# Historical analysis of innovation and research in physics instructional laboratories: Recurring themes and future directions

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[This paper is part of the Focused Collection on Instructional labs: Improving traditions and new directions.] Physics instructional labs have long been an area of pedagogical innovation and educational research. While current stakeholders in instructional labs are undoubtedly aware of the day's concerns, reform efforts, and empirical research within lab settings, likely less apparent are the deep-rooted connections today's deliberations have with those from multiple educational eras across the last 200 years. To this end, this paper provides a historical analysis of instructional laboratories in undergraduate physics education in the United States, with the goal of elucidating recurring themes in educational reform and research aimed at improving these learning environments. This work aims to synthesize the recursive themes present in the instructional laboratory landscape while summarizing how new research and pedagogical trends can promote further growth in this important learning environment. Through this analysis, commonly recurring themes are identified related to the longitudinal criticism of confirmatory, "cookbook" lab structures, the community's skepticism of instructional labs' abilities to reinforce lecture content, and the possibility of technological and societal obstructions which may implicitly limit innovative ideas, pedagogy, and research. By bringing to light these latent recursive themes, this work hopes to work toward helping break the cycle of criticism and stifled innovation alongside recent positive movements in evidence-based reforms and promising empirical research into student learning and engagement in instructional labs.

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## I. INTRODUCTION

Physics instructional labs in the United States have long been an area of pedagogical innovation and educational research since their inception in the mid-1800s. Contemporary educators and researchers are well aware of the existing criticisms of instructional lab environments, such as their inclinations toward prescriptive, "cookbook" lab procedures, emphasis on confirmatory experiments, or their minimization of genuine student inquiry and discovery, leading to diminishing student attitudes and interest in the discipline. While these criticisms are valid, they are not new but instead rooted in decades of historical precedent within the physics education community. To this end, this paper aims to synthesize the history of instructional physics labs in the United States, emphasizing curricular innovations, pedagogical criticisms, instructional goals, and student learning outcomes. Additionally, it explores the physics education research that has arisen from these innovations and criticisms, offering insights into pedagogical reform efforts and student learning experiences within these environments.

Throughout the paper, I highlight recurring and sometimes contradictory themes within each of these areas, illustrating how debates about instructional labs have cyclically resurfaced as the community revisits new ideas and questions concerning the efficacy and objectives of lab courses. As Meltzer and Otero aptly stated, "It can be surprising to realize that calls for physics education reform have remained relatively consistent in many ways during the past 100 years or more. … these themes were continuously rediscovered in each era as the intense and passionate debates of previous times were largely forgotten or overlooked" [1]. This observation, while originally applied to physics education in general, also holds true for our narrower examination of instructional labs. We will explore concerns about confirmatory, "cookbook" lab structures, the push for student-driven experimentation, and ongoing debates about the suitability of conventional laboratory courses for reinforcing lecture concepts.

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### A. Outline

This paper synthesizes the history of instructional physics labs in the U.S. Universities in the United Kingdom, greater Europe, and throughout the globe have undoubtedly had irreplaceable influences on the inception, growth, and transformation of physics labs. However, to maintain clarity and conciseness, this paper will only provide a comprehensive historical analysis of U.S. physics lab landscape, while wholly recognizing that U.S. instructional physics labs have certainly been influenced by international pedagogical and scholarly innovations in this realm.

This paper follows the chronological progression of the instructional labs landscape in the United States, starting from its inception and progressing to the present day. Section II delves into the foundational elements of the U.S. physics discipline in the early 1800s that led to the development of formal instructional labs. Section III discusses how societal and institutional demands in the United States placed a strain on the instructional labs' landscape, leading to the standardization of various aspects of lab pedagogy. This standardization triggered a cycle of community-wide criticism and individualized reform efforts, many of which remain topics of discussion today. Section IV explores evidence of earlier patterns of criticism and innovation within the community, similar to those observed during the enrollment surge at the turn of the 20th century. It also highlights some of the first fundamental physics education research (PER)-based studies in instructional labs, the findings of which parallel those of recent years. Section V examines how the introduction of computers and other technologies sparked renewed innovation and debate within the physics discipline. Sections VI and VII focus on the last three decades of efforts within the instructional labs community. Section VI discusses the emergence of formal evidence-based design through research-based instructional strategies, while Sec. VII explores the divergence of reform and research trajectories due to widespread debates about the state of science education in society. To conclude, Sec. VIII provides a discussion of the recurring themes presented in this synthesis and introduces new reflective questions for the community to consider as it navigates the increasingly complex landscape of instructional labs.

## II. THE GENESIS OF INSTRUCTIONAL PHYSICS LAB ENVIRONMENTS

### A. Faculty-led experimentation

Before the Industrial Revolution in the United States and globally, U.S.-based physics laboratories were typically run by individual physicists in their personal labs, often without institutional or external support [2–4]. To attract university students to collaborate in their labs, physicists employed elaborate experimental demonstrations to engage the collegiate science community. The aim was to attract the brightest and most curious students for training and mentorship [3–5]. For instance, Benjamin Silliman of Yale used electricity and magnetism experiments in his basement laboratory to instruct and recruit students. However, students in those early labs were mainly passive observers and had limited participation in experimentation. This apprenticeship model, with students receiving training and guidance from experienced research faculty, persisted from the early 19th century until the Industrial Revolution.

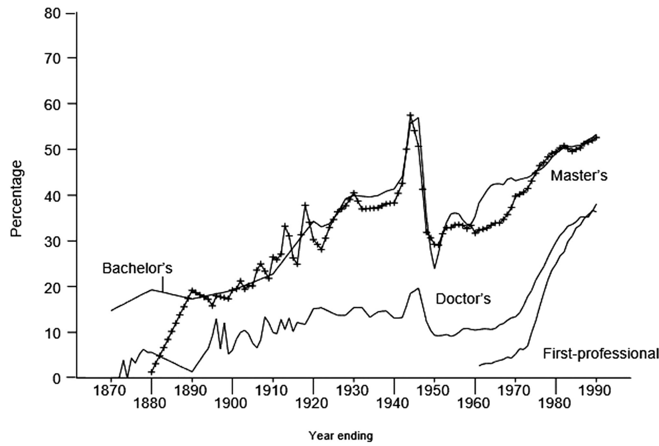


FIG. 1. Percentage of higher education degrees conferred to females, by level: 1869–1870 to 1989–1990 [7].

On a broader scale, collegiate education during this era primarily emphasized general science education and did not offer specialized courses or programs for students to follow [6]. Science education was geared toward engineering and technological innovation to benefit society, with relatively little emphasis on generating new theoretical knowledge [4]. Scientific learning primarily occurred through lectures and textbooks [3]. Additionally, enrollment during this period was limited, selective, and often excluded a significant portion of the U.S. population. In 1869, for example, only 21% of U.S. college students were female (see Fig. 1), and racial segregation persisted in most universities well into the 20th century [7,8]. As a result, overall enrollment was small and focused on different learning styles and outcomes that did not require instructional physics laboratories. Students interested in physics and the sciences were typically recruited individually by faculty and integrated into experimental research groups early in their education, with minimal formal coursework or training beyond the apprenticeship model.

### B. Transitioning to an instructional model

As physicists recruited and mentored students in their individual research labs, U.S. faculty gradually began developing more structured training programs for their students, in line with similar shifts occurring in European universities also. As early as 1825, Amos Eaton at Rensselaer Polytechnic Institute (RPI) pioneered curated instructional lab experiences designed not only to support his research but also to educate students in the broader sciences [3,5].

