Teachers' experiences with taking an open-ended approach in teaching labs in high school physics classes

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Although most teachers recognize the importance of taking investigative, open-ended approaches to students' learning experiences, implementing them in high school classes can be challenging for teachers. In this work, we analyzed data from multiple sources from a teaching Community of Practice (CoP) to investigate (a) barriers to taking an open-ended approach in teaching labs in physics classes, (b) shifts in teachers' beliefs about taking an open-ended approach during their engagement in a physics teaching CoP in a partnership program, and (c) a case study of one teacher whose shifts in perceptions about taking an open-ended approach in teaching labs led to her successful implementation in her class. The findings confirm the existence of well-known psychological and structural barriers that can prevent teachers from adopting investigative approaches in teaching physics labs. Moreover, we learned how the interaction of these barriers further complicates the adoption of open-ended approaches in physics classes. The study also revealed a significant gap between teachers' current practices and their desired methods of conducting labs, particularly in terms of structured versus open-ended approaches. The case study offered deeper insights into how shifts in teaching practices occur through changes in perceptions within a supportive CoP.

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I. INTRODUCTION

Reform-based lab instruction, often synonymous with an investigation-style or open-ended approach, offers students authentic science learning experiences [1,2] by allowing them to emulate the work of a scientist [3–5]. Specifically, lab experiments with a more open-ended inquiry approach enable students to make experimental decisions to solve scientific problems, thereby engaging them in the scientific process [2,6]. Despite teachers' awareness of the potential benefits of this approach in teaching labs, various barriers hinder its implementation. These barriers include time constraints and institutional factors [7–9], teachers' perceptions of their students' abilities [10–12], teachers' academic backgrounds, and classroom dynamics. Furthermore, the lack of access to general science materials [13] and lab-specific resources exacerbate the challenges of adopting an open-ended inquiry approach in teaching physics labs.

This paper explores whether the social and material resources available to high school physics teachers can help them overcome the barriers to implementing a more open-ended inquiry approach in teaching labs. The social resource in this study is a physics teaching Community of Practice (CoP) [14], while the material resource is a lab device called iOLab. Specifically, we seek to address the following research questions:

1. What are the barriers of taking a more open-ended inquiry approach in teaching labs in high school physics classrooms when teachers are provided with social and material resources?
2. What evidence, if any, indicates shifts in teachers' perceptions of taking open-ended lab approaches as a result of their participation in the CoP?
3. Is there evidence of a transition from a more structured lab format to a more open-ended lab approach among high school physics teachers in the CoP? If so, what factors facilitate this change?

This study contributes to science education research and physics education research in two ways. First, this study sheds light on high school teachers' perspectives on taking a more open-ended approach in teaching labs in science or physics classes and perceived barriers that may persist, even when equipment and community support are present. Second, this study advances the field toward a potential model for how community support by and for high school science teachers can create transformative and lasting changes in their pedagogical philosophy and classroom lab implementation toward a more open-ended approach.

II. LITERATURE REVIEW

A. Inquiry-based instruction, "scientific practices," and laboratory work

Over the past several decades, science education reform movements have advocated for investigative approaches that encourage students to participate more in the process of knowledge construction [15]. The shift from the term "scientific inquiry" to "scientific practices" reflects an effort to align science education with the actual work of scientists [2]. Both terms are used interchangeably in scientific texts. These practices, outlined in the framework for K-12 Science Education and incorporated into the Next Generation Science Standards (NGSS), include (i) asking questions (for science) and defining problems (for engineering); (ii) developing and using models; (iii) planning and carrying out investigations; (iv) analyzing and interpreting data; (v) using mathematics and computational thinking; (vi) constructing explanations (for science) and design solutions (for engineering); (vii) engaging in argument from evidence; and (viii) obtaining, evaluating, and communicating information [2]. While these practices define essential aspects of scientific work, simply listing them as instructional goals does not ensure that students are truly *doing science*. Without well-structured learning environments, students may engage with these practices in a fragmented or superficial manner rather than developing authentic scientific reasoning [16,17].

In the context of physics lab instruction, the American Association of Physics Teachers has enumerated six learning outcome focus areas for physics lab instruction: (i) constructing physics knowledge, (ii) developing and testing models, (iii) designing experiments, (iv) developing technical skills, (v) analyzing and visualizing data, and (vi) communicating physics knowledge and experimental results [18]. While these objectives align with scientific practices, their successful implementation depends on deviating from structured approaches in teaching labs and instead emphasizing student-driven design and redesign of experiments. The Investigative Science Learning Environment (ISLE) approach exemplifies this approach by engaging students in cycles of designing experiments, analyzing data, and refining models [3]. The ISLE approach in teaching labs has proved successful both in college and high school level physics classes, even in courses that include traditional lectures, providing students with opportunities to engage meaningfully with scientific ideas while still operating within a guided framework [19–21]. In the Illinois Physics and Secondary School Partnership (IPaSS)—the context of this research study—high school teachers are introduced to the ISLE approach and are provided with opportunities to implement it. Furthermore, the university labs and the equipment available to teachers are intentionally designed to support and promote the ISLE methodology.

This study emphasizes cultivating a "doing science" mindset, which involves adopting a more exploratory and open-ended approach in physics labs. It is important to note that an open-ended approach does not necessarily mean that all labs are entirely open. Instead, it refers to a progression toward giving students more autonomy in conducting investigations. This includes designing experiments, collecting and observing data, and interpreting results with minimal guidance, thus fostering deeper scientific engagement and critical thinking.

B. Open-ended labs: Are they really effective?

The focus on engaging students with scientific practices is linked to continued exploration and design of scaffolded, but not heavily prescribed, lab activities. Many educators and science education researchers have found a positive evidence in support of investigative science learning approaches such as inquiry-based laboratory work [2,6,22–24]. There is empirical evidence for inquiry-based lab instruction having a significantly positive impact on students [21,25,26]. For example, Buggé [21] found that students showed improved scientific abilities in physics when they were given a chance to revise their labs in an ISLE-approach classroom. These students had the opportunity to brainstorm ideas, observe demonstrations, participate in guided experiments, and engage in meaningful group discussions. Chatterjee *et al.* [25] noted that survey results from approximately 700 students working in inquiry-based labs revealed positive attitudes toward these labs, with students believing they learn more naturally and effectively in guided-inquiry settings. Other studies have also found that taking a more open-ended approach in teaching labs can support student development of content knowledge [27], make labs more enjoyable for students than closed investigations [28], improve students' agility with scientific processes [3], foster more positive student attitudes toward science [29], and promote student interest in science careers [30].

While such findings highlight the benefits of reducing procedural rigidity in labs, the terminology used to describe instructional designs often varies and lacks precision. Many labels and categorization schemes have been used to describe the level of prescription and scaffolding in an instructional lab activity. Akuma and Callaghan [31] considered four levels of inquiry-based instruction: confirmation, structured, directed, and open. They propose that as one moves from confirmation to open instruction, students are more likely to engage in a greater number of the eight NGSS scientific practices. In other categorizations, the levels of inquiry have been placed on a continuum [32], with more structured labs referred to as teacher driven, and open-ended inquiry labs as learner driven. Confirmation style and structured style labs have also been referred to as *cookbook* style labs where the procedure is given to the learner [30]. Evidence shows better gains in favor of guided-inquiry lab styles in science labs compared to open-ended inquiry when there is some preparation prior to the instruction or verbal guidance during instruction [16,33–35]. In comparison, studies of "cookbook" style, or more procedurally closed labs, do not show significant evidence in support of the development of physics content knowledge and expert beliefs about the experimental nature of physics among college-level students [36,37]. In such labs, learners conduct routine exercises and rarely reflect on their methodology and findings [38,39].

