Implementation of the photovoice methodology in a project-based upper-division physics course

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Photovoice is a type of participatory action research in which individuals document their experiences through photography. Through the taking, captioning, and reflecting on photographs that they have taken, participants are able to affect change within their communities. Participants also take part in an interview or focus group about their photos at the end of the photovoice process in which they determine themes that appear in their photos, allowing them to participate in the research being done. We used the photovoice methodology in a small, project-based, upper-division, physics capstone course at the University of Colorado Boulder, in which students worked on an authentic industry project in partnership with a company in the quantum industry. As an example of the types of research results and benefits one could obtain using photovoice, we present a discussion of how we implemented the photovoice process within this course and present some of our results, including students' experiences with the photovoice process. Photovoice may be particularly useful in understanding new, unique courses, as it allows students to co-create research that highlights ideas about the course that researchers would not know to ask about in more traditional research methodologies such as reflection questions.

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I. INTRODUCTION

Participatory action research (PAR) is a type of research that seeks to involve participants and researchers together in examining a problem and improving it [1,2]. As a type of PAR, photovoice enables participants to collaborate with researchers to affect change in their communities by participating in the taking of, captioning, and reflecting on photos [3]. In photovoice, participants take photos using a camera or a cell phone and reflect on their photographs either through captions or discussions with researchers. In the past, education researchers have used photovoice to provide empowering experiences for their students, as well as to gain new ideas about a wide range of student experiences, including student definitions of success [4] and access to higher education [5]. Finally, photovoice has been used as a pedagogical tool within a course about diversity [6].

Within physics courses, photovoice has been used to improve student learning and connection of physics to their everyday lives [7]; however, to our knowledge, it has not been previously used to study student experiences. It is also not a widespread methodology within physics courses, although it has been suggested as a tool for physics education researchers [4]. We therefore decided to implement the photovoice methodology within a small, upper-division physics capstone course called Quantum Forge (Q-Forge) both to improve the experience for students in the course and to explore this methodology in a new context. In this course, students partnered with a company in the quantum industry to collaboratively work on a real-world project. Photovoice was used to study students' experiences with teamwork, views about the quantum industry, and their experience with the course overall. This provided students the opportunity to participate in PAR with the goal of affecting change within the Q-Forge course while also contributing to answering our more traditional research questions related to these topics.

Because this is a new context in which this methodology has been used, our goal for this paper is to detail an implementation of photovoice in an upper-division physics capstone project course. We aim to communicate the unique aspects of our implementation, as well as to document how the students responded to this methodology and what types of results we achieved from implementing photovoice. We do not intend to present here a full analysis of our photovoice data; rather, the results presented here

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should be interpreted as the type of data one can obtain from using photovoice in a similar context. This may motivate future instructors and education researchers to consider incorporating photovoice or similar types of PAR into their own courses and research.

In this paper, we first present some additional background on photovoice (Sec. II), the context of the course in which we enacted this methodology (Sec. III), and a detailed section on how we implemented photovoice within this course (Sec. IV). Then, we address the methods we used to analyze the data we obtained (Sec. V) and move into some outcomes of our implementation of the photovoice methodology (Sec. VI), including both student reactions to the photovoice process and some of the themes that the student photos contained. We conclude by listing recommendations for future implementations of photovoice (Sec. VII), summarizing the outcomes of this implementation, and presenting some future work that will be done using these data, as well as future directions for research on the use of this methodology in physics courses (Sec. VIII). This work builds on our previous work detailing the results of student discussions about the photovoice process [8].

II. BACKGROUND

A. Participatory action research

PAR differs from traditional research in that its explicit aim is to affect change rather than to gather information [9]. The term "action research" was introduced in 1946 by social psychologist Kurt Lewin, who described it as "a cyclical process of planning, acting, observing, and ultimately reflecting on the action" [1,9]. While there is no singular definition of what constitutes PAR, the commonalities among definitions are that researchers and participants collaborate to address a problem and affect real-world change [1,9–11]. PAR seeks to explicitly change the paradigm around who has valuable knowledge by working with marginalized or vulnerable community members to do research and affect change in the community [1]. It treats participants as competent individuals who are able to engage fully in the research process in an effort to decentralize power from the researchers to the community of interest [1,9].

There are several advantages, as well as disadvantages, in implementing PAR. The advantages include that PAR has the opportunity to affect positive change in the community, it is collaborative, and it centers on the individuals being researched rather than centralizing the researchers. The disadvantages include that the community being researched may disagree on the problems to be solved and how they might be addressed, as well as the fact that the democratic research process may lead to competing agendas [9].

