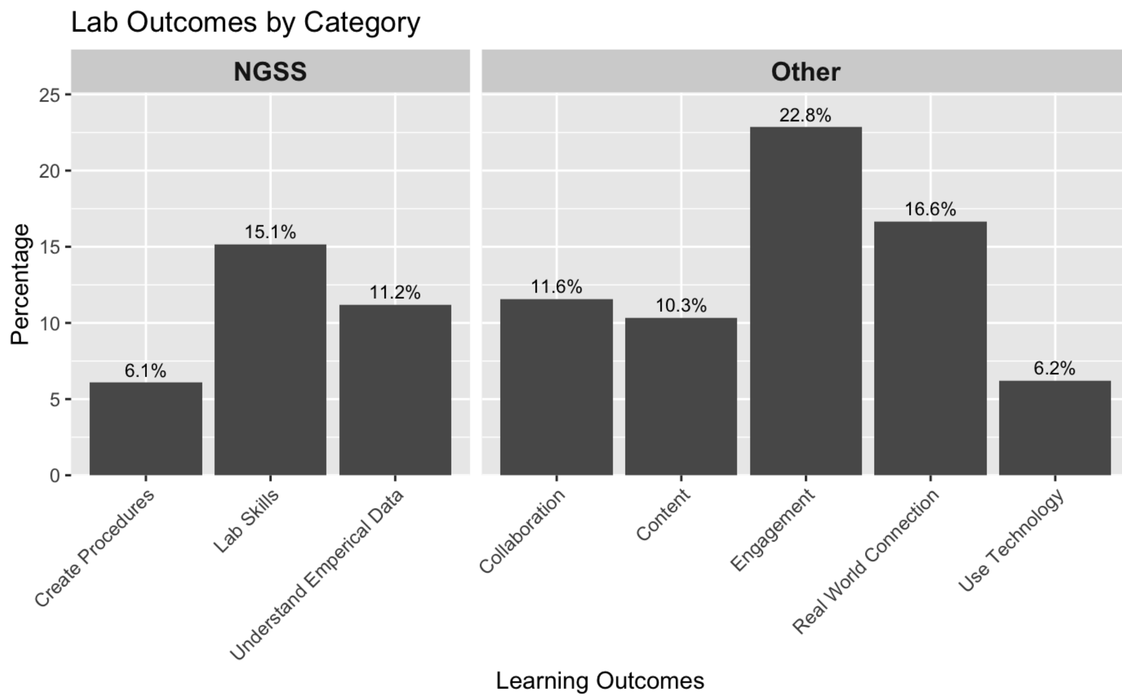

Fig. 2. Teachers Top Learning Outcomes. Most teachers saw a main outcome of labs as engaging, and helpful for drawing real world connections to science content. Teachers valued labs for their abilities to teach lab skills, and how to grapple with empirical data. Surprisingly, teachers also saw labs as valuable for fostering collaboration.

When doing experiments, teachers hope students can grow in their own knowledge in science and therefore evaluate information for themselves. As P4(i) noted: *"[by] understanding what the limitations of the [equipment] available are and how [they] fits into what scientists actually do with them...you could then be better informed...as opposed to just hearing from somebody that this is good or that is bad, or this is significant or insignificant."*

Teachers spoke about students expecting their labs to be exactly like simulations, or get the exact number as their classmate when collecting real data. In a real experiment, P1(s) noted when student's answers differ they would ask *"'Well, then who's wrong? You or me?' Like, they think that there's only one answer. And so getting them to kind of be comfortable [with ambiguity]. And before you second guess yourself, like, go back and look at what you did...can you both be right? Or can you both be wrong?"* P1(s) expressed wanting students to internalize the inherent variability in science, and instead of looking at exact numbers, they can evaluate the methods and uncertainties to determine scientific results.

Design Guideline

Teachers want technologies that improve learning lab skills while reflecting real experiments. 39% of teachers interviewed expressed desires for technology to help students learn lab skills. Additionally in the survey, teachers disliked current educational lab technologies (i.e., virtual labs) for their lack of realism (6%) and inability for students to grapple with empirical data (9%) (fig: 5). Nevertheless, they do appreciate the benefits of virtual technologies for their reduced cost (24%) and increased safety (24%).