In this work, we clarify our use of the term "open-ended labs" to reflect an instructional *approach* that moves away from prescriptive and procedural designs. However, the term "open-ended," as commonly used in the literature, does not always accurately capture what Akuma and Callaghan [31] define as level 4, where students still respond to a question posed by the instructor rather than generating their own. This definition includes open-inquiry and guided-inquiry labs or any design that significantly deviates from rigid, cookbook style, or confirmation-based labs. Further, we echo the views of those who see lab instruction in physics education as lying along a continuum rather than as a binary choice [16,32,40].

C. Barriers to taking an open-ended approach in teaching labs

Despite the availability of resources like the ISLE curricular materials [3], and a collective nod from researchers affirming the benefits of investigative-style approaches, teachers are often reluctant to take a more open-ended approach in lab instruction [7,41]. Some scholars have sought to enumerate and categorize the types of barriers that teachers face in taking a more open-ended approach to lab instruction. Cheung [41] enumerates 11 barriers including the lack of time, teacher beliefs, lack of effective inquiry materials, pedagogical problems, management problems, large classes, safety issues, fear of abetting student misconceptions, student complaints, assessment issues, and material demands (p. 109). Ramnarain [42] found similar barriers and categorized them into extrinsic and intrinsic challenges. Ramnarain considered intrinsic challenges to be related to teachers' competencies, including their perceived understanding of content knowledge, and extrinsic challenges to external factors such as short blocks of time and large class sizes. Taking an instructional design perspective, Akuma and Callaghan [31] related these challenges to different phases of instruction and categorized them into preparation, implementation, and assessment phase challenges.

Ultimately, whether a teacher chooses to adopt a more open-ended approach depends on various factors, including the lab goals, classroom dynamics, the time of year, the topic being taught, and the teacher's confidence in their disciplinary and technological skills. Consequently, teachers may choose to implement this approach only a few times throughout the school year. As Deters [27] suggests, the goal should be to integrate inquiry-based labs as often as possible. "Even conducting a few inquiry-based labs each year can significantly enhance students' critical thinking, self-confidence, and willingness to engage in scientific inquiry by the time they graduate" [27] (p. 1180). This underscores the importance of gradually integrating "open-ended" *approaches* into lab instruction, ensuring that students develop a robust understanding and appreciation for it.

D. Overcoming barriers using communities of practice (CoPs)

Although only a few reports exist on the mechanisms by which teachers may overcome structural barriers to implementing open-ended labs, some studies indicate that teachers' perceptions of open-ended lab instruction can become more favorable over time. For instance, sustained and intensive teacher PD focused on inquiry-based instruction [41] has been identified as an effective strategy for improving teachers' knowledge of inquiry-style experiments and fostering inquiry-oriented teaching identities [24,43,44]. To promote the teaching practices best suited to inquiry-style investigations touted by the NRC, researchers advocate for a stronger focus on inquiry-based instruction in both preservice teacher education programs [45,46] and in-service teacher PD [47]. Similarly, Dobber *et al.* [33], in their meta-analysis of 186 studies, identify targeted teacher training as an effective strategy for overcoming perception-related barriers to inquiry-based instruction.

Drawing on the Communities of Practice (CoP) model [14], we highlight the role of PD context in fostering teacher interactions that can lead to shifts in lab teaching practices. The CoP framework offers a situative perspective that explains how context influences social learning in a community, whether it be a workplace, a book group, or joining a new family [14,48]. The "community" in the CoP refers to a group of people who share a common interest or "shared enterprise" in a particular "domain" or area and engage in community practices to learn from each other [14]. Learning in Wenger's view is a social process, with many of the attributes of an apprenticeship model where less experienced members learn from more experienced ones [48]. In the process of becoming a member in the CoP—termed legitimate peripheral participation—one may start from being a "peripheral member" and then gradually transition to a "core member" through socialization, observation, and engagement over time, or remain a peripheral participant [14,48]. We believe that in the process of joining a teaching CoP, there are many exchanges of content, pedagogical, and technological knowledge. Opportunities that can transform teachers' beliefs in one or more ways that Bandura [49] names: (i) experiencing success by themselves; (ii) observing success by others; (iii) emotional arousal; and (iv) verbal persuasion—all of which can happen in PD settings. Therefore, it is important to investigate teachers' self-reported barriers in the presence of the community and trace gradual perception and practice shifts within the community.

III. METHODS

In this paper, we investigate physics teachers' approaches to lab instruction in the context of the Illinois Physics and Secondary Schools (IPaSS) partnership program. IPaSS is a partnership between the University of Illinois Urbana-Champaign (U of I) and Illinois high school physics teachers (Teaching Fellows). In the IPaSS program, teachers engage in prolonged physics-specific professional development (PD) with 100 h of in-person and online professional development per year for up to 4 years. The partnership's goal is to create a professional community of physics teachers by (a) sharing research-based, university-level physics materials; (b) facilitating teacher sharing of course materials with one another; (c) supporting teachers in implementing new course materials and activities throughout the year; and (d) supporting teachers in eventually becoming leaders and mentors in the program. Currently, the program is in its fifth year, and data collection and analysis for this study were conducted during years 3 and 4 of the program. Over time, teachers and the IPaSS team have formed a Community of Practice (CoP) wherein teaching materials, teaching experiences, and support are shared. All authors of this article are involved in the design, development, and facilitation of IPaSS PD and members of the CoP.

In IPaSS CoP, teachers engage in PD with a focus on curricular integration of the iOLab (Fig. 1), a multisensor lab device that is used in teaching introductory physics labs at the University of Illinois. The iOLab can be easily deployed to conduct hundreds of physics labs without requiring teachers to use any other lab equipment. Although the iOLab was created at U of I with university students in mind, it has been piloted successfully in secondary school classes [50]. The iOLab software allows teachers and students to analyze graphical data and measure a range of quantities (see Fig. 2). Teaching fellows and their students have free access to a class set of these devices as part of the program. According to Selen and Stelzer [51], the iOLab is effective in promoting students' freedom in designing their own lab experiments. It is worth noting that the introductory physics labs at U of I are inspired by the Investigative Science Learning Environment (ISLE) approach [3] in teaching labs where the focus is on empowering students to get creative in designing solutions to real-life situations.

In the PD meetings, teachers are introduced to the iOLab device by conducting some of the university labs and are encouraged to adapt these labs to their classroom context and/or develop their own iOLab-based labs. However, it is not a requirement of the PD that teachers take an open-ended approach in teaching labs or that they use the university labs which are open-ended. Throughout the school year, teachers have access to direct support from the developers of the lab device, and high school classroom-specific support from peers attempting similar lab reforms. By providing these materials and support opportunities within the CoP, the PD aims to give teachers the tools to overcome some of the barriers that they might have experienced otherwise.

A. Participants

Teachers in the IPaSS program come from diverse academic and teaching backgrounds, some of them holding

FIG. 1. iOLab system.

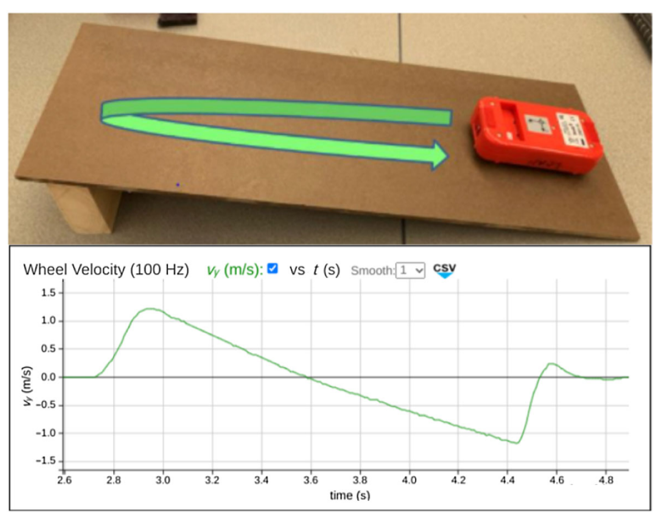

FIG. 2. An example of velocity data from the iOLab's wheel sensor from a kinematics lab.