In the latter half of the 19th century, several societal events triggered a shift in collegiate physics instruction. The U.S. Civil War was coming to an end, and young men were increasingly valuing education. Simultaneously, advancements in science and engineering, including those related to the military, highlighted the profound impact of scientific knowledge on the Industrial Revolution. The overall U.S. population was also growing, leading to a larger pool of college-aged students. These interconnected societal factors prompted universities in the late 1800s to concentrate on specialized scientific disciplines like physics, chemistry, and medicine. They allocated financial and human resources to develop practical and applicable courses and programs to meet the rising student demand. For example, in 1869, MIT established one of the earliest known sequences of instructional physics lab courses [1,9]. In 1886, President Eliot of Harvard commissioned the "Harvard Forty" [10], a set of physics experiments that influenced introductory physics instruction in the United States for the next half-century [1,5,11].

Despite the growing attention given to the sciences and their significance within universities and society, the number of instructional laboratories remained limited. By 1880, only approximately 10% of U.S. colleges and universities offered full-year instructional lab sequences [1].

## III. ENROLLMENT INCREASES AND STANDARDIZATION OF LAB CURRICULA

### A. Conflict between curricular goals and institutional demands

Educators and scientists soon began deliberating the philosophy of education and the role of theoretical and experimental sciences within education. Many physicists began advocating for increased laboratory instructional time, often focusing on promoting inductive reasoning and scientific discovery, where students would engage in direct experimentation to observe phenomena and develop preliminary knowledge [1]. For example, Rowland argued: "Let the student be brought face to face with nature; let him exercise his reason with respect to the simplest physical phenomenon, and then, in the laboratory, put his opinions to the test" [12]. Similarly, the National Educational Association in 1894 recommended that high school physics should include at least 50% laboratory work, emphasizing that textbook study alone was insufficient [13]. In conjunction, the report stated:

> It requires no argument to show that the study of a text-book of Chemistry or of Physics without laboratory work cannot give a satisfactory knowledge of these subjects and cannot furnish scientific training. Such study is of little, if any, value. On the other hand, the mere performing of experiments in a laboratory, however, well equipped the laboratory may be, cannot accomplish what is desired [13].

Similarly, Ames and Bliss wrote: "The object of an experiment in Physics is not simply to teach a student to measure quantities and to verify the laws of nature; it should also lead him to look closely into the methods made use of the theory of the instruments, the various sources of error, the possible deductions and applications of the principles involved" [14].

These discussions on the goals and methods of collegiate laboratory instruction ran parallel to a significant increase in university enrollment, resulting in conflicting pedagogical outcomes. On one hand, educators and physicists sought to transform physics laboratory courses to engage and inspire students, especially those in general education courses [15]. The "New Movement" in physics education, led by figures like Dewey and Mann, emphasized hands-on, experiential learning, relying on physical experimentation and the inductive method. The "Project Method" emerged among physics faculty, promoting student-driven projects that fostered critical thinking and problem-solving skills through active experimentation [1,15].

However, the rapid growth in university enrollment led to a surge in the student-faculty ratio within physics programs. Between 1899 and 1910, college enrollment in the United States increased by about 50%, with subsequent decades seeing even more substantial increases [7]. Enrollment in physics courses surged by 3000% from 1870 to 1940 (see Fig. 2). This enrollment boom presented challenges. While some instructors continued to embrace

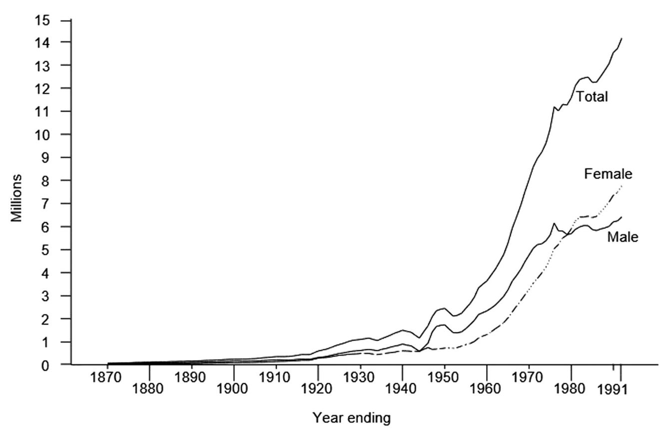


FIG. 2. Enrollment in institutions of higher education, by sex: 1869–1870 to 1990–1991 [7].

the New Movement and the Project Method [15–18], the majority of university-level lab courses shifted toward prescriptive, confirmatory, "cookbook" experiments. This transition aimed to accommodate the growing number of students while conserving resources and faculty time [9,14,19–24]. Notable examples include Hall's "Harvard Forty" experiments [10], initially designed for experiential learning but later converted into a confirmatory, prescriptive format. Similarly, Good's "Laboratory Projects in Physics" [22] were largely prescriptive, offering step-by-step instruction for students to investigate the concepts and principles underpinning physical apparatus such as siphons, hydrometers, engines, and microscopes.

Enrollment increases also led to concerns for physics programs. Faculty members, already stretched thin between teaching and research, often had to recruit graduate students to teach instructional labs, resulting in reduced pedagogical expertise in the classroom and diminished learning outcomes. Funding per capita decreased significantly, limiting resources for new equipment and apparatus despite technological advances and new research sparking interest in innovative experiments [3].

### B. Emergence of a national physics education dialogue

Amidst the increasing complexity of physics education issues, physics educators sought more structured means of communication, collaboration, and innovation. The American Association of Physics Teachers (AAPT) was founded in 1930 with the aim of promoting pedagogical training, offering instructional support across institutions, and serving as a platform for dialogue and innovation within the physics education community. AAPT's establishment was a response to growing concerns about the state of physics education in the United States and the relative neglect of education within the physics community [25]. In 1933, AAPT launched the American Journal of Physics (AJP), originally named the American Physics Teacher. This journal provided a vital space for educators and researchers to share their discoveries, pedagogical approaches, and advancements in physics education.

The founding of AAPT and the launch of AJP ignited ongoing discussions among physicists about the goals and methods of instructional labs. During this period, educators began to identify critical aspects of existing laboratory curricula, raising questions about implications and suggesting new pedagogical strategies. For example, in the first volume of AJP, Bless pondered the overarching objectives of instructional labs, questioning whether the focus should be on teaching students to follow specific directions or on nurturing their capacity for independent inquiry:

> … what is it we expect a student to get out of laboratory work? If the object is to teach the student to follow certain directions, then these detailed instructions are not only useful, but essential. However, no one would seriously maintain that there is great value in teaching the student to follow instructions of disciplinary character [26].

Similarly, Owen expressed doubts about whether the prevailing laboratory structure encouraged the development of experimental skills and positive scientific attitudes. He argued that conventional experiments often followed predetermined procedures and lacked opportunities for students to explore scientific phenomena with an open mind:

> But how well does the ordinary laboratory experience contribute to the development of skill in applying the scientific method and of desirable attitudes and habits that should go with it? Consider that in the usual experiment someone else states the problem, develops the theory showing how general principles apply, outlines how the information is to be obtained and how it is to be interpreted and, in many cases, determines what the conclusion must be. Originality, open-mindedness, even intellectual honesty are not encouraged [27].

Norris criticized certain popular experiments for their focus on confirmatory procedures that failed to engage students in authentic scientific inquiry or meaningful measurement techniques:

> a number of the experiments in measurement appear to be too elementary for the college level … while a certain amount of duplication is necessary, it often proves wasteful of the student's time to arrive at the same conclusions by almost similar methods, thus preventing his study of other important fields [23].

Kruglak contributed to the dialogue by highlighting the misconception that the scientific method necessitated detailed, prescriptive experimentation: "… the spirit of scientific inquiry degenerates into a habit of collecting the same data that has been collected by millions of other bored students" [28]. Similarly, Frank raised concerns about the failure of conventional science instruction to cultivate critical thinking and prevent a rote, uninspired approach to scientific exploration [29].