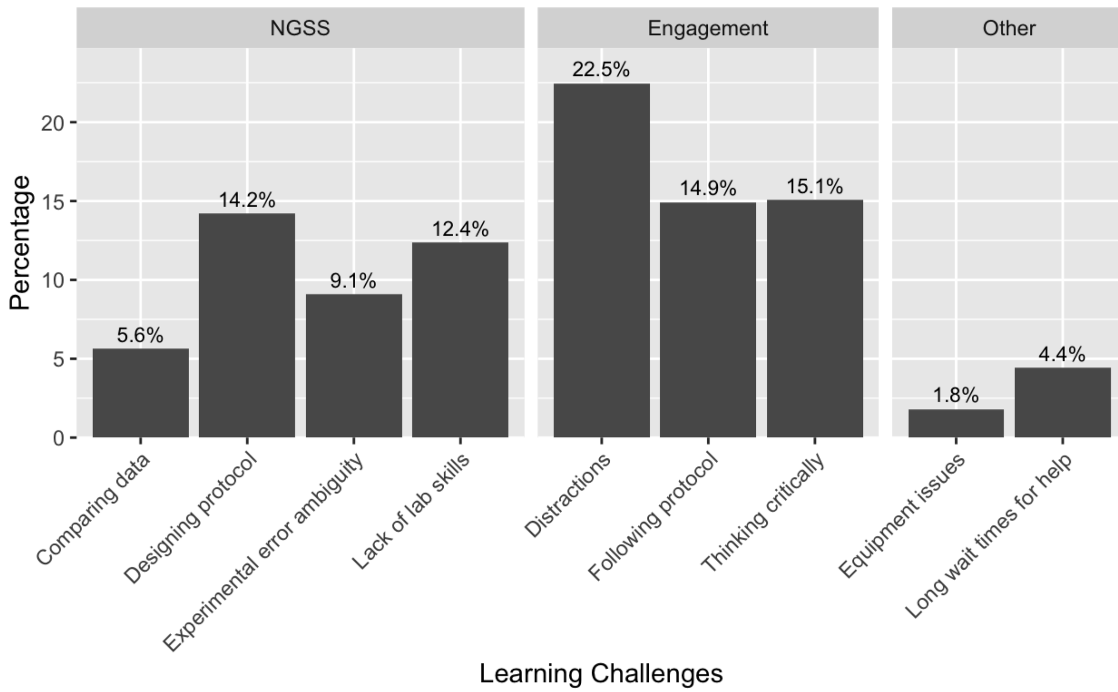

Fig. 3. Students Top Learning Challenges: Students often face many distractions from achieving teachers' desired lab outcomes. Most notably, they are often distracted, and have trouble following a protocol or thinking critically about why they are performing particular activities. They also struggle with NGSS practices, such as designing a protocol, lab skills, and data analysis with experimental ambiguity.

Technology can augment lab skills by reflecting real tools and real errors. Augmented reality (AR) can improve the experience of learning lab skills while making virtual labs feel more realistic. AR can substitute materials by allowing students to practice skills such as titrating or using a microscope by augmenting low-cost alternatives. Villanueva et. al used common items like spoons and QR codes to provide haptic feedback for virtual scientific equipment such as graduated cylinders [69]. In a similar vein, 3D-printed microscopes or burrets can be combined with AR to help students practice using the equipment if they do not have access to expensive or dangerous materials. However, when collecting simulated data, being able to also simulate the ambiguity, potential for contamination, and systematic error that comes with empirical data is also necessary and not yet realized within current tools.

5.1.2 Designing Procedures: Supporting Student-Designed Investigations. With the push towards inquiry-based labs, project-based learning, and NGSS, there is a desire for students to start creating their own procedures (i.e. hypotheses, protocols, and isolating variables) as well. 6% of teachers saw creating procedures as a top lab outcome (fig: 2). However, many hurdles, such as a lack of content knowledge, interest, and materials for student-led inquiry created limits for many of the teachers surveyed, causing some to actively shy away from it.

For teachers who do incorporate the creation of procedures into their labs, they found students often struggle. P5(i) notes that the combination of new content and learning to design a procedure is very taxing for students: *"when they come to my class, they haven't been asked to actually design an experiment and [now] have to think about, you know, all*

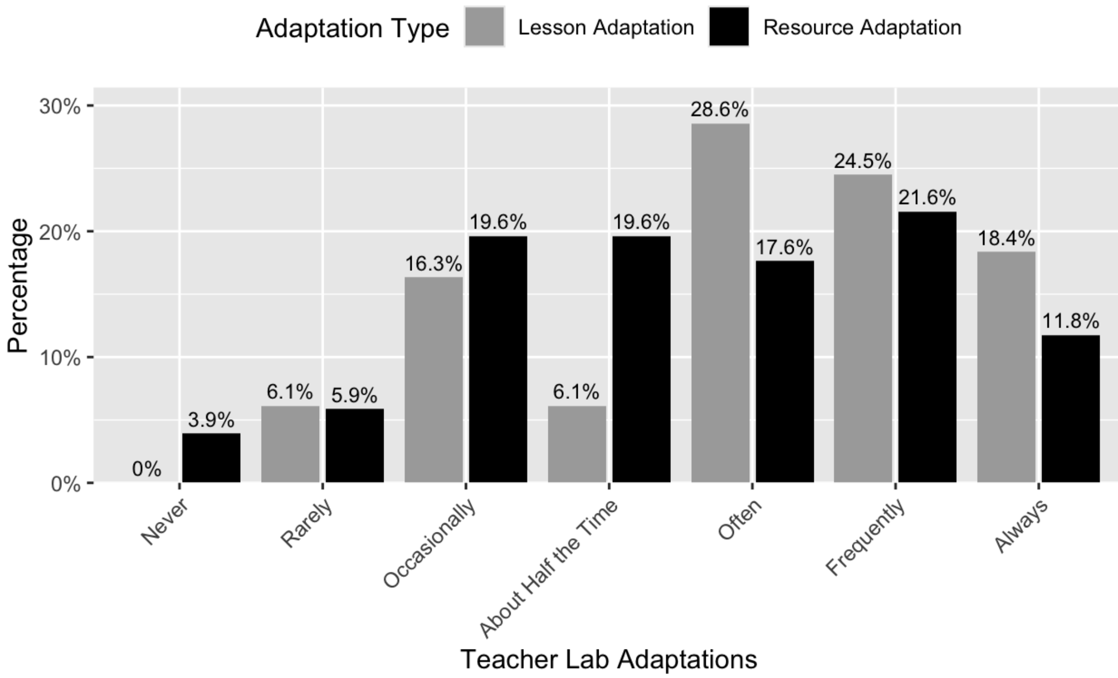

Fig. 4. Frequency Teachers Adapt Labs: Almost all teachers surveyed were adapting labs in some form of fashion, most often to scaffold for student needs or changing curriculum demands. Teachers also adapted their labs do to constraints in resources, though the frequency mostly even across teachers surveyed.

the different variables that they have to keep in control...it's a lot more taxing on them, plus they're also having to apply concepts that they're learning in the class."