TABLE I. Participating teachers' information. Total number of teachers is 38. *Denotes a field wherein the number of teachers overlaps.

Category	Details	Count
Locale	Urban	8
	Suburban	20
	Town	6
	Rural	4
Degree	Physics	18
	Nonphysics	20
Years of experience	0–5 years	10
	6–10	11
	11–15	3
	16–20	7
	21–25	3
	25+	4
Courses taught*	AP physics	27
	Regular physics	33
	Other sciences	15
Title 1 or ≥ 40% Low Income	Yes	20
	No	14
	No data available	4

degrees outside of physics, teaching a variety of physics courses spanning from general physics to Advanced Placement (AP) Physics courses. The range of experience is from 0 to 32 years, and more than half of them teach in Title 1 schools (a designation indicating that >40% students attending the school come from low-income households). Using a convenience sampling method, the participants in this study—38 teachers—are a subset of a bigger population (50 teachers) who are currently enrolled in the program. Table I shows information on the participating teachers.

B. Data collection

To answer the research questions, we collected data from multiple sources allowing us to triangulate the results [52] (see Table II). In line with RQ1, we collected text, video, and pictorial data to qualitatively inquire about teachers' self-reported barriers to taking an open-ended approach in teaching physics labs. To start, as part of an online PD meeting, we recorded a subset of four teachers' reflections on their attempts to take a more open-ended approach in teaching labs. The last 18 min of the meeting video when teachers discussed their views about different types of labs in their classes, was transcribed. In this meeting, we prompted the teachers to talk about assessing labs, lab structures (structured vs open-ended), and scaffolding physics labs. As a follow-up to this conversation, we created two open-response survey questions to document 21 teachers' views (12 women and 9 men) on lab instruction. The open-response survey items came from a longer survey that was administered in the Spring 2023 semester (February), asking teachers to reflect on the value of the meetings and provide recommendations for improvements. Two questions were added to capture a wider range of teachers' views of lab instruction (including barriers to and value of implementation). Question (1): What do you

TABLE II. Research questions, data sources, analysis, and data types.

Research questions	Data sources	Analysis	Type of data
RQ1: What are the barriers to adopting a more open-ended inquiry approach in teaching labs in high school physics classrooms when the teachers are provided with social and material resources?	• 1-h online PD video (subset of 4 teachers) • Open-ended survey (21 teachers) • Embodied rating task (27 teachers)	• Deductive coding based on *a priori* codes from literature • Inductive approach for emergent codes	• Text data • Video data • Pictorial data
RQ2: What evidence, if any, indicates shifts in teachers' perceptions of taking open-ended lab approaches as a result of their participation in the Community of Practice?	• Guided inquiry survey (GIS) (14 teachers) • Embodied rating task (27 teachers)	• Descriptive statistics • Paired-sample t test	• Numerical Likert scale data 1–5 (strongly agree-strongly disagree) • Pictorial data
RQ3: Is there evidence of a transition from a more structured lab format to a more open-ended lab approach among high school physics teachers? If so, what factors facilitate this change?	• 45-min/one period Classroom observation (Dawn) • 30-min interview (Dawn) • 15-min online planning video (Dawn)	• Qualitative inductive coding	• Text data • Video data

consider to be some of the challenges with running open-ended/less structured labs? If you have tried more open-ended labs, how has this gone for you and your students? Question (2): What do you value in terms of student skills built from labs? How are students doing with these skills this year in general?

In alignment with RQ2, we took a quantitative approach in considering teachers' past and present perceptions of taking an open-ended approach in teaching labs, and their future ideal use of this instructional style. To pursue this aim, we collected retrospective survey data from 14 teachers (7 women and 7 men) who had participated in the program for one to three years. The survey aimed to assess how their current perceptions of open-ended lab instruction compared to their views when they first joined the program. Here, we adopted the Guided Inquiry Survey (GIS) [41] to probe physics teachers' perceptions of taking an open-ended approach in teaching labs. GIS is a validated survey originally developed to examine chemistry teachers' perceptions of teaching labs across three constructs: (i) the value of guided-inquiry labs, (ii) the limitations of cookbook style labs, and (iii) the implementation of guided-inquiry labs. Each construct has four items, making GIS a 12-item survey. The original GIS uses a seven-point Likert scale with agreement options ranging from "strongly disagree" to "strongly agree." GIS has been used to gather teachers' perceptions of guided-inquiry labs in chemistry education, with versions available in both English and Chinese for use in diverse linguistic contexts [41]. We administered this survey in a retrospective manner in June 2023 to better capture the effect of the community on perceived shifts in their beliefs about using an open-ended approach. Retrospective surveys have participants reflect on past events at a single point in time [53,54]. Some examples of GIS questions are "Most students like guided-inquiry experiments more than structured inquiry experiments" and "Guided-inquiry experiments can provide more opportunities for students to apply physics knowledge than structured inquiry experiments." Instead of a seven-point Likert scale, we chose to use a five-point scale with the same range of agreement options as the original GIS survey (see Supplemental Material [55] for questions and constructs).

The embodied rating task was a data source that was used to inform both research questions 1 and 2. In this task, a total of 27 teachers participated, 19 men and 8 women. The rating task occurred during the in-person PD in August 2023 with 31 teachers who had been in the program between 0 and 4 years. Four teachers did not participate. In this task, we asked teachers to physically stand somewhere between the continuum of structured vs open-ended labs based on how they are implementing labs in their classes. Next, they were asked to reposition themselves according to the type of labs that they wished to do. During this task, the PD facilitators prompted teachers to talk about their approach to lab instruction and why they repositioned themselves.

Addressing RQ3, the data sources focused on developing a case study of Dawn, a novice physics teacher with a biology background in a small rural school who also teaches biology, chemistry, zoology, and astronomy. Dawn had been in the program for two years and showed a shift in her practices toward taking a more open-ended approach in teaching labs. For this case study, we conducted two hours of observation from two periods in Dawn's classroom and conducted a 30-min semistructured interview with her during May 2023. Additionally, we analyzed a 15-min video from an online one-on-one meeting between Dawn and one of the PD facilitators. In this meeting, Dawn talked about her experience of taking an open-ended approach in teaching one lab in her class for the first time. All data for this study was collected within 9 months—between December 2022 and August 2023.

C. Data analysis procedure

The PD video and online planning video were hand transcribed. Together with data from the open-response survey, they were coded inductively with MAXQDA software using grounded theory techniques [56]. Other qualitative data including classroom observation and planning video with facilitator, were not fully transcribed, but some excerpts were transcribed to corroborate with other forms of data. For RQ2, the GIS survey items for each construct were added up, averaged, and plotted. For this survey, we used a paired sample t test to compare the self-reported perspectives of teachers before joining the program (pre) and now (post). The normality of the dataset was assessed prior to conducting the t test using the Shapiro-Wilk test. In the retrospective GIS survey, there was no time gap between the collection of the pre- and postdata. The participants were asked to reflect on their views before joining the program and after it, but at a single point in time.