While these critiques were valuable, the physics education community also proposed solutions to address the challenges in instructional labs. For example, Norris argues that one of the fundamental goals of experimentation is to "understand the science better" [23]. As such, students should be provided "a complete description of the theory of any given experiment." In essence, if students have an initial theoretical underpinning and an average set of skills to apply toward experimental apparatus, the student should be able to "perform the experiment and use the apparatus fairly intelligently." In parallel, experiments should be designed and presented to "stimulate the student's capacity for reasoning or his ingenuity." Owen presents ideas from the general science education community that may be of interest in solving the "cookbook" lab dilemma:

> For example, the simple pendulum experiment might be done by ignoring all theory behind it and asking the student to determine how the period of a simple pendulum is related to its mass and length *and giving no further instructions*. The instructor, with his considerable experience in the field, sometimes forgets the importance of letting the student have the thrill that comes from finding out for himself that the period does not depend on the mass. He must be careful not to let his impatience to *get things done* blind him to the real progress the student makes. It is probably easier to follow a manual and show that the formula $T = 2\pi(\frac{l}{g})^{\frac{1}{2}}$ is experimentally verified than it is to arrive alone at a purely negative result that the period of a simple pendulum is not proportional to its length, but if the student accomplishes only that much, he has probably done himself more good than he would by a very careful verification of the formula [27].

Kruglak similarly argues:

> Conventional laboratory work does not begin to tap a small fraction of a student's resourcefulness. What better way is there to teach that the scientific method is not a superhighway than to place the student in a situation where he will experience the same failures, make the same mistakes, suffer the same accidents, and explore the same blind alleys as the research scientist in the course of his daily work? [28].

Evident from these three examples is the emergence of disparate ideas and opinions on how to respond to common criticisms about the structure and goals of instructional labs: while Norris, for example, advocates for a full introduction of theoretical principles to support student experimentation, Owen disagrees and instead advocates for students to build theoretical principles through empirical study. This theme of divergent ideas and opinions continues across various threads throughout the following decades.

This period also witnessed the development of innovative pedagogical efforts. As physics program enrollments surged, faculty members created specialized physics course sequences to cater to distinct student populations, such as those pursuing careers in medicine [a precursor for the modern-day introductory physics for life sciences (IPLS) curriculum] [30,31]. Faculty also began conducting rudimentary physics education research, investigating student attitudes toward different types of laboratory experiments. Rinehart conducted one of the earliest known physics education studies, collecting qualitative survey data from students in instructional labs to assess their experimental preferences [32]. While limited by contemporary standards, this survey-based approach laid the groundwork for future studies into instructional labs' outcomes and student experiences.

In summary, this period witnessed substantial growth in dialogues within the physics education community and marked the genesis of fundamental physics education research. Physicists engaged in critical discussions about redefining the core objectives of instructional physics labs, addressing issues in prescriptive, conventional lab manuals, and proposing new ideas to align with community-defined goals. Diverse perspectives emerged on how labs should be structured and what outcomes they should aim to achieve. These discussions provided a foundational repository of ideas and insights that would guide instructional labs' innovation and research for the next several decades.

## IV. DIVERGING CURRICULAR INNOVATION AND THE SPARK OF PHYSICS EDUCATION RESEARCH IN INSTRUCTIONAL LABS

Following World War II, the physics education community experienced a period of continued growth and intense deliberation. This period witnessed ongoing critique of existing laboratory curricula, particularly the conventional "cookbook" labs. Simultaneously, educators engaged in more deliberate discussions regarding the desired goals and outcomes of instructional labs. Alongside these discussions, instructional faculty began developing and presenting new laboratory structures, ranging from slight variations of traditional labs to fully "free" labs. They also grappled with institutional challenges, such as limited funding, TA training, and the surge in enrollment.

During this time, the American Association of Physics Teachers (AAPT) played a pivotal role by releasing its first comprehensive set of instructional lab recommendations for the broader community [33]. This marked a significant milestone in the community-wide innovation and dialogue surrounding physics education.

Moreover, this era unfolded against the backdrop of a heightened societal focus on science education, driven by the Cold War and the U.S.'s race with the USSR in the field of space exploration. The establishment of the National Science Foundation (NSF) in 1950 ushered in a substantial increase in financial support for science education. Notably, within 3 years of NSF's founding, national funding for science education saw a tenfold increase [1,34].

This confluence of factors set the stage for a period of dynamic change and innovation in physics education, as well as the emergence of physics education research within the realm of instructional labs.

### A. Continued criticism of "cookbook" labs

The physics education community persistently directed its attention toward conventional "cookbook" labs as a central source of dissatisfaction with instructional lab experiences. A multitude of articles, published in venues such as the American Journal of Physics (AJP), illuminated the long-standing issues associated with these traditional lab formats. These critiques often echoed concerns that had initially emerged in the decades preceding World War II, but they delved into greater detail. Many of these criticisms contended that the rigid, procedural nature of traditional labs fell short of achieving both conceptual and practical learning objectives. These concerns resonated with the earlier critiques of established "cookbook" manuals, including the well-known "Harvard Forty" experiments:

- Hazzard pointed out that laboratories frequently served as training grounds for instrument operation rather than fostering a deep understanding of physical principles. The analytical aspect of problem-solving was overshadowed by mathematical computations, with minimal emphasis on qualitative explanations [35].
- Crawford criticized the practice of providing students with detailed instruction sheets that not only specified the phenomenon to be investigated but also outlined the theory behind it, the required measurements, and the procedures for data collection. Such an approach, Crawford argued, guided students toward a predetermined conclusion, offering little opportunity for them to engage in genuine exploration or investigation without reliance on instructions [36].
- Landis advocated for a shift in the laboratory experience, asserting that students should gain insights into the essence of scientific inquiry rather than merely acquiring knowledge about scientific achievements. He emphasized the importance of placing students in roles that mirrored those of experimental scientists, engaged in tackling novel problems, devising innovative methods, and seeking new knowledge. This approach aimed to reduce the emphasis on replicating and confirming previous work in favor of fostering a spirit of exploration and discovery [37].

These critiques ran parallel to continuous efforts to redefine the goals and curricula of instructional labs, seeking to align them with evolving educational objectives and the changing needs of students.

### B. Refining instructional lab goals and outcomes

During this period, the physics education community placed increasing emphasis on deliberating instructional lab goals and outcomes, engaging in high-level discussions about the broader conceptual and experimental objectives of laboratory instruction. Faculty members continued to prioritize conceptual learning, asserting that hands-on experimentation could lead to a deeper understanding of physical principles, a perspective that had its roots in the early inclusion of instructional labs in university curricula [13,14,19,38].

Educators also advocated for laboratory experiences as a means of nurturing students' inquiry skills, scientific curiosity, and appreciation for the scientific discovery process. Increasingly, educators began to focus on individual learning goals related to experimentation, including precision and uncertainty in measurements, inquiry methods, experimental design, and data analysis techniques [39]. However, this shift toward individualized learning goals would not become commonplace until the turn of the 21st century.

Simultaneously, significant attention was directed toward the assessment of student learning in instructional labs. Prior to this period, assessments typically consisted of written lab reports, lab exams, performance exams, or exit interviews. As new pedagogical ideas emerged and criticism of existing curricula continued, educators began to reevaluate their assessment methods. Several studies highlighted the need to refine assessment strategies due to the escalating enrollment and the resulting strain on instructional staff [40,41].

These refinements often centered on the alignment between the assessment structure and the intended learning outcomes. For instance, some educators challenged the established practice of using written lab exams, arguing that such assessments were inadequate for evaluating students' hands-on experimental skills [42]. Others questioned the utility of lab reports and notebooks, particularly when these did not align with the specific learning objectives of the course. King and Stumpf contended that lab reports were valuable assessment tools when written scientific communication was a specific instructional goal but could be counterproductive otherwise [43,44]. Kshatriya and Thumm highlighted the usefulness of lab notebooks for students to maintain meticulous records of experimental procedures in preparation for subsequent technical reports and performance exams [45].

Over time, the use of written lab exams, designed to assess students' hands-on experimental skills using a paper-and-pencil format, declined in prominence. Instead, performance exams and report writing gained prominence as more suitable and effective assessment methods [46]. These changes reflected the evolving understanding of how best to evaluate students' learning in the laboratory setting.