It can be difficult for students to grasp learning new scientific phenomena and how to create procedures simultaneously. P5(i) experienced a similar challenge when students in his class had to apply equations during experiments: *"There's no questions to answer. I just give them: 'Find me [the experimental constant]...You know the equations.' That's hard for them...it's hard for them to do it without guidance."*

Design Guideline

Teachers desire technology to help students craft experimental procedures. 67% of teachers interviewed talked about allowing students to experiment with different variables and seeing its results before implementing the experiment. 14% of survey responses also saw these what-if scenarios as one of the top values of laboratory teaching technologies (fig: 5).

Technology can support experimental design through guided exploration. Technology can scaffold students in designing procedures by guiding them through steps such as variable isolation and contamination control, while prompting them to reflect on and improve their methods. Interactive text-based tools can provide practice in identifying confounding variables and strategies for controlling them.

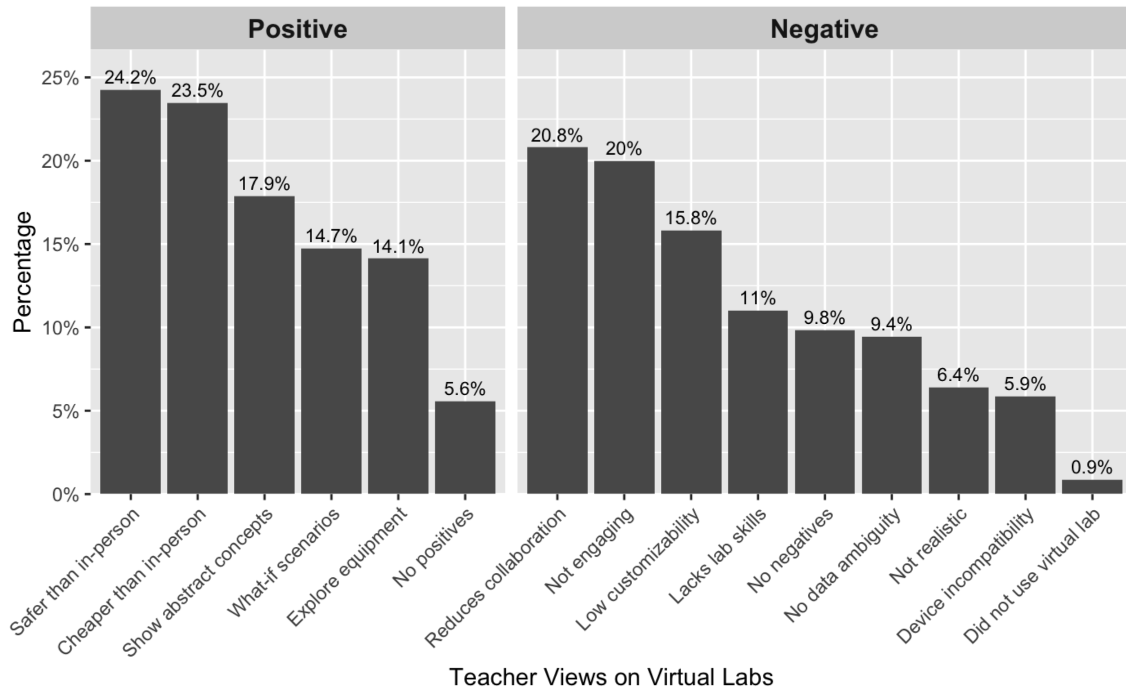

Fig. 5. Teachers' Views of Virtual Labs: Overall, teachers like virtual labs due to their safety and cost, as well as their ability to show abstract concepts and explore 'what-if' scenarios. However, they dislike how they reduce collaboration, are not engaging, don't teach lab skills, and lack the customizability teachers need.

5.2 Students Math and English literary skills limit their abilities to engage in laboratories successfully

Many teachers reported that students lack prior knowledge that hindered their ability to effectively learn about various science phenomena. Teachers cannot guarantee that students are proficient in middle school skills, and therefore must support and scaffold learning to teach both grade level science and prior pre-requisites. Particularly for science labs, teachers reported students having a lack of prior knowledge skills in data literacy, mathematics, and english literacy.

5.2.1 From Numbers to Meaning: Building Data Literacy and Mathematical Practices. Teachers also noticed students' difficulty in collecting, analyzing, and interpreting real data. They mentioned the importance of instilling scientific practices, such as the importance of conducting multiple trials, as well as teaching basic graphical and statitical analysis (e.g., mean, median, mode, and percent yield).

During the interviews, many teachers indicated that students' math skills are not at the level expected for high school science (50%). Some teachers indicated students struggled with simple algebraic manipulations, while others could not apply the math skills they had learned in the past.

> "… they understand the concept. But trying to put the concept to the model, to the mathematical model, can be a struggle… we actually want them to understand that linkage between the real world and the model" - P6(i)

As a result, teachers are constantly scaffolding lab activities to reduce the amount of math necessary, as well as opting for sensemaking, or focusing on trends and patterns to showcase concepts without math.

Data literacy is also important for science labs. 39% of teachers during the interviews discussed graphics and data analysis as a prior knowledge struggle, and 6% of surveyed teachers cite comparing data as a top learning challenge. Students must learn how to articulate cause and effect relationships, make predictions based on data, and draw conclusions. However, this first requires students to be able to determine what data is relevant to answer a question, as well as how that data can best be presented in order to answer the question:

> "You can make all kinds of observations, qualitative or quantitative. But if you're trying to answer a question...[you have to be able to determine] what are the pieces that are relevant. . . so that you can support a claim with relevant data, not just whatever data you happen to be able to understand." - P4(i)

Design Guideline

Dynamic visualizations can make math and data analysis accessible during labs. Having scaffolds for laboratory graphical analysis was requested by 28% of interviewed teachers. 50% desired technology to allow for more dynamic graphical visualizations.

Technology can support experimental design through guided exploration. Technology can link visual observations to mathematical models by generating interactive graphs. Tools like Venier [5] and phyphox [7] already provide real-time feedback, but extending them to show invisible processes such as energy transfer could help students recognize patterns and build conceptual models. For example, graphs could update dynamically as students move a pendulum or combine atoms, and students could compare different graph types to discuss which best communicates their results.