We conducted a pictorial analysis of the embodied rating task by creating and digitizing two images that represent the two parts of the task. By taking screenshots from the workshop videos, we were able to accurately position teachers along a continuum, replicating where they stood. We then created a second image showing where they moved to when they adjusted their positions. Through these images, we created arrows that indicate their initial and final positions, as well as the direction and extent of change along the continuum.

Qualitative and quantitative analyses were primarily conducted by one researcher (HT). For RQ1, a priori coding scheme based on a review of the literature was used to code 142 segments (111 survey segments and 31 online PD transcript segments), and then the emerging codes were added to the scheme. After initial coding, the final list of nine codes was discussed between authors and

TABLE III. Coded segments of barriers to implementing open-ended labs in physics classes ($n = 21$ teachers). *Mentioned the code only in online PD. **New codes added to the coding scheme after 9 months of initial coding.

Category	Code	Teachers who mentioned the code at least once	Data source
Structural barrier	Insufficient time in class	Lisa, Arnav, Patrick, Daniel, Sabrina, Grant, Veronica, Marcus, Emily, Philip, Dawn*, Susan, Henry	Survey and online PD
	More work for teacher	Henry	Survey
	Large class sizes	Susan, Henry	Survey
	Difficulty in assessment	Patrick*, Emily*	Online PD
	No access to materials**	Marcus	Survey
Teachers' perceptions of students' abilities	Students' lack of interest in investigation**	Amy	Survey
	Students' lack of focus in investigation**	Marcus	Survey
	Students' lack of familiarity with investigative teaching	Patrick, Jeff, Serena, Tony, Philip, Katie	Survey
	Students' lack of confidence	Francesca, Kayla	Survey
	Students' unproductive struggle	Daniel, Sophia, Henry, Patrick*, Arnav*, Lisa	Survey and online PD
Teachers' perceptions of their own abilities	Teachers' lack of content knowledge	Emily, Dawn	Survey and online PD
	Teachers' lack of technological knowledge	Veronica, Dawn*	Survey and online PD

three categories emerged. Nine months after the initial coding, the same coder recoded the data to test the intrarater reliability of the coding scheme. Four instances of partial disagreement led to adding three new codes in the coding scheme (indicated in Table III): Students' lack of interest, lack of focus, and inaccessibility to materials. The intrarater Cohen's Kappa reliability for each of the 12 codes was 0.93. For RQ3, an inductive approach was taken to record one teacher's experience with taking an open-ended approach in teaching labs in her physics class. In her interview and the research team's subsequent coding, the focus was on identifying both the positive and negative experiences that she had with this approach.

IV. FINDINGS

A. RQ1: Teachers' self-reported barriers in taking an open-ended approach in teaching physics labs

The result of our analysis for RQ1—teachers' self-reported barriers—revealed that while teachers showed a genuine interest in adopting a more open-ended approach in teaching labs, they felt hindered by several constraints. In an online PD, an open-response survey, and a rating task, three challenges in implementing an open-ended approach in teaching labs emerged: structural barriers, teachers' perceptions of their students' abilities, and teachers' perceptions of their own abilities. Table III summarizes all codes and categories used in the analysis. Below, we go through each of these three categories in more detail.

1. Structural barriers

Analyzing teachers' statements revealed some structural barriers [27,57] that teachers had experienced or considered in taking an open-ended approach to teaching labs. Some of the most frequently cited structural barriers were limited class time, increased workload for teachers, large class sizes, challenges in assessment, and limited access to materials.

Insufficient time in class was cited most frequently (11 teachers out of 21) as a barrier that hinders teachers' desires to take a more open-ended approach. Depending on the school, teachers in our program had class periods as short as 40 min to blocks as long as 90 min. For teachers with shorter blocks of time, time management was a bigger challenge when it came to taking a more open-ended approach to teaching labs. Many cited how time constraints can become exacerbated by other structural barriers such as large class sizes and short blocks of planning time. For example, some teachers described how time constraints, combined with larger class sizes, can catalyze an even more stressful teaching scenario (See Table IV for stacking barriers). Two veteran teachers (>25 years of physics teaching experience) with large class sizes (>24) describe this stacking effect of structural barriers. Susan, a teacher in a large public suburban school, focused on class size as the main barrier. She highlighted that individual attention and the ability to monitor students' work are key in preventing small flaws in procedural design or data collection that can snowball into a confusing result during the analysis phase. Henry, a teacher in a medium-sized, Title 1 rural setting school referenced the challenges of a populous class that creates more work for teachers taking a more open-ended approach: "[having a more open lab prompt] required work on my end to meet with every group and make sure they aren't going down a path that wastes their time, and it

TABLE IV. Some coded segments that presented multiple barriers.

Teacher name	Segment	Assigned codes	Category
Susan	"Large class sizes and the need for smaller group sizes to maximize student participation make it challenging to help individuals."	Insufficient time in class, large class sizes	Structural barriers
Lisa	"Giving students the time needed to play and try things out is one of the hardest things. We just don't have the large blocks of time that a college class has weekly. There's no way to allow for 3 h of lab time per week; sometimes 1 h is tough to fit in. I also found on a recent lab that a number of groups were using what I would consider to be an invalid set of procedures, but I missed this because I was pushing for them to design their own rather do it my way."	Insufficient time in class Students' unproductive struggle	Structural barriers Teachers' perceptions of students' abilities
Emily	"Part of my struggle is that I lack the background knowledge to steer the students in the right direction without giving too much guidance. It also takes so much time."	Insufficient time in class Teachers' lack of content knowledge	Structural barriers Teachers' perceptions of their own abilities

is harder now that my class sizes are larger this year." This quote was coded as indicating both "insufficient time in class" and "more work for teacher" as the named barriers.

2. Teachers' perceptions of their students' abilities or feelings

A total of 14 teachers (66.6%) cited students' abilities in dealing with investigative-style challenges as a barrier to implementing open-ended labs. Hence, teachers advocated for more guided and structured labs with prescriptive procedures to support students in reaching scientific conclusions. Survey data also revealed that teachers' low perceptions of their students' *abilities* were related to:

a. Students' unfamiliarity with investigative science learning approaches (six teachers),
b. Students' "unproductive struggle" when completing labs with fewer scaffolds (five teachers), and
c. Students' lack of interest, focus, or confidence, which leads to anxiety and giving up on lab tasks (four teachers; see Table III).

However, at the same time, teachers expressed a desire to train students to tackle the challenges of investigative approaches, if the time barrier was absent.

Examples of teacher statements on how students' lack of familiarity with investigative science learning is a challenge for open-ended labs include: "Students are not often asked to be creative and have difficulties setting labs up from scratch," or "I think it's very hard for students who are not used to this to adjust." These statements described student discomfort that stems from the lack of prior exposure to more open-ended tasks in their education. Similarly, Katie wrote, "the lower-level students haven't gained the inquiry skills to be 'set free' just yet. I believe it could still be a product of the COVID years […] but students struggle immensely with answering open-ended questions, let alone designing an open-ended lab."

Among the teachers who referred to students' struggles in handling more open-ended style labs was Tony, a novice physics teacher who, despite his genuine interest in open-ended approaches, believed his students "do not even know where to begin." The same concern was also raised by other teachers, like Patrick and Arnav. Patrick believed students' struggles become "distracting" and will eventually eat up so much of class time. To help them stay on track, Henry noted that teachers often take on additional work "I find that if I don't make students call me over when they are analyzing the iOLab graphs, they will misinterpret the data, at least at the early part of the semester." However, like most of the teachers in the program, he still saw benefits in incorporating such labs, at least in theory: "Another reason I like open-ended labs is the students sharing what they've learned at the end, and theoretically there's more learning in the class if the students are all answering slightly different questions."