### C. Divergent curricular innovation

During this period, many faculty members who were critical of the existing state of instructional labs took it upon themselves to develop curricular adaptations aimed at moving away from conventional approaches and toward achieving both conceptual and experimental learning goals [3,47]. This era witnessed the emergence of a wide spectrum of curricular innovations, spanning from scaffolded laboratory instruction and guided inquiry to "free" labs (also known as divergent or open labs) and fully autonomous labs [48]. One notable trend during this period was the increasing interest in "free" labs, which marked a clear contrast from traditional "cookbook" labs. In "free" labs, students were given neither explicit instructions nor assigned experiments. Instead, they were expected to explore topics of their own choosing using methods they had devised and apparatus they had designed, built, or assembled [33].

AAPT's focus on the concept of "free" labs in its 1957 report led to numerous universities experimenting with this approach in their instructional lab sequences. This shift toward more open-ended, student-driven lab experiences gained traction at various institutions [38,49–53]. However, not all institutions were ready to fully embrace "free" labs. Some opted for an intermediate approach known as guided inquiry. In guided inquiry labs, students retained some level of structure and instructor guidance, but this guidance was less prescriptive compared to conventional labs [54–56]. In some cases, this intermediate approach remained consistent throughout a student's course experience, while in others, faculty members adopted a scaffolded approach. In a scaffolded approach, students initially received more guidance to gain experience and confidence, and then this guidance was progressively reduced as they advanced through the course [57].

The diversity of instructional interventions in physics education during this period was not limited to the United States and was documented internationally as well [58–60]. This era marked a significant departure from the traditional "cookbook" labs and highlighted the willingness of educators to explore alternative instructional strategies to enhance student learning in the laboratory setting.

### D. Lack of widespread pedagogical change

Despite the significant criticism and innovative efforts during this period, widespread pedagogical change in physics instructional labs was notably resistant to take hold. The various curricular innovations discussed, from guided inquiry to "free" labs, were adopted by only a small subset of faculty and institutions, and progress was slow over several decades. In 1953, Brown observed that only a few institutions had attempted scaffolded instruction, where students eventually designed their experiments by the end of the term [3]. He also noted that even fewer institutions had embraced "free" labs, with success stories primarily coming from institutions with liberal arts student populations and low student-faculty ratios. Four years later, AAPT published recommendations that discussed the conventional versus "free" labs, acknowledging that the latter had not seen extensive adoption across the nation [33].

In 1960, Kruglak conducted a survey of 520 U.S. universities, revealing that 65% of institutions were still using conventional lab approaches, 23% were employing a "partly free" approach (such as guided inquiry), and only 1.3% were using a "completely free" approach [47]. Subsequent scholarship offered little evidence of significant pedagogical changes toward more open-ended approaches, away from conventional methods.

This resistance to pedagogical change may have stemmed from a hesitancy to believe that allowing students to experiment "freely" would result in meaningful learning outcomes. Menzie argued: "How is one to teach this process of inquiry? It can't be left to the chance that by doing simple (or complex) exercises the student will mystically acquire this technique of being intelligent" [5].

Even advocates for "free" labs often suggest that students should be provided with initial guidance and direction to establish experimental goals before being allowed to choose their own methods and draw conclusions [49]. For instance, Ivany and Parlett, who spearheaded some of the most definitive discussions on instructional lab goals related to free labs, detailed that students must be given enough guidance and initial direction to set experimental goals before they should be allowed to choose for themselves their own experimental methods and conclusions [49]. In another example, Prescott and Anger (1970) promoted the concept of "free" labs but included guiding questions in their lab materials to steer student experimentation [54]. Therefore, many instructors across the educational landscape found a transition toward student-driven instruction appealing, but they identified instructional scaffolding as necessary for effective learning or retained elements from existing curricula that could not be easily discarded.

Additionally, resistance to change might have been influenced by ongoing institutional challenges that hindered pedagogical innovation. The increasing enrollment in physics programs through the mid-20th century created additional pressure on institutions to provide instruction, resulting in higher student-faculty ratios [61]. Even with increased funding from the newly established NSF, institutions still struggled to maintain cost-effective instructional lab systems. Labs were estimated to cost 3 times more than lectures, factoring in expenses related to space, salaries, equipment, and more [62]. Moreover, by the late 1960s, instructional labs were predominantly taught by graduate teaching assistants (TAs) [49]. This made it increasingly challenging for faculty instructors to invest time and resources into more complex pedagogical structures that might not be appropriately implemented by inexperienced TAs [38]. While TA training was beginning to emerge as a topic of discussion and a goal within the physics education community, its impact was not yet evident to the extent required to enable comprehensive curricular reform. These institutional issues acted as significant barriers to widespread pedagogical change in instructional labs.

| Problem | Major N | Major % | No-major N | No-major % | Total N | Total % |
|---|---|---|---|---|---|---|
| Equipment—insufficient and/or inadequate | 45 | 12.7 | 55 | 24.3 | 100 | 17.2 |
| Space—inadequate | 16 | 4.5 | 22 | 9.8 | 38 | 6.5 |
| Staff—insufficient or poorly qualified | 54 | 15.2 | 12 | 5.3 | 66 | 11.4 |
| Staff—training and motivation | 15 | 4.2 | 0 | 0 | 15 | 2.6 |
| Time to do a good job | 24 | 6.7 | 8 | 3.5 | 32 | 5.5 |
| Student motivation | 31 | 8.8 | 15 | 6.6 | 46 | 7.9 |
| Student background deficiencies | 11 | 3.1 | 13 | 5.8 | 24 | 4.5 |
| Avoiding "cookbook" | 34 | 9.6 | 18 | 8.0 | 52 | 8.9 |
| Good lab manual or new experiments | 13 | 3.7 | 10 | 4.4 | 23 | 4.0 |
| Evaluation | 20 | 5.7 | 11 | 4.9 | 31 | 5.3 |
| No problems | 4 | 1.1 | 3 | 1.3 | 7 | 1.2 |
| Miscellaneous | 45 | 12.7 | 36 | 16.0 | 81 | 14.0 |
| No response | 41 | 11.6 | 23 | 10.2 | 64 | 11.0 |
| Total | 353 | 100% | 226 | 100% | 579 | 100% |

FIG. 3. Kruglak's survey analysis of instructional problems faced by faculty in instructional physics labs [47].

### E. Budding research in instructional labs

During the period discussed, the physics education community began some of its earliest physics education research (PER) efforts, primarily focusing on assessing the effectiveness of existing and new pedagogical approaches in instructional labs. AAPT's 1957 lab recommendations highlighted the growing interest in evaluating laboratory teaching effectiveness. This reflected two key aspects that remain relevant in today's PER community. First, pedagogical reforms require rigorous mechanisms for determining their success, moving away from subjective, informal, and small-scale studies conducted before World War II. Second, to use these evaluation mechanisms effectively, instructors and researchers must first clearly define the objectives of the laboratory and establish the relative importance of various goals in instructional labs.

It is evident that the success of evaluating pedagogical reforms hinges on careful consideration of these objectives. Without a clear understanding of what needs to be measured, it is challenging to design effective research instruments for assessment. During this period, however, there was still considerable debate about the intended goals and outcomes of instructional labs, to the extent that only the most fundamental and overarching objectives were being assessed empirically. The consensus was that instructional labs should aim to promote both conceptual understanding and students' competence in experimental skills.

Haym Kruglak was one of the early pioneers in PER focused on instructional labs. As early as the 1950s, he began evaluating the effectiveness of conventional labs compared to other instructional methods like lecture alone or instructor-led demonstrations. His research in 1952 demonstrated that students enrolled in conventional labs did not significantly outperform other student groups (i.e., no lab enrollment) in terms of pre-post gains in conceptual mechanics theory [63,64]. This finding indicated that conventional labs did not effectively reinforce lecture content but may slightly enhance basic experimental skills. Kruglak's study also revealed that conventional lab instruction was slightly better than demonstrations in teaching "simple manipulatory skills and techniques," as measured by performance exams [63,64]. However, this advantage did not extend to written lab evaluations, supporting earlier discussions that written lab exams might not be conducive forms of assessment in lab instruction.