To address math gaps, technology can integrate short interactive activities that reinforce algebraic skills, such as balancing equations or solving formulas, directly within lab work. Virtual systems have shown promise [21, 36], but extending them to physical experiments—for instance, overlaying formulas for friction in physics or molecular motion under changing conditions—could strengthen the connection between observations and equations. Allowing students to toggle between visual and mathematical models may further support their ability to interpret scientific phenomena.

5.2.2 Teachers Struggle to support students with varied English/Reading abilities. For students to fully engage in high school science labs, reading comprehension and English proficiency are essential. Lab activities typically rely on written instructions, procedural steps, safety information, and follow-up analysis tasks. When students struggle with reading or with English as an additional language, they face significant barriers to participation—misreading a procedure can lead not only to conceptual misunderstandings but also to safety risks. Teachers reported that a wide range of students fall into this category: some read below grade level, some are still acquiring English proficiency, and others are well ahead of their peers. In our interview 28% of teachers indicated students' English or language difficulties impacted engagement during their labs:

> "The hardest part is, kids are not reading as they used to. . . when you throw them a question to answer, they only get three words and use their own interpretation. They're not reading what the question is asking." - P7(i)

Similarly, P8(i) described students who could explain scientific ideas orally but could not express them in written English:

> "They can give me a decent explanation in their own language, but when I ask them to write it in English, it's like a whole different concept, because they can't write it."

These accounts underscore that language and literacy skills are not just parallel goals but also enablers of science learning in labs.

Design Guideline

To address these challenges, educational technologies should explicitly support differentiated instruction for reading and language. While research prototypes often overlook this dimension, integrating such supports is a relatively straightforward adaptation that could broaden participation and equity. For instance, large language models and translation tools can dynamically simply and adapt text to different reading levels [63], and translate key instructions into multiple languages [3]. Embedding features such as text-to-speech, real-time vocabulary support, or side-by-side simplified instructions could ensure that students with varied literacy skills can still safely and productively engage in labs.

Technology should support differentiated language instruction. Such tools not only help students keep pace with their peers in science but also contribute to developing literacy skills through science practice itself. Rather than treating reading ability as a prerequisite barrier, technology could transform labs into dual learning opportunities: spaces for scientific inquiry and for growth in reading and language skills.

5.3 Teachers desire to connect what students learn in the classroom to real world contexts

16% of teachers listed connecting to the real world as a top laboratory outcome (fig: 2). Ultimately, school is to help prepare students for their next step in life, and that only works if they are able to transfer what they're learning in the classroom to their own life context. They are therefore always trying to connect laboratories to relevant student experiences and broader impacts. Through this connection, they are able to help students make a personal connection with the material, also increasing cognitive engagement and motivation. Beyond content transfer in the classroom, teachers also indicated a desire to help students understand the broader impacts of scientific content.

5.3.1 From Nail Polish to Nitrogen Cycles: Customizing Learning For Everyday Contexts. Teachers also expressed desires for technology to improve personal relevance for students. For some students, this may mean simply introducing them to concepts they will learn in class. For example, P9(s), who teaches Environmental Science stated many students are unfamiliar with plant life. Other teachers wanted to relate phenomena to common experiences students have seen before, such as using nail polish to explain molecular bonding or puddles to demonstrate surface tension. However, current technology often fails to help students make these connections:

> [When speaking about simulations] "Here's a hydrogen stick, [and] a bond. Here's another hydrogen stick, [they] bond to the oxygen. You made H2O." [Now discussing students' confusion] "'Okay, but what's H2O?'...[Simulations are] visual, yes, but it's a lack of real world connection [to] visuals." - P8(i)

When relating to students' own personal experiences, they become more primed to learn about the phenomena, as they recognize that the things important to them are also important in science. For example, P4(i) used students' experience with fishing to draw connections between water quality and fish capacity:

> "I really wanted them to just be able to relate to the experience...[for example, we would discuss biological] phenomena and the fish and all that, and they were talking about, 'oh, I remember I used

> to go, you know, fishing with my uncle…and then there wasn't as much fish anymore. Now I'm understanding why'" - P4(i)

Teachers also take students' personally relevant stories to build metaphors and analogies to help teach concepts, but often struggle to fully convey the idea without a visual stimuli. For example, P10(i) describes trying to explain the effect of salt on solubility:

> "water and alcohol are happy together, but as soon as salt comes in, salt, you know, the salt and the water like each other more…And so they, you know, [kick] the alcohol out, that is hard, I think, for students to grasp at a molecular level…I don't even know if I have a good visual in my head about what that actually looks like as a process." P10(i)

In another classroom, students were able to physically perform the lab and see alcohol separating from the salty water, but could not descirbe the mechanism by which it occurs. For many microsopic processes *"[its difficult to] describe a microscopic phenomenon with a macroscopic analogy." - P8(i)*

Design Guideline

Teachers are always adapting to provide personal support for struggling students with changing classroom contexts (e.g., students forgetting their devices, screen-time restrictions). To assist teachers in providing for these dynamic needs **technology should adapt to personal and classroom contexts to support every student.** For instance, programs could auto-generate paper worksheets for students without laptop access, while interactive models or language models could provide alternative explanations or answer individual questions about lab content [17]. By flexibly adjusting to these logistical and learning needs, technology can ensure that all students are able to participate meaningfully in laboratory activities.

Personalization can also come from connecting science concepts to familiar objects and experiences. Augmented overlays might display molecular formulas and structures on everyday items such as graphene, or visualize forces and processes when observing physical phenomena such as surface tension or friction. By situating science in daily and cultural contexts, such as gardening, fishing, or hair styling, technology can help students see science as directly relevant to their lives and understand its broader importance.