Teachers also reflected on students' *feelings* when taking a more open-ended approach, reporting feelings of student frustration or anxiety when they had tried a more open-ended lab task. For instance, Kayla and Tony found that a motivating factor in their use of more prescriptive labs is that this style can offer students a solution to a problem after just 45–60 min, thus boosting their confidence. This reduces the risks of student frustration and provides students with a more satisfying sense of closure and success each class period. Amy recognized that taking a more open-ended approach requires significant scaffolding, but also that there is a point at which the tasks become increasingly closed when scaffolding begins to pass into a territory that feels more like handholding. Amy expressed frustration with trying to implement labs that challenge student expectations, "When I try to take away some of the scaffolding, the kids in 3rd and 7th period just sit there and stare at each other. They have no interest in exploring, they just want a recipe to follow." Kayla also mentioned, "open-ended or less structured labs can be a challenge because students tend to be not confident in the material, which leads to students more frequently giving up." Patrick works in a small, rural setting Title 1 school and faces similar challenges. In the online PD session, he described concerns about making his lessons too challenging and "scaring students off," referencing a culture of avoiding academic challenges in his school community. In the survey, Patrick cited concerns about multiday investigations that may not yield sufficiently impactful conclusions to justify the time invested. Serena, with a small class roster like Patrick, considered scaffolding as a silver bullet that can reduce student anxiety while navigating looser lab structures. She wrote, "I find that most students become anxious when they don't have step-by-step procedures on a lab handout. From my experience, this highlights the work teachers must do to help students become comfortable with productive struggle." She referenced "productive struggle," noting that it is a teacher's job to "help students become comfortable" by exposing them to these more open tasks. It is worth noting that in the year of the survey, Serena had a class of less than ten students and may have felt more confident in her ability to provide effective real-time scaffolds to her students as a result.

3. Teachers perceptions of their own abilities

The third category of barriers in our analysis is teachers' perceptions of their own abilities, which refers to their perceived gaps in content (Physics) and/or technological knowledge (iOLab proficiency). This concern was most strongly articulated by two novice teachers holding non-physics degrees. During the online PD, these two teachers saw their insufficient physics content knowledge as a barrier to taking an open-ended approach in teaching labs. They were mainly worried about the content-related questions coming from students during lab work that do not follow a rote procedure that they can prerehearse. They referred to their potential inability or uncertainty in quickly and correctly answering questions that may spontaneously arise in an open-ended lab setting as a significant barrier: "Part of my struggle is that I lack the background knowledge to steer the students in the right direction without giving too much guidance. It also takes so much time."

Similar to their concerns about the inability to provide immediate feedback to students' content-related questions described above, teachers expressed concerns about technology-related questions that might come up in more open-ended lab styles. Teachers cited the possibility of students choosing from multiple iOLab sensors to complete the same open-ended activity, which would require teachers to be proficient with multiple sensors and methods that may come up. While teachers appreciated having access to the U of I team, they still found the delay of up to 24 h in getting a response too long for their students. As Dawn stated, "[students] need the right answer right away, and they can't wait."

4. Multiple barriers at work

In the survey, teachers commented on taking an open-ended approach in a way that revealed the interwoven nature of structural and/or perception-related barriers in teaching labs. The "Insufficient time in class" barrier is the common thread in these connections of barriers. Table IV shows examples of responses for which barrier codes from different categories were assigned along with "Insufficient time in class." The examples show how other barriers can stack on the time barriers to make it more significant. For instance, Susan worries that large class sizes make it hard to support individual students, which is further tied to insufficient class time. Similarly, Lisa fears running out of time due to her perception of students' abilities, while Emily's concern stems from her own sense of competency.

Our analysis also revealed that teachers' instructional lab goals were central to the selection of lab styles. For instance, during the online PD, Emily talked about a teacher's lab goals as a factor that can determine how teachers pick a particular style of lab over another. Other teachers in attendance nodded in agreement when Emily said, "A lot of [teacher decisions] come to the ultimate goal of the lab. Sometimes my goal is just to take data and apply the data in specific ways. But sometimes the goal is to assess a specific problem. I think all types of labs have a place in science. Sometimes you need them to analyze something to eventually be able to do an open-ended lab." Moreover, some teachers, like Patrick, placed a philosophical emphasis on concluding a topic or reaching a final group conclusion aligned with a physics-specific learning goal within a single class period. Even experienced teachers with a strong drive to promote student creativity and critical thinking felt conflicted about how to strike a balance when confronted with time constraints. For instance, Lisa wrote about wanting to allow students to "play" but also finds this challenging in a single 1-h period.

However, these teachers saw these barriers as surmountable with the right strategy or shift in mindset about instructional goals. As part of the sharing in the PD, some teachers embraced the messiness of open-ended labs in the high school setting as a learning process. For example, Philip viewed the goal of early iOLab experiments as teaching students to become comfortable tinkering in the lab, as opposed to teaching them neatly packaged physics concepts that fit within canonical textbook physics. Yet, at the same time, he articulated the process of student learning as a long game that often benefits students in subsequent years.

B. RQ2: Shifts in teachers' perceptions of taking an open-ended approach in physics labs within a physics teaching community of practice

For RQ2, we explored teachers' perspectives on taking an open-ended approach in teaching labs using the Guided Inquiry Scale [41] survey, and an in-person embodied rating task. The Guided Inquiry Scale (GIS) survey was

TABLE V. Paired-sample *t*-test results of GIS survey with 14 teachers.

Measure	Before IPaSS mean (SD)	After IPaSS mean (SD)	t value	p value	Cohen's d
Value of guided inquiry	3.43 (0.92)	4.52 (0.37)	4.84	<0.001	1.3
Limitation of cookbook style labs	3.32 (0.82)	4.20 (0.72)	4.83	<0.001	1.2
Implementation of guided-inquiry labs	3.14 (0.77)	3.84 (0.55)	3.55	0.004	0.95

administered at the beginning of the fourth IPaSS summer PD. At this point, cohorts 1–3 teachers had been in the program for at least one year, so we were able to gain insights into their perceived changes in attitude toward open-ended approaches in teaching labs as a result of participating in the program. To this end, we administered the survey in a retrospective form [53,54] and asked them to answer each item as they were thinking about it before joining the program and at the moment of completing the survey. The results are presented in Table V.

1. Survey results

The GIS survey measures three constructs: the value of guided-inquiry labs, the limitations of cookbook style labs, and the implementation of guided-inquiry labs. The Shapiro-Wilk test indicated that the data were normally distributed for all variables ($p > 0.05$) allowing for the use of a t test. The result of the t-test is shown in Table V. Paired-sample t test results reveal a change in teachers' value of guided-inquiry labs, limitations of cookbook style labs, and implementation of guided-inquiry labs during their engagement with the program for these physics teachers at a $p \leq 0.004$, with d ranging from 0.95 to 1.3. This indicates that the 14 sampled teachers perceived an increase in their value of open-ended inquiry labs after participating in the program. Additionally, teachers' awareness of the limitations of cookbook style labs increased over time. Finally, the results also revealed more positive perceptions related to implementing guided-inquiry labs. It is worth noting that the GIS survey constructs differentiate between guided-inquiry style labs and cookbook style labs, and we are not equating guided inquiry with open inquiry. What is important here is that we are investigating teachers' preferences in terms of shifts in taking a more open-ended *approach* which can have different levels of scaffolds as opposed to implementing open-ended style labs.