Beyond evaluating the efficacy of conventional labs, Kruglak and his colleagues conducted large-scale surveys to gain insights into the state of instructional lab instruction in the United States. In 1960, Kruglak found that approximately 64% of physics labs in the United States were using a conventional approach, 20% were employing a "partly free" or guided inquiry approach, and only around 1% were using a "completely free" approach. Their study also investigated common teaching problems faced by faculty, many of which continue to be relevant to faculty today (see Fig. 3). Additionally, Kruglak and colleagues explored how various academic factors might influence student performance in laboratory courses, including lab group size, scholastic aptitude tests, and GPA. Among these, GPA was found to be mildly predictive of laboratory performance [65]. These early research trajectories were similar to recent efforts to understand instructional methods and faculty perspectives in instructional labs [66].

However, most early research in instructional labs lacked the rigorous methodologies needed to provide conclusive evidence of pedagogical change. Many educators relied on student questionnaires or surveys to assess student preferences or interests, and these instruments and studies were not explicitly designed for assessing specific innovations or goals within the instructional context (e.g., Refs. [54,67]). Some studies used a combination of rigorous methods and subjective analyses, often using course-based data to argue for a course's efficacy but without employing quantitative statistical analysis to provide supportive evidence (e.g., Ref. [68]).

Overall, while early efforts in PER related to instructional labs showed promise, they were still in their infancy, and more rigorous research methodologies were needed to support evidence-based pedagogical changes in physics education.

## V. INTEGRATION OF TECHNOLOGY AND REFINEMENT OF LAB GOALS

In the latter half of the 20th century, the integration of technology, particularly computers, fundamentally transformed the landscape of physics lab instruction. By 1980, physics educators were beginning to incorporate computers into various aspects of lab instruction, including data collection, analysis, simulations, remote learning, and more. Some faculty embraced these innovations on a large scale, completely overhauling their lab courses to integrate computers throughout the entire experimental process, from prelab instruction to experimentation and postlab assessment (e.g., Refs. [69,70]). As computer equipment and associated apparatus became more commonplace in scientific and academic settings, the costs of these materials began dropping significantly, helping to alleviate some of the financial constraints with regard to equipment maintenance and refurbishment [69]. Later, faculty began focusing on developing students' computational skills, cognizant of the growing need for computational knowledge as the digital and computer landscape unfolded in academia, industry, and society [71,72].

At a more detailed level, instructors started identifying specific educational goals that could be achieved through computer integration. During the 1970s and 1980s, many papers published in AJP explored the use of computers to improve error propagation and least squares analyses, essential tools for analyzing measurement uncertainty (e.g., Refs. [73–75]). Additionally, electronics equipment was directly integrated into computational models for more detailed analysis (e.g., Refs. [75–78]; see Fig. 4).

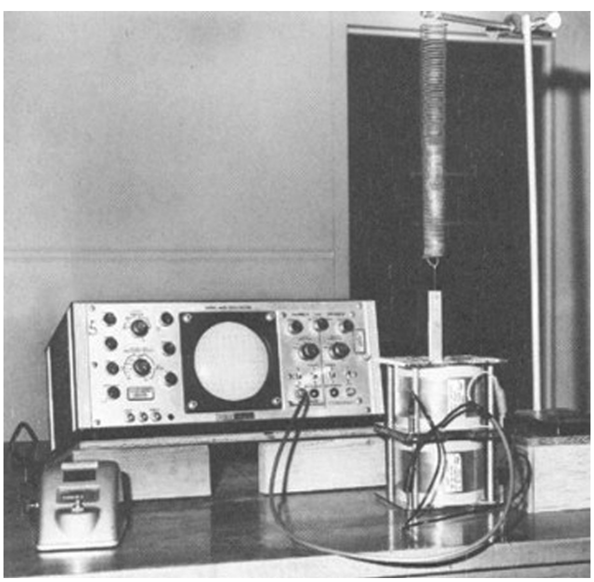

FIG. 4. Experimental setup for electromagnetic induction experiment with computational calculations and graphing [77].

This period also saw the emergence of computer-based simulations that could be integrated into laboratory experiments. For example, Wilson [79] developed computer-based simulations for experiments related to the speed of light and the photoelectric effect, similar to modern simulations like PhET [80,81]. Hoffmaster used VCR video recording equipment to collect and analyze motion data in mechanics laboratories [82], foreshadowing modern video integration platforms such as Vernier, Pasco, and Pivot Interactives [83–85]. Furthermore, advancements in technology led to the development of microcomputer-based sensors like motion detectors [86], enabling new methods of data collection and analysis that were not previously feasible with traditional experimental measurement techniques.

### A. Revisiting the longstanding instructional labs criticism

Despite the integration of new technology and experimental tools, the criticism of traditional "cookbook" labs persisted in the latter half of the 20th century. Faculty and researchers continued to voice concerns about the structure and outcomes of instructional labs, now with greater specificity due to increasing empirical attention to instruction and curricular outcomes. They emphasized that labs should help students explore physical phenomena not easily accessible in lectures, while also developing skills in discovery, design, measurement, analysis, and reasoning [87–89].

Criticism of traditional labs remained largely consistent with previous decades, highlighting their inadequacy in achieving broader goals of conceptual understanding and the enhancement of experimental skills. This persistent criticism can be attributed, in part, to the resistance to pedagogical change in the latter 20th century, even as new experimental tools and technology became available. The adoption of these tools did not always lead to significant pedagogical reforms that could better align with educational objectives. Most laboratory courses continued with the same conventional, confirmatory structure that had been commonplace since the introduction of labs over 100 years earlier. A possible interpretation of this might be that educators gravitated toward innovation through the integration of new apparatus at the expense of focusing on pedagogical interventions that might instead focus more heavily on meeting the broad educational goals not met with conventional lab structure.

One of the most controversial arguments during this period came from Toothacker in 1983 [90], who presented a review of then-current scholarship in physics and other disciplines (e.g., Refs. [42,53,63,64,91–94]), regarding the efficacy of instructional labs across multiple perceived goals. In this meta-analysis, Toothacker argued that conventional lab instruction failed to meet established learning goals, including reinforcing conceptual material, improving student attitudes toward experimentation and scientific inquiry, and outperforming other learning environments like demonstrations or simulations in teaching experimental skills. As a response, Toothacker proposed eliminating introductory physics instructional labs altogether and replacing them with a dedicated experimentation course for physics majors.

While Toothacker's proposal did not gain widespread support, it ignited a renewed discussion about the role of labs in achieving educational objectives. Many scholars argued that labs should move away from merely reinforcing lecture content and instead prioritize the instruction of practical skills like measurement and uncertainty [95], observation, modeling, and experimental design [96]. Additionally, there was a growing emphasis on adopting more rigorous methods for instructional reform, such as a backward design approach that involves identifying course goals, aligning instruction and assessment, designing curricula, and iteratively implementing, assessing, and adapting the curriculum [97].

In summary, despite ongoing criticism and calls for reform, traditional instructional labs persisted, and the debate over their pedagogical goals and effectiveness continued into the late 20th century.

## VI. AN INTERTWINING OF RESEARCH AND INNOVATION IN INSTRUCTIONAL LABS: EVIDENCE-BASED DESIGN

### A. Evidence-based instructional lab reform

The late 20th century marked a period of significant innovation and reform in instructional labs, driven by evidence-based design and a growing emphasis on educational goals. AAPT's 1998 report outlined five fundamental goals for introductory physics labs, emphasizing (i) the art of experimentation, (ii) experimental and analytical skills, (iii) conceptual learning, (iv) understanding the basis of knowledge in physics, and (v) developing collaborative learning skills. In these goals, they document how laboratory activities should be largely student driven, from design to implementation to analysis, in line with earlier calls to remove the prescriptive, cookbook structure of lab manuals. A newfound focus on experimental troubleshooting emerged, an experimental skill often alluded to but not conclusively discussed in prior phases of instructional reform; this troubleshooting ran alongside other commonly discussed skills such as measurement uncertainty, use of computers for analysis, observational skills, etc. In comparing AAPT's 1998 goals with their 1957 report, it is evident that increased specificity had been given to the *goals* of the laboratory course in contrast to their *structure*, which represented a shift in focus from how labs were structured to what goals they should achieve, aligning with the broader adoption of backward design principles in science education.