5.3.2 From Classroom to Society: Linking Science Labs to Real-World Issues. In terms of relating to broader implications, teachers reported that they like to tie their labs into current events, such as vaccines during COVID, diabetes, ocean acidification, or food additives. They feel this can help not only to increase learning, but also to help students become productive members of society. There was also an interest in helping students understand how everything is connected–energy, carbon cycles, ecosystems, etc. P4(i) noted:

> "we're looking at photosynthesis and respiration. What does that have to do with ecosystems…Because now you understand where the energy comes from...light energy [gets] converted to chemical energy [and then to] kinetic, and then eventually [to] heat...now you can see why the increasing CO2...changes in the ecosystem." - P4(i)

Building connections means that students can relate different topics, such as energy transfer and photosynthesis, and synthesize them to build connections to different phenomena, such as climate change and ecosystem disruption. This connection to photosynthesis, energy, and cycles helps students understand the bigger picture of science, and how it is helpful not just for a class, but also for understanding the broader world. Teachers therefore try to incorporate these aspects into their labs. Teachers mentioned connecting labs to why vaccines can be useful, school nutrition, and climate change. As P11(i) noted:

> "Right now, we're dealing with oceans...and it deals with how the CO2 from pollution falls in the ocean and it acidifies the ocean. And how that affects that change in acidity [and] can affect classification of the shells, you know, oysters and other stuff. And in the experiment that they're going to do, they're going to put shells on solutions of different pH and they get to see...how the changes really affect the calcification." - P11(i)

P11(i) has students test shells in different levels of pH to observe how acidity changes the calcification, which in tern changes the shells classification. Students must tie in knowledge of chemistry and acidity to make connections in biological classification.

Additionally, teachers will also tie the changes students see in labs to broader implications in daily life, such as ecosystems and medicine. In particular, P7(i) uses candles and stoichiometry to demonstrate climate change. She states *"is a very powerful...the product of, you know, of burning candle...I will [later] refer back to [it]...so they not only just learn the basic chemistry, but the usage."* Students calculated the amount of CO2 produced by a candle, and extrapolated it to burning fossil fuels. By tying chemistry concepts like stoichiometry into the broader impacts of climate, students are able to not only see how science information is discovered, but also cement the importance of science for the discovery and purpose behind various policies.

Design Guideline

Teachers are always trying to connect different learning concepts to relate to students' lives, whether that be showing how water quality relates to fishing or candles relate to climate change. This relevence of science in everyday life can help students understand the importance of science, and why we conduct experiments.

Technology can help by showing science in various aspects of a student's life. For example, probing students why some people's hair is curlier than others can draw from biology, chemistry, environmental systems, and physics. While it may not touch on the exact lesson students are focused on, showing how science in general impacts every aspect of life. Additionally, technology can probe students to consider the broader impacts of their results, and help translate their learning beyond the classroom. AI can help to generate various scenarios for students to try applying their knowledge to and using the data to answer questions.

5.4 Adaptation, Collaboration, and Engagement

Outside of focusing on NGSS, supporting student prior knowledge, and connecting science in the classroom to real world context, teachers emphasized the importance of collaboration and engagement during labs. Additionally, to best accommodate NGSS, students' prior knowledge, and changing world context, teachers are always adapting their labs, and need technology to be flexible enough to adapt for those needs. This section details teachers views of collaboration, engagement, and adaptation for science labs

5.4.1 Teachers value and want more collaboration in the classroom. 12% of teachers see collaboration as a top outcome of science labs, and 20% dislike that virtual labs reduce this collaboration. They expressed a desire for students not only to contribute individually, but also to engage meaningfully with peers—articulating observations, debating interpretations, and co-constructing knowledge. As P12(s) described:

> "I don't want to structure a class around the idea that I give them information, and they have to memorize it, because I'm some super smart authority person. But we can get the tools to test the ideas. And that the ideas are right, because they work, not because someone tells you."

Participants described science as inherently social, noting that authentic engagement with scientific practices involves collective sense-making and shared inquiry. To this end, teachers intentionally structured labs to foster student collaboration, often forming small groups to encourage joint exploration and discussion. Teachers expressed a desire for students not only to contribute individually, but also to engage meaningfully with peers—articulating observations, debating interpretations, and co-constructing knowledge. P4(i) elaborated on this vision by describing a classroom practice grounded in epistemic negotiation and social learning.

> "[Collaboration requires them to] renegotiate what it means to learn… [discuss] an issue that is not so readily available. They have to discuss it and come up with opinions… And then going to do some sense-making activities so that they can come back to the question and say, 'How did this inform us?'" - P4(i)

This emphasis on collaborative inquiry aligns with constructivist theories of learning [32] and reflects a growing interest in designing technologies and environments that support group cognition, epistemic agency, and dialogic engagement in STEM education.

Design Guideline

Research in computer supported collaborative learning (e.g., [41, 59, 64, 65]) works to help facilitate more collaboration in learning with technology. However, when it comes to science labs, technology is often created to be used by a single student. **Technology should support authentic discussions and scientific collaborations.** Incorporating spaces for students to share and discuss their different results, can help to encourage collaboration, as well as encouraging healthy debate on what phenomena, confounds or errors could have taken place.