PAR has been used in educational contexts in the past as a way to value student voices [12–15]. For example, PAR has been used to allow high-school social science students to research issues that affect their communities [15], to investigate access to higher education in South Africa [5], and to involve students in a project investigating the effects of a school closure in their community [13]. These studies allowed for voices that are usually marginalized to be centered within the research process, leading to research results that highlight unique local knowledge [5,13,15]. PAR encompasses a wide variety of research techniques, and these examples of PAR are different from photovoice in that the students do not document their lives using photography. Nonetheless, these examples demonstrate how students can be involved in research where the explicit aim is to affect change in their community.

B. Photovoice

Photovoice was developed by Caroline Wang and Mary Ann Burris in the 1990s. It was originally developed as a tool for the promotion of public health and has been popularized within this context [16], but it has also been used widely in other contexts such as the social sciences and education [17].

Borrowing from three distinct theoretical frameworks, empowerment education for critical consciousness, feminist theory, and documentary photography, photovoice is action oriented and participant centered [18]. Empowerment education is based on Wallerstein and Bernstein's [19] application of Paulo Freire's ideas [20], which are based on the idea that education begins with the central issues in people's lives. Through discussion, empowerment education seeks to enable individuals to identify shared issues in their lives and then create individual, community, and institutional change [18]. Photovoice uses the theory of empowerment education because the photos begin this discussion of important issues in a community and empower individuals to identify and address their shared issues [18,19].

Another aspect of the theory behind photovoice is feminist theory. Feminist theories are diverse, but one thing they have in common is that they critique the assumption that women are not autonomous actors in the world [18]. Photovoice embodies feminist theory by treating women as authorities over their own lives and their experiences as valuable to the community at large. Photovoice originated as a methodology used primarily with women, and it aligns with Rhoda Linton's six characteristics of feminist activities that include cooperative group activity being central and the need for freedom from the *status quo* [18,21].

Finally, photovoice is based on the theory of documentary photography, which uses the visual image to document a wide variety of social factors that impact communities [22]. Photographs have the potential to be a powerful tool for research due to the fact that they contain enormous amounts of information [23]. Photovoice uses this same idea as documentary photography but counters it by putting

the camera in the hands of the people who would otherwise be photographed and allowing them to be the recorders of their own experiences [18].

There are three main goals to the photovoice methodology. The first goal is to enable people to record and document their community's strengths and concerns. The second is to promote critical dialogue about community issues through discussion of the photographs and the third is to reach policymakers [3].

Several advantages in using photovoice as a research methodology exist, in addition to the benefits of PAR as a whole. They include that it places value on knowledge owned by community members rather than researchers, it uses the power of the visual image to describe the experience of individuals, and it can depict not only community needs but also community assets. Furthermore, photovoice can allow participants to have a sense of ownership over their photographs as well as the research by engaging them with the tool of the camera [3].

While photovoice is an incredibly powerful tool for affecting social change, it does have its limitations. For instance, photovoice is a subjective tool where what participants choose to photograph (and not to photograph) affects the research outcomes. Furthermore, photovoice may reproduce traditional power stratifications. Despite placing the camera in the hands of the community members, financial support, and ultimate control over the research remains in the hands of those in power. According to the developers of the photovoice methodology, this fact requires additional scrutiny in order to ensure that the participants are truly being valued as co-creators of the research [3]. Additionally, photographs are a difficult medium to analyze and scalability is a continued concern for the application of photovoice [3].

Photovoice has been used in a wide array of contexts, predominantly in health, social science, and education. Photovoice projects are usually relatively small, ranging from roughly 5 to 20 participants [24], who can vary in age from adolescents to seniors [25]. Within an educational context, participants in photovoice projects are often students [24].

C. Examples of photovoice

Photovoice as a concept was utilized for the first time with the Yunnan Women's Reproductive Health and Development Program. This program took place in the Yunnan region of China. Facilitators there asked women to photograph "the spirit of village women's everyday lives." Over the course of 3 days, the women each took a full roll of film, discussed what it was like to take photographs for the first time, and received their photographs back, which prompted further discussion. Then, the women selected the photos that they had taken that they considered the most significant and created narratives for these photographs through discussion and the creation of captions for them. Finally, the women identified issues, themes, or theories that they saw arising in their own photos. For example, one theme that resonated with the women in the study was the lack of access to clean water. The photos taken as a part of the photovoice helped to focus attention on this problem, highlighting the need for the construction of clean water reservoirs in the region [3].