Several lab reform efforts in the late 20th century embraced evidence-based design and integrated physics education research (PER) methodologies to assess and refine their approaches. Some notable examples include:

- Socratic dialogue labs (SDLs): Developed by Richard Hake in the early 1990s, SDLs aimed to engage students in conceptual conflict, scaffolded experimentation, and Socratic discussions with instructors and peers [98,99]. Hake's research showed that SDLs led to higher student pre-post gains on the Force Concept Inventory (FCI) compared to traditional labs, though additional research on other learning processes (e.g., scientific reasoning, experimentation, collaboration, etc.) was not conducted. However, SDLs had limitations in addressing experimental skills development, due in part to their somewhat prescriptive format and limited use of computers and physical sensors.
- RealTime Physics: Thornton and colleagues developed RealTime Physics in the 1990s to respond to growing calls to utilize lab environments to build students' conceptual learning and integrate computers and digital sensors for experimentation [100]. RealTime Physics focused on active learning and allowed students to visualize and analyze physical data via microcomputer-based laboratory (MBL) tools and computers. The RealTime Physics lab project was part of a larger effort to design active learning laboratories that would integrate recent PER scholarship and "allow students to take an active role in their learning and encourage them to construct physical knowledge for themselves, from actual observations" [101]. Research showed that students in RealTime Physics labs had significantly higher pre-post raw gains on the force and motion conceptual evaluation (FMCE) compared to those in traditional labs.
- Interactive Science Learning Environment (ISLE): The ISLE framework, developed by Etkina *et al.*, aimed to engage students in inquiry-based learning processes, such as observing physical phenomena, predicting outcomes, conducting experiments, and drawing conclusions from analyzed data [102–104]. ISLE labs prioritized the development of scientific abilities, such as experimental design, equipment use, modeling, and data analysis. Research indicated that ISLE labs improved students' scientific abilities [105], engagement in experimental design [103,106,107], and sensemaking skills [107].

These lab reform efforts exemplified the integration of evidence-based practices into instructional labs, with a focus on achieving specific educational goals related to conceptual understanding, scientific reasoning, and experimental skills. They contributed to a broader movement within physics education to transform traditional labs into more effective and engaging learning environments.

### B. Lab-lecture integration—Studio physics

The late 20th century witnessed a significant transformation in physics education with the introduction of studio or workshop physics courses. These courses represented a departure from traditional lecture and lab formats, integrating laboratory experiments, problem-solving activities, and theoretical discussions within an interactive and collaborative classroom setting.

Notable studio physics initiatives, such as Workshop Physics [108], CUPLE Studio [109], MIT's TEAL/Studio Physics Project [110], and the Student-Centered Active Learning Environment with Upside-down Pedagogies (SCALE-UP) approach [111,112], emerged as pioneers of this pedagogical approach. Studio courses featured reorganized classroom spaces that encouraged student-student interactions and increased instructor support (see Fig. 5). In addition to transforming the nature of students' laboratory work, many of these initiatives aimed to address long-standing concerns regarding the limitations of traditional lecture-based learning. Studio courses exploded into the physics education community as a new and exciting pedagogical tool that was thought to alleviate many long-standing concerns about conventional lab instruction and lecture environments. Studios quickly emerged as a widespread reform success in terms of national implementation, as numerous efforts were initiated across U.S. universities to adapt and implement the Studio approach into physics programs nationwide. The success and dissemination of studio physics courses were facilitated by conferences, publications, and professional networking.

The introduction of studio courses provided physics education researchers with a new platform for conducting studies on educational reform. Researchers used rigorous research instruments to assess the effectiveness of studio courses in achieving their intended learning goals. Studies showed that studio courses led to higher conceptual knowledge gains, as measured by the Force Concept Inventory (FCI), Force and Motion Conceptual Evaluation (FMCE), and Conceptual Survey of Electricity and Magnetism (CSEM) [111]. These courses also exhibited lower failure rates and higher attendance compared to traditional lecture-based courses (e.g., Refs. [113,114]). Some studies indicated a reduction in gender gaps in conceptual gains, highlighting the inclusive nature of studio courses [115].

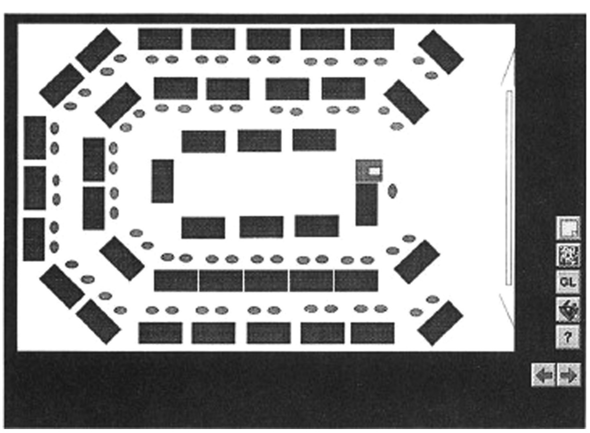

FIG. 5. CUPLE Studio classroom schematic [109].

While many studies supported the effectiveness of studio courses, there were debates within the physics education community regarding their efficacy. Some studies suggested that studio courses might not always improve student problem-solving abilities [113]. Other studies identified nuances in the studio implementation, discussing how a studio approach alone may not be causally related to improved conceptual gains, but rather that the studio approach lends itself well to other research-based instructional strategies (RBIS) that do support these improved assessment outcomes [116] (see also Ref. [117]). Additionally, the impact of the studio approach on experimental skills, such as experimental design, measurement techniques, and analytical methods, remained a topic of research interest.

In summary, the introduction of studio physics courses represented a significant shift in physics education, emphasizing interactive and collaborative learning environments. These courses were associated with improved conceptual knowledge and inclusive outcomes, although research continues to explore their impact on other aspects of physics education, including experimental skills.

## VII. EMERGING DIRECTIONS OF PHYSICS EDUCATION RESEARCH IN INSTRUCTIONAL LABS

### A. A new era of laboratory goals

The early 21st century marked a significant shift in the goals and priorities of physics education within instructional labs. This transformation was driven by a broader movement toward evidence-based reform in science education, from K-12 through higher education, with an emphasis on adapting curricula to meet the demands of an increasingly competitive and technologically advanced scientific landscape. The Next Generation Science Standards and other educational frameworks underscored the need for modernizing and rethinking laboratory education (see Ref. [118–122]).

In response to these changes, the American Association of Physics Teachers (AAPT) published the "AAPT Recommendation for the Undergraduate Physics Laboratory Curriculum" in 2014 [123]. This document introduced a set of comprehensive goals for instructional lab courses, emphasizing the development of students' skills and competencies as future physicists. These goals included constructing knowledge, modeling, designing experiments, developing technical and practical laboratory skills, analyzing and visualizing data, and communicating physics. This marked a departure from earlier recommendations by AAPT, as it encouraged a deeper and more integrated approach to experimentation via scientific modeling, active engagement in conceptual learning via experimentation, connecting lab work to real-world systems, and scientific communication.