5.4.2 Customizing for Context: Teachers as Adaptors of Inconsistent Technologies . Learning new concepts is challenging, and teachers often rely on multiple analogies, demonstrations, and resources to help students. One simulation or video is rarely sufficient; in fact, most teachers in our survey reported adapting labs more than half the time (fig: 4). However, 15% of teachers cited lack of customizability as a top dislike of virtual labs (fig: 5). For example, P2(i) described how a simulation of evaporation used heat from below rather than sunlight, making it harder for students to connect the model to real-world phenomena:

> "one of the things that I really talk about is the sunlight hitting the water, and then that leading to… evaporation. And for whatever reason… [the simulation] has the heat source being on the bottom… breaking all of [the molecules], as opposed to… a single photon of energy coming from the sun, hitting, you know, two molecules and causing the excitation state. [Since the simulation is] not a perfect metaphor that, you know, they don't completely get it"

Teachers also wanted technology that adapts to students' specific learning needs. For instance, while a simulation may depict generic bonding, instructors often wanted to highlight interactions between specific elements, such as carbon and hydrogen. Inconsistent visual styles across simulations further compound confusion: different colors, icons, or abstract symbols make it difficult for students to synthesize ideas when teachers combine multiple tools. P8(i) noted that abstract representations like letters and lines distracted from showing recognizable structures such as diamond or graphite. Sometimes teachers only requested small adjustments(i.e., like schemes) to align with curricular materials, but in other cases, teachers sought richer representation. P13(i) highlights this with a thermodynamics simulation:

> "[If I] alter the temperature or pressure [on the simulation], it doesn't necessarily show, you know, like a, like a phase change graph. . . [it gives] qualitative data. And sometimes you want the other and it's not there."

Design Guideline

When teachers speak about having adaptable technology, they want the agency to customize learning scenarios and simulations for their teaching style. This includes the ability to adjust visuals to mirror the textbook descriptions and representations, as consistent visuals help students better focus on the learning concept. **Technology needs customizable representations to support teacher agency in classroom integration.** This could be achieved through extensive interviews or content analysis to understand the design space of what representations teachers prefer, matching representations to common curricula, or utilizing natural language to allow teachers to create their own representations.

Additionally, technology can better adapt to current curriculum by integrating with current teaching aids. For example, students currently learn about molecular bonding via ball and stick model. AR can augment on top of these models, allowing students to see the Lewis dot structures, molecular forces, and bond energy. Or, instead of showing generic bonds on a generic atom, students could see how the atom in their particular homework problem bonds, and start generating mental models or schemas across various molecules to better understand molecular forces. In physics, AR can show the force diagrams in real time during labs [34], real time energy transfer, or even how molecules are moving during surface tension, solubility, and reaction labs.

5.4.3 From Compliance to Curiosity: Building Cognitive Engagement in the Lab. *"[students] just get used to following the instructions and not thinking about the instructions. They don't often question why they're asked to do a certain step, they just do it." - P12(s)*

Without proper motivation, students can become disengaged and simply just go through the motions. 23% of survey respondents listed distractions, as a common struggle for students. Additionally, 23% of teachers reported engagement as a top outcome for classroom labs.

Physical labs and demos help to provide this engagement. While videos are helpful *"there's sort of the visceral experience of touching it yourself or seeing it with your own eyes and real life in the classroom." - P14(i)*

He would demonstrate Newton's laws of motion by using a student's skateboard and backpack, throwing the backpack, and having students watch how he would move backwards on the skateboard. While this could of course be done in a simulation, it is a different experience having seen it with your own eyes, and helps students to begin to question why, and therefore prepare them for an inquiry-level mindset.

P1(s) describes this as a personal connection, and said many students preferred kinesthetic engagement over technology engagement as *"it's just more meaningful when you can see it happen right in front of you."* She stated that some students would rather go outside and simulate an ecosystem than do a technology simulation on the same topic. Or they'd prefer to watch a real animal move towards or away from different stimuli instead of seeing in on a computer. For microscopy, apart from the required learning objective on how to use a microscope, students simply enjoy physically interacting with the equipment rather than simulating it online. It's not that *"one is necessarily better than the other, but for high school kids...being able to use their hands to build something gives them immense joy." - P15(i)*

Design Guideline

Most consumer technologies for educational labs are virtual simulations or remote labs students can mindlessly click through. 20% of teachers' top dislike of virtual labs was their lack of engagement. While this may reflect current consumer products, as research has shown educational technology to be engaging [15, 49, 70]. However, research findings do not always transfer in uncontrolled contexts [78]. To help students cognitively engage during labs, **technology should augment, not replace hands-on experiences.**. For example, showing how molecules influence the pH of a solution, or where energy is transferred in a system can help keep students more engaged vs just seeing a pH meter or temperature probe change. While technology has been shown to help students engage by organizing lab procedures [40], providing authentic and engaging embodiment and constructivist activities can also help add engagement without compromising learning.

6 Discussion

Teachers in our study highlighted a need for tools that go beyond content delivery to scaffold NGSS skills, prior knowledge. In this discussion, we argue for shifting the design of lab technologies towards supporting higher skill learning, supporting authentic, physical lab practice, adapting to student knowledge foundations, and preserving teacher agency.

6.1 Technology should support more higher skill learning

Simulation-based laboratories have proven useful for reducing costs, providing safe experiences, and introducing abstract and concepts [18, 62, 67, 72]. Many teachers in our study acknowledged these benefits, particularly for pre-labs, make-up labs, or in contexts where resources are limited. However, simulations often present "perfect" data and bypass the embodied skills of science [39]. While previous work has done well to help with a specific learning content , or probing reflection and inquiry during lab activities [43, 73], teachers expressed a desire for technology to assist with preparing students for the complexities of real laboratory practice.

Digital scaffolds can help by guiding students to isolate variables, explore "what-if" scenarios, and simulate experimental design before moving to physical labs. Such supports would allow students to practice the full research process—designing, iterating, and analyzing—rather than only executing procedures. By centering skills and practices rather than content alone, technology-enhanced labs can better achieve the broader goals of science education. Teachers framed these outcomes not just as preparation for STEM careers, but as essential for citizenship: learning to evaluate evidence, understand limitations, and make informed judgments in debates about health, environment, and policy. In doing so, technology can go beyond demonstrating phenomena [37, 66, 68] to also address sources of error, variable control, and data interpretation. Technologies that highlight these practices can help students see science not only as a body of knowledge but as a fallible, collaborative, and socially relevant process.