2. Rating task results

The embodied rating task was administered after we learned about teachers' valuing of taking open-ended approaches (in GIS survey) and perceived challenges (online PD and open-response survey). This in-person task included teachers who had joined the program at any point in the first 4 years of IPaSS. This task took place at the fourth summer PD and gave us a sense of how far teachers felt they were from meeting their future goals concerning open-ended approaches in teaching labs. The task required teachers to line up twice. First, they were asked to position themselves according to where they believed they currently were in terms of teaching physics labs, with the left side of the room representing open-ended labs and the right side representing structured labs. The second time, they were asked to stand where they desired to be on this spectrum when teaching labs in their class.

The main result is that teachers mostly wanted to move more toward open-ended lab approaches than where they currently were. Figure 3 depicts teachers' movement between where they were and where they desired to be in teaching physics labs. Names are placed at the teachers' starting point. The end points of the arrows indicate where the teachers wish to be. The majority, i.e., 19 out of 27 teachers moved to the left toward open-ended labs.

By contrast, seven teachers did not move from their initial positions, indicating that they were content with their lab style at the time of the rating task. Out of these seven teachers, three teachers were closer to the structured end of

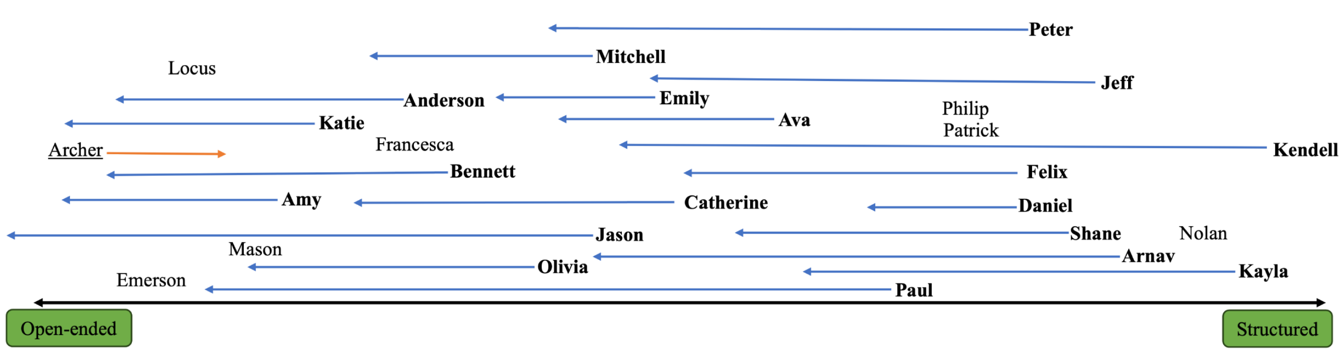

FIG. 3. Teachers' movement between their current and desired positions in teaching physics Labs.

the continuum (Nolan, Philip, and Patrick), and four teachers were closer to the open-ended end (Emerson, Locus, Mason, and Francesca). Archer, who was currently at the extreme side of using open-ended labs, moved slightly to the right, indicating a desire for a little more structure.

Even teachers who desired more open-ended labs in their courses may have stayed closer to the structured end of the lab continuum, indicating barriers to fully buying into the value of open-ended labs in their courses. For instance, Kayla moved towards wanting more open-ended labs but still remained closer to the structured side. Kayla explained, "what I have found from nine years of teaching is that different classes have different needs and if you want them to actually get something out of the lab, I have to very clearly structure it in a way that they're going to get something out of that lab. Because I have students that do open-ended labs they are like that was fun and then I'm like what did you learn and they don't tell me anything."

C. RQ3: Evidence of change from a more structured lab to a more open-ended approach: A case study

Next, we present a compelling case of a teacher whose perceptions and practices showed a change. Dawn is a relatively new teacher with two years of experience in teaching physics in a rural high school at the time of data collection which happened during her second and third year in the PD program (during her first year, she was not teaching physics). Dawn, who holds a degree in biology (out-of-field teacher), initially gravitated toward structured labs driven by a belief about her deficiencies in physics content and technological knowledge particularly with the iOLab device. She talked about these knowledge deficiencies in an online PD session. Five months later, when we approached her to schedule a classroom observation, she surprised us by opting to run an open-ended inquiry lab for the first time in her class, even though it was not a requirement for PD observations. She adopted a lab that simulates measuring the relative size of an exoplanet as it travels in front of a star. In the lab, a lamp has the role of a star, the iOLab serves as a telescope, and beads represent exoplanets. Students are tasked with measuring the size of the beads (exoplanets) with the iOLab (telescope). This version had been used previously by another IPaSS teaching fellow (who is not among the participants in this study) at a Title 1 town school. Students are asked about the size of the unknown planets (beads) by comparing the reduction in light to known planets (beads). For this lab, students had access to iOLab devices, beads, lamps, strings, and other standard classroom equipment, such as measuring tapes and rulers. Although Dawn offered structure in this lab activity, she perceived this lab as a significant shift towards open-ended approaches in her class compared to the typical step-by-step cookbook style labs she uses. Below, we present the results of documenting her shift during her journey as an IPaSS teaching fellow.

1. First-time implementation of an open-ended lab: Challenges and opportunities

The lab took two class periods, of which the first period was observed. Dawn started the class by stating the lab goal: determine the size of an unknown exoplanet with the iOLab. Then, Dawn showed students a picture of a possible setup and talked about lab report requirements. Video data from the observation and observation notes confirmed that Dawn was taking a more open-ended approach than was typical for her. Although this lab activity was more open-ended than those Dawn typically uses—requiring students to determine the investigation design—it still maintained structure in the following ways. First, the investigation question ("what is the size of an unknown exoplanet?") was posed by the teacher and not by the student. Student-generated questions are a feature of more open-ended style labs [31]. Second, by showing an example of a possible setup, including the iOLab light sensor, lamp, beads, and reference "exoplanet," the teacher scaffolded the students' design of the lab. Third, the teacher provided some guidance to students throughout the lab without spelling out the details of the prototypical experiment. For instance, the teacher hinted that the beads should be installed on a level surface, and they should be moving, just like real exoplanets (see Fig. 4 for an example of a student lab setup). Hence, while offering more opportunities for student-led design than the typical directed cookbook style labs used in her course, Dawn incorporated significant structure and guidance.

During our postobservation online meeting, the first author (HT) conducted a semistructured interview to prompt Dawn to talk about her experience and feelings about conducting the lab in her class. HT started the interview by expressing gratitude and excitement about the visit, then asked for her overall impression of the lab.

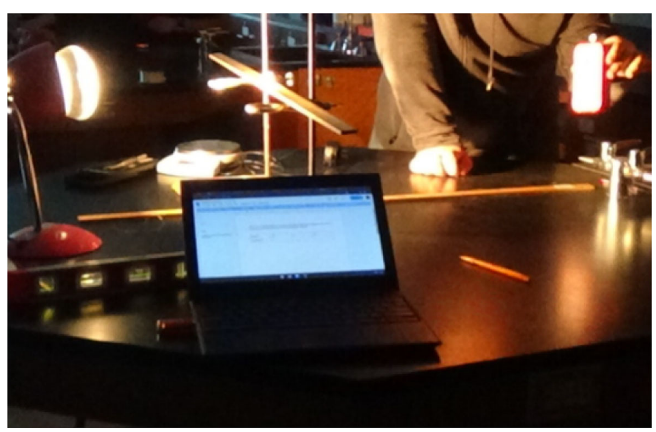

FIG. 4. An example of a student's setup for determining the size of the exoplanet with iOLab.

Dawn initially mentioned that things went "pretty good," but she made sure to provide a balanced perspective by pointing out both positive aspects and challenges. One concern she raised was with the lab reports, which she described as "a little scary" because it was the students' first attempt." However, she also shared that some students got good data, which was encouraging for her. She then explained the difficulty in getting students to set up the lab correctly:

> I had quite a few that I kind of had to steer more. Like they were just having the planet hang in front of the sun. And so I was trying to get them to… It needs to move. Exoplanets move, right? So, a few of them I had to push a little bit further on that. They didn't quite have that thought process.