This new set of recommendations by AAPT ignited discussions within the physics education community about the purpose and outcomes of instructional labs. It prompted a renewed debate about the effectiveness of traditional physics lab instruction in achieving established learning goals, similar to those brought by Kruglak in the mid-20th century and Toothacker in the latter 20th century. Most notably, work by Holmes and colleagues [124–126] suggested, similar to studies throughout the prior 50 years (e.g., Refs. [42,53,63,64,90–94]), that conventional lab instruction does not reinforce lecture content. These findings have since been a considerable topic of discussion and debate among the community, with various researchers and educators considering how to generalize the findings and implement new pedagogy. It is important to note that these findings, while significant, do not extend to nontraditional lab contexts (e.g., "free" labs and labs focused on experimental practices) or studio physics courses.

This research had a significant impact on physics education, partly due to the extensive dissemination efforts by the research group and the reputation of Carl Wieman, a Nobel Laureate and prominent figure in innovative physics educational methods [81]. Physics programs across the United States began considering how to respond to these calls for reform. There was a growing consensus that labs should shift away from merely reinforcing lecture content and instead focus on other essential skills, such as experimental design, critical thinking, and understanding measurement uncertainty [123,127–129].

In sum, the early 21st century witnessed a reevaluation of the goals and practices in physics instructional labs. AAPT's new recommendations, alongside emerging research, ignited a wave of discussions and reforms aimed at aligning lab instruction with the evolving needs of physics education and the demands of a changing scientific landscape.

### B. Nuances in curricular development—Individualized outcomes

In the 21st century, instructional lab reform efforts in physics education became more nuanced and diverse, reflecting a growing skepticism about the traditional approach of reinforcing lecture content in labs. Faculty members and researchers began exploring alternative educational outcomes to shape their lab courses. Several key themes emerged in this period:

1. Student modeling: Some instructors adopted student modeling as a central framework for their instructional labs (e.g., Refs. [130–134]). This approach encouraged students to develop conceptual models of physical phenomena and refine them through experimentation. Researchers explored the effectiveness of this approach in promoting conceptual understanding and scientific reasoning.
2. Scientific communication: Another focus was on enhancing students' scientific communication skills, incorporating activities like writing lab reports and maintaining experimental notebooks [135,136]. The goal was to help students build communication skills to promote scientific literacy.
3. Critical thinking, computation, and data analysis: Several lab reform efforts prioritized critical thinking skills and data analysis. In these reforms, students are often encouraged to engage in rigorous analysis of experimental data, draw conclusions, and think critically about the implications of their findings (e.g., Ref. [127]). Computation is also integrated into lab courses more frequently to equip students with computational skills relevant to an increasingly computational scientific workforce (e.g., Refs. [137,138]).
4. Collaborative experimentation: Collaborative experimentation is a prominent overarching focus in many instructional labs. While the degree of implementation varies, notable examples include the development of communities of practice to foster a collaborative learning environment and prepare students for teamwork in scientific research settings (e.g., Ref. [139]).
5. Interdisciplinary thinking: In response to the increasing interdisciplinarity of scientific research, some lab courses incorporated interdisciplinary thinking (e.g., Refs. [140,141]). Students in these courses are often exposed to connections between physics and other fields, helping them build connections across disciplines and explore and recognize the broader context of scientific inquiry.

However, despite these innovative approaches and the growing body of research on effective lab practices, traditional curricular structures persist in many physics programs. The reinforcement of lecture content and the development of basic experimental skills remained common goals of introductory physics lab courses [66]. Very few introductory lab courses utilize an exploratory or inquiry-focused approach (historically described as "guided" or "free"), as compared to the conventional prescriptive and confirmatory nature. As a result, many of the learning goals outlined above are not commonly met in current lab environments, in addition to frequent omissions of student agency, decision making, and scientific modeling. Concurrently, much of the data analysis taking place is prescriptive and does not involve significant student reasoning or interpretation. Overall, while the quality of recent instructional lab innovation has significantly increased, it has not yet transitioned into significant quantifiable growth throughout the community-at-large. This resistance to change was attributed to factors such as institutional constraints, a lack of awareness of new innovations, and the preservation of tradition. These efforts, however, continue to lay the groundwork for potential future reforms and continued discussions about the role and goals of instructional labs in physics education.

### C. An explosion of parallel research paths

During this period, physics education research (PER) in instructional labs is witnessing an explosion of new and rigorous efforts aimed at critically analyzing the effectiveness of various instructional reforms. The increased nuance in reform efforts is paralleled by a broader scope and diversity of research themes within the instructional labs landscape. Several prominent empirical themes are currently emerging:

#### *1. Equity, attitudes, collaboration, and agency*

Issues of equity, particularly in relation to gender and other demographic factors, gained prominence within the physics education research community. Researchers began examining how gender dynamics and instructional approaches influenced students' access and opportunities for equitable engagement in experimentation. Some interventions were found to mitigate gender inequity, such as supporting minoritized students in leadership roles within lab groups. Additionally, studies explored how different instructional approaches and techniques affected students' attitudes toward experimentation.

Issues of equity and its intersections with other factors, such as gender, student collaboration, agency, and student attitudes and perceptions, gained prominence within the physics education research community. PER researchers are now taking a critical lens to these issues to determine what barriers might be interwoven into the instructional labs' framework and how new innovations can promote parity across the student population; this runs parallel to growing efforts of this form in physics education more broadly (e.g., Refs. [142–145]). For example, studies have examined how gender dynamics in group-based labs may promote inequity of students' access and opportunities to equitably engage in experimentation (e.g., Refs. [146–148]). In several of these studies, nuances in instructional approaches were identified that implicitly create gender inequity among lab groups, including approaches specifically designed to mitigate these issues. Conversely, some interventions resulted in promoting equity, including supporting minoritized students to fulfill leadership roles in lab groups [149].

Tangentially, researchers have renewed their focus on how various instructional approaches or techniques might impact students' attitudes toward experimentation. The Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS) was developed to measure students' pre- and postcourse attitudes in physics labs. Implementation of the E-CLASS across various lab courses indicated that conventional labs reinforcing lecture concepts often led to negative changes in students' attitudes, while reformed courses emphasizing experimental skills resulted in positive or neutral changes in these attitudes [66,147,150–155]. These results also suggested that reformed courses, even those not explicitly designed to mitigate gender inequity, may reduce the gender gap in students' pre-post experimental attitudes [156].

Many instructors aimed to promote students' experimental agency and decision making, moving away from prescriptive "cookbook" lab structures. Research indicated that shifts toward more open-ended, inquiry-based instructional formats increased students' opportunities for experimental agency and decision making [155,157–160]. Overall, these studies suggest that reform-based lab instruction that prioritizes equitable, student-centered experimentation may result in improved student agency and attitudes, which could in turn be at least indirectly related to other experimental outcomes.

#### *2. Computation, virtual simulations, and remote instruction*

In recent years, advancements in technology have enabled educators to incorporate new pedagogical tools into instructional labs, with the aim of enhancing student conceptual learning, reasoning processes, and experimental skills. Similarly, the COVID-19 pandemic created significant shifts in instructional methods, namely in the advent of remote laboratory instruction, allowing researchers a new venue in which to analyze student learning and collaboration.

Virtual simulations, such as PhET simulations and other adaptations, have become more common in laboratory activities and lecture demonstrations. Educators interested in reinforcing lecture concepts have recently questioned whether the use of virtual simulations may improve student conceptual learning beyond traditional experimentation. In numerous studies, researchers have shown that virtual simulations typically meet or exceed conventional labs in terms of student conceptual learning gains [161–164].

These simulations, along with other pedagogical tools such as virtual reality and augmented reality (e.g., [165]), became useful tools for many educators during the rapid onset of the COVID-19 pandemic, which forced instructional labs to remote settings. This immediate shift in instructional landscape resulted in unintended shifts in learning outcomes and student experiences, while preserving others. For example, as many expected, remote instruction during the COVID-19 pandemic forced instructors to shift their goals away from experimental processes toward conceptual learning [166]. Likewise, collaborative learning diminished, even with the adaptation of video conferencing [166,167]. However, remote labs were able to meet roughly the same outputs of students' experimental attitudes compared to in-person instruction [167]. They also were shown to provide students additional experimental agency, though this may have indirectly been related to the reduction in collaborative experimentation [167].