6.2 Technology should support, not replace the physical aspect of labs

Teachers in our study emphasized that hands-on interaction fosters curiosity in ways virtual simulations cannot. Manipulating equipment, observing reactions, and feeling forces motivates students to ask questions and pursue inquiry—echoing constructivist perspectives that meaningful learning is grounded in embodied experience [12, 25]. Advances in computer vision, wearables, and extended reality now offer ways to amplify this curiosity [37, 61]. Privious work has shown invisible phenomena over static objects [68, 74]. However, extending these technologies to revealing invisible phenomena over dynamic physical observations can enrich ordinary lab activities while maintaining their authenticity.

At the same time, teachers stressed that technology should support—not undermine—physical collaboration. Students benefit from debating interpretations, negotiating meaning, and engaging in shared inquiry, which deepens understanding through articulation and argumentation [60]. Past work has began to foster this collaboration by creating shared interaction spaces [43, 49], and can be extended within science labs by facilitating group dashboards of real-time data, or scaffolding discussion around divergent results. Rather than standardizing experiments to guarantee uniform outcomes, technologies should surface variability and error as opportunities for collaborative reasoning.

6.3 Technology should adapt to student knowledge foundations

Students frequently struggled to connect mathematical models with real-world observations. Even those proficient in math classes found it difficult to apply procedures in laboratory contexts. This gap highlights the need for technologies that dynamically link physical experimentation with mathematical representation. Prior tools have advanced data literacy [33, 35], but similar capabilities could be built into common student graphing tools (e.g., [2]). By embedding this support directly into lab activities, technology can help integrate mathematical literacy into authentic science practice rather than treating it as separate coursework.

Teachers also highlighted the challenge of supporting students with varied English literacy, from struggling readers to multilingual learners. These gaps limit students' ability to follow instructions, interpret prompts, and explain their reasoning. While translation and reading-level adaptation tools exist [8, 63], they are rarely integrated into lab-specific platforms. Embedding adaptive scaffolds can make labs more accessible by providing real-time, differentiated instruction.

6.4 Technology should center teacher agency in customization

Personalized learning platforms can tailor content to individual learners [26, 27], but no algorithm can capture the full nuance of classroom practice. Our participants reported constantly adapting labs for curriculum shifts, current events, and to fit their student interests and cultural backgrounds. They also reported piecing together disparate tools, videos, and simulations, often correcting confusing or inconsistent representations (e.g., a simulation showing heat from below instead of sunlight). Such adaptations rely on teachers' pedagogical expertise and classroom knowledge—elements that rigid systems cannot anticipate.

Current tools often function like static PDFs: useful but difficult to modify. Instead, they should operate more like PowerPoint Slides—providing flexible, ready-made content that teachers can rearrange, edit, and adapt. A customizable simulation that lets teachers adjust visuals or link concepts to familiar analogies (e.g., nail polish for solubility or fishing for ecosystems) would make integration seamless. This flexibility reduces confusion, strengthens connections to curricula and lived experience, and preserves teacher expertise as the driver of learning.

7 Limitations/Future Work

The geographic and demographic diversity of our sample, while more representative than many educational technology studies, still reflects limitations that future work should address. Our focus on [anonymized schools, while spanning diverse socioeconomic contexts, may not capture regional variations in curricular emphasis, testing pressures, or administrative support for technology integration. International perspectives would be particularly valuable for understanding how different educational systems and cultural contexts shape teachers' technology needs and adoption patterns.

Additionally, while teacher perspectives are essential for understanding adoption barriers and design requirements, this represents only one part of the complex ecosystem of educational technology implementation. Future work should investigate how the insights we gained from teachers align with or diverge from student experiences, administrative priorities, and quantitative learning impact. Longitudinal studies tracking the implementation of technologies designed according to our guidelines would provide crucial evidence about whether our teacher-centered design principles translate to improved classroom practices and student learning.

In this work, we do not compare across schools by socioeconomic status, given the limited representation of high-poverty schools (only 5% of our sample), the many uncollected contextual factors that shape laboratory environments (e.g., administration, teacher tenure, class size, and course level), and our focus on centering teachers' nuanced perspectives to inform educational technology design rather than reducing them to binary contrasts. Future work could compare how views of educational technology changes against different demographic factors, such as socioeconomic status, district policy, environmental region, or class size. Lastly, due to constraints on teachers time, we were unable to dive further into material cost and set up challenges of labs during interviews. Future work could explore how the logistical realities of high school labs shape the adoption and impact of educational technologies.

8 Conclusion

Our mixed-method approach—site visits, surveys, and interviews—was essential for capturing the diversity of teachers' contexts. Observing classrooms directly revealed physical constraints and spatial dynamics that would have been invisible in remote data collection. High school science in the U.S. is far from uniform: differences in student demographics, resources, district policies, and community contexts all shape how teachers adapt labs. Without attending to this diversity, design recommendations risk privileging well-resourced settings and overlooking the adaptations teachers make to connect labs to students' prior knowledge and lived experiences. Capturing this full range of perspectives is critical to designing technologies that work across varied school environments, not just in principle.

Although the focus of this work is on science laboratories, the themes raised by teachers resonate across educational domains. Many of the challenges described—such as scaffolding for students with varying prior knowledge, designing procedures for open-ended inquiry, or helping learners grapple with ambiguous data—are equally central to project-based learning (PBL) and experiential learning more broadly. For instance, PBL requires students to create, test, and refine solutions in collaborative settings, often encountering the same ambiguity and procedural challenges present in science labs. Likewise, experiential learning contexts in history, engineering, or the arts share the need for flexible scaffolds, adaptable technology, and teacher control over representations and context. By centering teachers and learning from their situated expertise, we can generate design insights that generalize to a broader class of learning environments where inquiry, iteration, and collaboration are paramount.