In the next prompt, HT tried to capture Dawn's feelings about this lab by directly asking her how it went compared to what she expected. In response, Dawn shared that her expectations were higher and that she thought the setup would be easier for the students:

> I mean it probably went worse than I thought it would. I thought that it would be obvious to how to move the exoplanets across the sun…So I just, I don't know. I just kind of assumed that they would all figure that out, especially when I even had the picture of the little person with the string like this, you know so…. so that was a little, I mean I wouldn't say disappointing, but you know I expected more.

It is possible that Dawn was thinking of this lab as an easy one to start doing open-ended labs, but the experience somehow went against her expectations. Revisiting the topic of lab reports, Dawn took responsibility for not providing enough scaffolding and not preparing the students adequately before the lab.

> And then, like I said with the lab reports, they were pretty awful. Just honest, right? But I feel like I hadn't given them enough scaffolding to get them to a great lab report, because, like I said, they had hardly written anything in physics, so I think I needed to scaffold it more throughout the year before just throwing it on them.

After hearing Dawn's frustrations with the lab reports and lab setup, HT asked whether she would be interested in repeating similar lab styles in her class. She quickly responded to this question with confidence in her voice:

> Oh, yeah, uhm. I even looked into buying more lamps with my school money this year, so that I can do it with astronomy next year.

HT then asked a follow-up question about what made her confident in repeating this style of lab despite the challenges. Dawn highlighted a few interesting points. First, she emphasized the value of observing students' thinking processes, which she attributed to the "openness" of the task: "I liked watching them think" or "I loved them be able to think and kind of discuss it with each other. That's always fun." Dawn also reflected on how allowing students to figure things out on their own is a valuable exercise for her, despite the challenge she faces in resisting the urge to intervene: "And it is difficult for me very much not to tell them how to do it. (laughing) Like, do it!"

Second, she talked about the importance of having students do the lab with the iOLab device, especially if they attend U of I:

> And I liked using the iOLab being able to use the iOLab more just because I have so many students that end up going to U of I, maybe not in physics, but they do end up going to the U of I, and if they do end up going into physics at U of I, [it] would be nice if they already have the iOLab knowledge, experience. So, I like that.

Third, she brought back the issue of poor lab reports, this time attributing the problem to a bigger issue at the school level, where students haven't been adequately prepared across all science subjects:

> I think in our school we have not done well at teaching lab reports, and so I think some of our students are going to already start behind in college if they are in a science major. So, I'm hoping to kind of start building that a little bit more into my upper chemistry, like my chemistry and my zoology and astronomy and physics, so that they can have more experience with it.

2. Shift in perception-related barriers by deemphasizing the "right answer" and disrupting the "perfect teacher" image

Five months before Dawn's exoplanet lab class session, Dawn attended an online PD (data collected for RQ1 of this study) in which we asked teachers to talk about their approaches to teaching physics labs. When teachers started talking about open-ended and structured labs, Dawn shared her perceived barriers, related to a lack of physics and technology knowledge, preventing her from deviating from structured labs:

> It's knowledge-based, and I don't know physics enough to let them just go, because then they ask me questions, and I don't know the answer to it. And so, it's a comfort level, definitely having it laid out. And that especially not only, I don't

> know the physics necessarily, I also don't know the iOLab. So, if something goes wrong, I don't understand why it's, you know, showing something.

During the interview, when HT reminded Dawn of her initial concerns, she reiterated them, adding, "I think it's always daunting." However, this time she talked about two approaches that made her confident to take a risk and try a more open-ended approach in her class. First, she talked about the importance of deemphasizing the "right" answer by taking an iterative approach: taking data, improving the experiment, and repeating the data collection:

> And so doing this lab, specifically, with it, it really helped like maybe they didn't get the right answer. And I kept telling them, you know, it's okay if you don't get the right answer as long as we get the actual data, and we don't fudge our data, right? (laugh) And we get the conclusions from the data. And we learn to improve the experiment. And so, I think that just even having the experience like it gave me a little bit more confidence in being able to do that,

On a related note, Dawn talked about accepting losing control and letting students use a different approach than she would have used:

> I didn't know if the hanging down planet not moving would show the same results as a moving planet did. and so just letting them do it and let's see, you know. And it was okay, and it worked, and so and, but, I could show them. You know that your data wasn't as accurate as this one's data because his [planet] was moving. You know, so.

The second approach that boosted Dawn's confidence involved disrupting the notion of "perfect teacher." Seeing more experienced teachers in PD sessions who are still in their learning journeys shifted Dawn's perception away from waiting to accumulate more experience before taking a more open-ended approach:

> I mean definitely seeing that even extremely experienced teachers don't have it all and don't know it all. I would think that all of the teachers in this PD would tell you they don't know it all, and they don't teach perfectly, and they aren't…. I would say, even most of us probably wouldn't even say that we're good teachers, which is to say like we do what we can. I don't want to call them old because they're like 10 years older than me, but you know, like Arnav, saying that he has so much to learn, and he is so close to retirement. And it's like realizing that the perfect teacher that I've built up in my head does not exist, and you don't have to be perfect to start. That we are still learning. Yeah, every year, even our last year, before we retire, you know. Carl was retired. So, you know, he was learning up until so.

Being a Teaching Fellow in the IPaSS CoP and witnessing that even experienced teachers sometimes encounter challenges changed Dawn's perceptions about herself and her capabilities. Seeing the experience and knowledge gap diminish, Dawn now thought she was as competent as other teachers, and if they could take a more open-ended approach, so could she.

Along the same lines, in the open-response survey (collected for RQ1), Dawn emphasized the importance of learning from teachers in the IPaSS community:

> [The IPaSS community] has helped me immeasurably. First and foremost, helping me understand the physics better. Second, hearing all the different ways of the approach to teaching. I feel like I have learned how to step back more (still need a lot of work) and let them [students]figure things out.

3. Sharing the experience with the community

Before the summer PD, IPaSS teachers are encouraged to present something from the past school year at the PD. To help teachers with this process and ensure that the summer PD program is coherent, PD facilitators and teachers have meetings in spring to plan teachers' presentations. The 13-min planning meeting with Dawn was recorded, partially transcribed, and analyzed. Dawn chose to present her exoplanet lab to her colleagues. One thing she mentioned in the meeting was how giving students the liberty to come up with a design gave rise to many different ways of doing the lab: "I wish I had taken more pictures when the students were doing it because some of them came up with some different ways of doing it." In the planning meeting, it was determined that Dawn would share the student brainstorming phase with her IPaSS peers, so they could get a sense of how she starts the lab.

Dawn claimed that the IPaSS CoP convinced her that it is okay not to be "the perfect teacher," and this gave her confidence to conduct a more open-ended lab style. Dawn's successful transition to taking a more open-ended approach in her class with the observation of students' different ways of doing it allowed her to showcase it as a successful example to other physics teachers in the community. In the in-person PD session, Dawn introduced her adapted lab and talked about this experience as a successful investigation example illustrating students' scientific thinking. This case study illustrates how important the influence of a CoP can be on teachers like Dawn, facilitating transformative shifts in perceptions that are reflected in classroom practices.

V. DISCUSSION

In this work, we investigated the barriers to taking a more open-ended approach in teaching labs among high school physics teachers after removing some prevalent barriers such as lack of access to lab equipment and a community for support. We further examined the role of the community in instigating change among teachers and documented a case illustrating a novice teacher overcoming seemingly persistent barriers.