Overall, the integration of virtual simulations and the transition to remote instruction have opened new avenues for enhancing instructional labs, particularly in terms of conceptual learning and experimental agency.

#### 3. Measurement uncertainty

Efforts to enhance students' understanding of experimental error and measurement uncertainty have gained momentum in recent years. Researchers have developed specific pedagogical tools aimed at improving students' abilities and reasoning processes in this area.

For instance, during the development of a new laboratory course sequence, researchers introduced the Physics Measurement Questionnaire (PMQ) to assess the extent of student understanding of measurement uncertainty and statistics [168]. Their findings indicate that focused reform efforts resulted in students improving their abilities to communicate their reasoning about measurement uncertainty and related calculations compared to students in conventional laboratory courses. This research also aligns with prior studies that suggested conventional labs can enhance students' measurement uncertainty skills, albeit without concurrent improvement in reasoning skills [169]. In related work, these researchers have explored instructors' views and perspectives on measurement uncertainty and its role in instructional physics [170]. These efforts aim to provide valuable insights into the instructional landscape and contribute to the ongoing development of effective pedagogical strategies in this area.

Future research endeavors seek to expand on these findings and potentially develop formal research and pedagogical assessment instruments for broader dissemination across instructional labs.

#### 4. Experimental processes, skills, and reasoning

In recent years, there has been a growing emphasis on developing and assessing various experimental reasoning processes within instructional labs. Physics educators and researchers are increasingly interested in enhancing students' abilities in scientific modeling, experimental design, data analysis, and sensemaking, all of which contribute to the overarching goal of cultivating students who can "think like a physicist."

Several laboratory reform efforts, including the ISLE framework, prioritize inquiry-based experimentation, where students have agency over their lab work and are encouraged to pose scientific questions, engineer experiments, test models, and troubleshoot systems. These approaches has been shown to promote students' abilities in experimental design [107,171,172], which involves constructing experiments to answer scientific questions and troubleshooting systems logically and through problem solving.

Model-based reasoning, another experimental reasoning process, is closely related to experimental design. Model-based reasoning encompasses activities such as "constructing models of the measurement tools and physical system, making predictions, making measurements, interpreting measurements using the measurement model, comparison between predictions and measurements, and several pathways for revision of the models and apparatus" [173]. Researchers have presented promising results that labs prioritizing student engagement in modeling do result in students' increased engagement and abilities in model-based reasoning [132,173,174]. Intimately related, in turn, to model-based reasoning is critical thinking, or "the ability to use data and evidence to decide what to trust and what to do" [175] and data processing, or "the ability to handle [experimental] data" and reason about "the nature of measurement and uncertainty" [176].

Experimental design, model-based reasoning, critical thinking, and data processing can all be subsumed by a larger learning process of sensemaking. Sensemaking, in a broad sense, can be defined as a "dynamic process of building or revising an explanation in order to "figure something out"—to ascertain the mechanism underlying a phenomenon in order to resolve a gap or inconsistency in one's understanding" [177]. Thus, some educators and researchers have worked to scaffold laboratory instruction to provide a more open-ended environment in which students can engage in multiple forms of experimental sensemaking (e.g., Refs. [107,140]). Recent studies have focused on how sensemaking processes emerge from open-ended, inquiry-based labs [178], with some work beginning to build connections between sensemaking and other reasoning processes [179].

Overall, the study of various reasoning processes in instructional labs has witnessed a surge of interest and research. While each empirical trajectory is often tied to specific educational innovations, there is still room for further scholarship to build more comprehensive connections and provide a nuanced understanding of student learning related to experimental reasoning processes in lab settings.

## VIII. DISCUSSION

This paper presented a historical analysis of the instructional labs landscape from their inception in the early 1800s to the present day. By focusing on the chronological progression, this review identified several recurring themes, each of which leads the community to consider new reflective questions as we collectively embark on new pathways to innovate and investigate instructional lab curriculum.

First and foremost, the persistence of the cookbook lab structure, characterized by prescriptive and confirmatory experiments, despite longstanding criticism, is a central theme. This raises questions about the resistance to change within the instructional labs community and the factors that have contributed to the longevity of this traditional format.

A second recurring theme across the historical landscape is criticism of labs' inability to support students' learning of lecture concepts. Advocates from the early 1900s, researchers from the 1950s, and new studies in the last 10 years have all suggested that conventional instructional labs are incapable of reinforcing lecture material beyond other instructional approaches. The community's responses to these studies have been mixed, with some advocating for a revision in lab goals toward experimental skills, and others arguing for a dissolution of the instruction lab altogether. Likewise, some current educators and researchers are not convinced that a complete abandonment of this conceptual learning goal in labs is the most effective strategy. Rather, they often argue that new instructional methods or tools might be better suited to meet this goal in ways that conventional labs were unable to. Thus, it remains an open question of whether the instructional lab environment can be effectively designed to reinforce lecture content, and if so, what mechanisms must be in place and what impact might this have on other tangential learning outcomes.

Third, as each new era unfolded, new societal or technological changes emerged that either supported or hindered the innovation and research within the instructional labs environment. Most notably, the introduction of cost-effective computers into instructional labs opened the doors to new digital apparatus, possibly at the expense of a continued focus on specifying instructional goals and pedagogical structure. From a societal lens, the formation of community and governmental bodies, such as AAPT and NSF, helped spur new eras of pedagogical innovation. With this comes an outstanding question of what broad restrictive elements of the current instructional labs' landscape might be causing innovative or empirical narrow-mindedness, limiting the community's opportunities to engage in radical and trailblazing new ventures.

This historical analysis, in unearthing common themes throughout the history of instructional labs, has identified numerous questions the community has explored throughout the last 200 years. For many of the questions below, there is no clear consensus from the instructional labs community, neither historically nor at the present time. Thus, we as a community must continue to grapple with these questions, both together as a community body and individually within our respective institutions and classrooms.

- Why have "cookbook"-style, confirmatory, prescriptive labs persisted throughout decades of well-founded criticism?
- Is it possible for the instructional labs community to develop a comprehensive set of instructional goals for student learning in lab settings? If so, how does it depend on the student population? How does it depend on the lab level (e.g., introductory vs advanced)?
- What are the most effective and efficient ways to assess student learning and engagement in labs?
- What student populations should be enrolling in physics laboratory courses?
- What elements of physics conceptual knowledge and experimental skills are most relevant for the current and upcoming student population?
- How does the community effectively adapt instructional methods to emergent technologies (e.g., computation, virtual learning environments, generative AI, etc.)?

An argument could be made that these and other questions must be continuously revisited by the community in order to effectively assess the current state of instructional labs.

While this paper discusses three prominent recurring themes in the instructional labs' landscape, other recurring patterns are likely present, with saliency dependent on the perspective and experiences of each reader in their role as educator, curriculum developer, researcher, student, or some mixture of these roles together. This historical analysis was crafted to provide a comprehensive review of the instructional labs landscape and serve as a stepping stone for the community's continued discussion surrounding the state of labs and the roles we all have in collectively improving lab instruction in the future. This work calls attention to a necessary focus on the precedents set by educators and researchers before us, from which we can glean new insight and learn from debates and outcomes in order to traverse new intellectual territory and not repeat the work and discussions of the past. While many of the topics and results currently being discussed and debated in today's educational landscape are synonymous with those of eras before, our current community also has access to new technological, theoretical, and methodological tools that can be instrumental in breaking new ground in instructional labs. To leverage these effectively, we should be attentive to the recurring patterns from the last 200 years and work diligently to integrate this prior knowledge into our discussion and scholarship. While it is unlikely that an expanded and increasingly diverse instructional labs community will reach a unanimous consensus on the goals and strategies within the labs' landscape, we can undoubtedly work to build commonality and mutual understanding, working to promote improved outcomes and pedagogies that can be taken up and utilized by new educators in years to come.

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