Furthermore, the teacher agency issues we identified extend beyond science education to any domain where effective instruction requires deep contextual knowledge and pedagogical adaptation. Whether supporting historical inquiry projects, community service learning, or maker-space activities, teachers need technologies that function as flexible tools rather than rigid curricula. This is not unique to science labs. Educational technologies across domains should provide powerful foundations that teachers can adapt rather than locked systems that constrain pedagogical decision-making.

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A Semi-Structured Interview Guide

A.1 Background and Lab Creation Process

(1) How would you describe running [discipline] experiments to a new teacher starting at [school]?
(2) Think back to when you first started teaching: How did you go about creating labs? What is your process now?
(3) Are there any particular sources that you use? Why do you go to these sources?
  - What do you like about them?
  - What do you dislike about them?
(4) Some teachers I have talked to mentioned most labs they find are insufficient for their classes and need to be heavily adapted. What is the process like for you?
  - Is there anything you wish was available?
(5) This process seems hard—does it take up a lot of your time outside of school hours?
  - *Probe:* Ballpark how much if not stated (1 hour, 10 hours, etc.)

A.2 Student Challenges and Learning Difficulties

(1) Are there particular lab procedures that are routinely difficult for students to learn?
  - Can you walk me through the last time you were trying to teach [specific procedure] and they had trouble?
(2) Are there particular concepts you are trying to teach during a lab that are routinely difficult for students to learn?
  - Can you walk me through the last time you were trying to teach [specific concept] and they had trouble?

A.3 Resources and Budget

(1) Some teachers report a lack of resources for their science classes. What is this like for you?
- Do you have an example of when the lack of resources affected a lab?

(2) Approximately, what is the process for purchasing equipment each year?
- Is there a set budget? Approximately how much ($100, $10,000)?

(3) What would your lab experiments be like if you had all the resources you needed?

A.4 Successful and Unsuccessful Lab Implementations

(1) Describe a successful lab you have implemented in the past. What made it successful?
- Why did you do this lab?
- Can you describe the implementation process from idea to execution?
- What was easy about it (if not mentioned)?
- Did you encounter any hiccups or difficulties?
- What made that part difficult?

(2) Are there any labs you have implemented that did not go well? What happened?
- Can you describe the implementation process from idea to execution?
- Where did it go wrong? (if not mentioned)
- Why do you think that happened?

A.5 Learning Outcomes and Goals

(1) What outcomes do you try to achieve when running a lab?
- What do you want students to learn?
  - Content?
  - Demonstration of content?
  - Skills?
- Do you have an example of a lab that achieves all of these outcomes?
  - Tell me more about it.
- Could this be achieved with a virtual lab?
  - Why or why not?

A.6 Virtual Labs

(1) Are you familiar with virtual labs? What do you like/dislike about them?
- Have you used one before? Tell me about it.
  - How do they compare to physical labs?
  - What did you like/what are the benefits?
  - What did you dislike?
  - Did you feel something was missing from the experience?
- How did it go? Can you describe the implementation process from idea to execution.
  - Did you encounter any hiccups or difficulties?

B Online Survey to Teachers

(1) When implementing a new lab for your classroom, how often did you adapt/omit labs this year to suit your lesson purposes? (Ex: adding scaffolding for students, changing aspects to suit particular student needs, adapting to particular content/curriculum demands, etc.)
- Never
- Rarely
- Sometimes
- Often
- Always

(2) When implementing a new lab for your classroom, how often do you adapt/omit labs this year due to physical constraints? (Ex: lack of/inadequate resources, equipment, facilities, etc.)
- Never
- Rarely
- Sometimes
- Often
- Always

(3) **Outcome:** When deciding to implement a lab in your classroom, what are the top learning outcomes that you are trying to achieve? Choose up to 3.
- Foster engagement/excitement for students
- Teach students lab skills (using equipment, recording data, lab safety, etc.)
- Increase collaboration/teamwork
- Understanding ambiguity/variations in empirical data (precision, measurement error etc.)
- Use technology
- Creating experimental procedures
- Connecting content in class to the real world
- Deepen content understanding
- None of the above

(4) **Challenge:** What are the top challenges your students have while conducting labs in your classroom? Choose up to 3.
- Following a lab protocol
- Designing their own protocol
- Ambiguity/inevitability of experimental error
- Thinking critically about each step in the experiment process (understanding the why behind actions)
- Distractions (on cell phone, not paying attention, etc)
- Equipment/materials cause failures with the lab
- Long wait times to get help
- Lack of necessary lab skills
- Comparing data
- None of the above

(5) **Adaption:** When preparing labs for your classroom, what are some of your top challenges? Choose up to 3.

- Long set-up times
- Adapting labs to suit NGSS standards
- Adapting labs for English Language Learners
- Adapting labs for the materials/equipment available
- Adapting labs to increase engagement
- Adapting labs to to focus on a different concept
- None of the above

(6) **Virtual Lab Advantages:** What do you like most about virtual labs? Choose up to 3.

- Nothing. I do not like them
- Create "what if" scenarios / add a variety of variables
- Cheaper/less materials than in person labs
- Safer than in person labs
- Explore the operation of science equipment/how stuff works
- Show abstract concepts
- None of the above
- I do not use virtual labs

(7) **Virtual Lab Disadvantages:** What do you dislike most about virtual labs? Choose up to 3.

- Nothing. They are great
- Does not teach lab skills
- Limited customizability
- Not realistic
- Incompatible with school devices
- Reduces teamwork/collaboration
- Not engaging
- Does not show ambiguity of empirical data (data is too perfect)
- None of the above
- I do not use virtual labs

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