A. Barriers to taking an open-ended approach in teaching labs in physics classes

This study revealed that, despite having access to a Community of Practice (CoP) for support and the iOLab to facilitate an open-ended inquiry approach, teachers continued to face structural and perception-related barriers when trying to shift from a structured lab format to a more open-ended approach. These barriers are consistent with those identified in previous research, where teachers did not benefit from social and material support [57,58]. Regardless of their experience or expertise levels, teachers reported facing structural barriers, perception-related barriers, or a combination of both. The results also indicated that perception-related barriers concerning teachers' views of their own physics content and technological knowledge are primarily found among novice teachers with nonphysics backgrounds. Experienced teachers and those with physics backgrounds found structural barriers, such as short class periods, to be more problematic.

While a common approach to mitigate novice teachers' concern about inadequate content knowledge might involve simply teaching novice teachers specific physics content, this method may not fully instill the desired level of confidence in their teaching abilities. Our case study illustrates how teachers can build confidence within the CoP even without mastering every aspect of the content. By observing more experienced teachers and faculty in physics who are still learning and acknowledging that learning is a collaborative process where people with different levels of knowledge can grow together, novice teachers can feel more assured in their abilities. For example, Dawn no longer waits to achieve a certain level of knowledge or experience before adopting a more open-ended approach. Instead, she embraces the risk, understanding that she does not have to be the perfect teacher, and does not attribute any lack of success to her background. Another important finding in the case of Dawn was that when perception-related barriers were addressed, structural barriers could be subsequently resolved more effectively. Therefore, perception-related barriers held greater significance in this case. Once she overcame her content and technological barriers, she no longer reported a lack of time in class for taking an open-ended approach. This finding could possibly extend to other teachers' contexts and experiences and could be the focus of future work.

B. Impact of professional development and support on changing teachers' perceptions and practices

Different data sources in this study revealed that physics teachers increasingly valued and wanted to take a more open-ended approach in teaching labs during their participation in IPaSS CoP. The retrospective survey results show that teachers perceive increasingly valuing guided-inquiry labs over cookbook-style ones during their time in the teacher CoP, and, despite their growing awareness of the challenges of implementing guided-inquiry, the embodied rating task showed that most teachers wanted to incorporate more guided-inquiry labs in their teaching. Because open-ended lab instructional materials and pedagogies were a significant focus of the teacher CoP's work, it is reasonable to hypothesize that participation in this teacher CoP supported these shifts and the desire to implement more open-ended labs.

In addition, the case study of Dawn goes beyond these self-reported shifts and desires to shift toward a more open-ended approach to illustrate the mechanisms through which teachers can get help from the community, overcome barriers, and change their practices. First, we learned that the vulnerability displayed by experienced teachers helped disrupt the view of the "perfect teacher" for novice teachers like Dawn. The case study results revealed that just being in the community and interacting with more experienced teachers do not guarantee change. What instigated change for our novice teacher, was witnessing the learning journeys of veteran members with all the challenges and failures they still face. Disrupting the image of a "perfect teacher" for Dawn was an inflection point where she found herself confident enough to take risks in her class. The specific examples of Arnav and Carl that Dawn mentioned here are the stories of more experienced teachers sharing vulnerability that helped in the same way. This builds on our previous work in the same program that demonstrated the importance of showing vulnerability by veteran teachers in opening communication doors toward better learning and support [59].

Second, we learned that teachers need time to develop trust with the CoP for the change to happen at the perception and practice levels. Some teachers need a significant amount of time to feel comfortable making sustainable changes to their practices. For Dawn, this duration was as long as two years. Depending on teachers' background and the structure of the PD and community activities, this duration may vary. Hence, the benefits of community involvement do not arise immediately after joining or by membership in a community per se. This work adds to the literature in favor of prolonged PD for in-service teachers [60] by emphasizing the importance of prolonged PD activities in a responsive way for novice teachers and teachers with diverse science backgrounds.

C. Considerations for designing professional development

Several studies in the literature underscore the importance of professional development for supporting reform-based teaching practices by using strategies such as weekly meetings, presemester workshops, and building a community of learners [19,24,43,44]. While echoing these recognized strategies and designing them into a prolonged PD, we argue that giving teachers epistemic agency [61,62] -cognitive authority to decide which knowledge is valuable [63] in their context—by flexible implementation of materials is key. In this approach, which we call responsive professional development elsewhere [64], we encourage PD designers to attend to teachers' needs and design PD experiences based on those needs. One manifestation of attentiveness, highlighted in Dawn's narrative, involved the flexible implementation of materials without requiring her to follow a prescribed timeline. This flexibility offered Dawn an absorption period that lasted for two years before she decided to implement an open-ended approach in teaching a physics lab. We surmise that this flexible approach from PD facilitators may be a particularly important component in supporting novice teachers and those with nonphysics backgrounds. Future works should consider PD structures such as *flexibility* in studying teacher perception and practice change.

To support teachers in removing some structural barriers, it is important to have them practice taking a more open-ended approach in doing labs during PD sessions. Considering the importance of this strategy, the IPaSS program, created designated time and space during in-person PD sessions for teachers to try new ways of doing labs before testing in their classes. We suggest that PD programs focusing on labs encourage teachers to work through the labs in as many different ways as they can consider prior to implementation, and build space to do so in the PD. Additionally, programs could benefit from creating a repository for each lab where teachers can document pedagogical, technological, and physics content challenges that arise during implementation so that teachers implementing that lab in the future will begin with a solid baseline.

VI. LIMITATIONS AND FUTURE RESEARCH

One limitation of this study is the retrospective nature of the GIS survey, which required teachers to reflect on their experiences before joining the IPaSS community. While this approach enables an evaluation of change over time, it introduces recall bias, a common challenge in self-reported surveys. Additionally, teachers may respond in ways they perceive as desirable to researchers, given their awareness of the professional development activities and the emphasis on open-ended lab instruction promoted by the U of I team and other teacher advocates. To address this limitation, future research could integrate multiple data sources to strengthen the validity of its findings. Conducting pre- and postsurveys would capture shifts in participants' beliefs in real time, reducing reliance on retrospective reflections. Interviews could further clarify teachers' reasoning behind their survey responses, providing insight into whether their reported beliefs stem from genuine pedagogical thinking rather than social desirability bias. Moreover, collecting classroom data on teachers' implementation of open-ended labs would allow researchers to examine whether reported shifts in pedagogical beliefs correspond to actual changes in instructional practice. Given that teachers' perceptions of their instructional practices may differ from their enacted pedagogies, triangulating survey responses with interviews, classroom observations, and rubric-based analyses can provide a more accurate and comprehensive picture of teachers' instructional shifts.

A second limitation involves the embodied rating task administered in this study. Social desirability bias may have been involved, as participants reported their attitudes publicly within the community. While teachers appeared comfortable acknowledging that their labs are structured, some may have presented themselves in a manner they believed would be perceived more favorably. Again, analysis of teachers' reasons for their choices in this rating task would provide more support that these ratings reflected more in-depth pedagogical thinking rather than socially driven decision making. Similar to survey limitation, collecting data on classroom practice can help show whether teachers act on these self-reported desires to shift lab pedagogies. In our case, we note that teacher self-report may be insufficient to capture teacher practice accurately. For instance, Dawn described her lab as open ended, but the researcher's observation identified the ways in which it was more open ended in style, yet still highly scaffolded. Future research could explore this issue by using observation rubrics that assess the degree of openness [65] to better understand the discrepancies between teacher perception and practice.

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DATA AVAILABILITY

The data supporting this study's findings are available within the article.

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