The methodology was then expanded to be used in other public health settings, including to investigate family, maternal, and child health in the San Francisco Bay Area [26] and to investigate youth and adult violence in Flint, Michigan [27]. Both of these implementations of photovoice involved a training session where participants learned about the methodology, were given cameras, and participated in a group discussion after the photos were taken. In these discussions, participants were split into groups of around ten individuals and asked to freewrite about the photos they took that were their favorites or the most impactful, and the participants then discussed the photos among themselves [26,27]. These photovoice projects allowed researchers to gain information that was not biased by researchers "assumptions and judgments" [26].

Within education as a whole, photovoice has been used in a variety of contexts, including as a pedagogical opportunity in a course teaching about diversity [6] and as a way to reconceptualize student definitions of success [4]. In a class about diversity, the photovoice activity was presented to students as an assignment where they were documenting a concern that they had about their community [6], whereas the definitions of success came from middle school students who volunteered to participate in the photovoice activity to discuss their ideas of success [4]. Group discussions about the photos were had in both of these contexts, with the students in the course about diversity having whole-group discussions about their photos and the middle school students meeting in pairs to discuss about their photos [4,6].

While photovoice has been used within education more broadly, as shown in the examples above, it has also been recently used in the context of physics education as a method for assessing and improving student learning [7,28] and to describe the condition of physics instructional laboratories [29]. When assessing student learning, one instructor had students relate photos that they took to the concepts they learned in class and then followed up this experience with a group discussion so that the instructor could better understand students learning about electricity and magnetism [7]. Photovoice has also been used with preservice teachers to understand the condition of instructional physics labs in rural Indonesia, allowing researchers to gain insight into the readiness of physics labs to support student learning [29].

All of these settings used photovoice as a research methodology or a pedagogical tool; however, the exact implementation varied. For example, focus groups were a

variety of different sizes, from the entire group [6] to just a pair of participants [4]. The audience for the results of the research also differed from policymakers [3] to fellow students [6]. Nonetheless, all of these contexts implemented some form of group discussion about the photos and involved participants taking photos of their experiences within their communities and participating in research that could affect change in those communities. We retain those aspects while implementing photovoice within the new context of an upper-division physics capstone course.

III. COURSE CONTEXT

Q-Forge is a new course at the University of Colorado (CU) Boulder that serves upper-division undergraduate physics and engineering physics students. In lieu of taking an advanced lab course or participating in an undergraduate research experience or internship, students can enroll in Q-Forge, where they collaborate with an industry partner on an authentic project. This allows students who are interested in working in industry directly after graduation to get experience doing authentic industry work, potentially expanding their opportunities for future employment in quantum industry. While there is an application process for students to enroll in Q-Forge, this process is to select for students who are interested in entering the industry after graduation rather than going to graduate school. As of the 2023–2024 academic year, there have consistently been more spaces available in the course than students interested in taking it, meaning that all students who applied were accepted into the course. Q-Forge was initiated by a National Science Foundation (NSF) Quantum Leap Challenge Institute called Quantum Systems through Entangled Science and Engineering (Q-SEnSE). One of the goals of Q-SEnSE is to develop a "quantum-savvy workforce" [30]. The need for developing a quantum workforce has been identified by several recent publications [31,32] along with the identification of the necessary skills required by this burgeoning industry [31,33–36].

Aiming to meet these needs for a new, more expansive quantum workforce, Q-Forge is modeled after traditional senior design capstone projects, which are common in engineering degree programs [37–39]. In Q-Forge, students develop skills in the design, construction, and testing of devices that will ultimately be used in quantum technologies. While one goal of the course is for students to participate in an authentic industry project, other goals of the course include that students build the skills necessary to be competent members of the quantum workforce following their graduation, become motivated to pursue a career in the quantum industry, and feel that they are capable of pursuing such a career.

Q-Forge, a yearlong course, ran for the first time starting in the Fall 2022 semester with eight students enrolled in the course. There were six men, Reese, Nicholas, Jasper, Patrick, Owen, and Charlie, and two women, Nina and Stella (all names are pseudonyms). All of the students self-identified as white. In the transition to the Spring 2023 semester, Nicholas, Patrick, and Charlie graduated leaving five students enrolled in the course. The students worked together on a single industry project, a teamwork context that was vastly different than what most students had experienced in the past.

During the 2022–2023 academic year, the Q-Forge students partnered with a company in the quantum industry to work on a project optimizing heat exchangers for dilution refrigerators. Throughout the Fall semester, the students were focused on developing simulations for the heat exchangers and CAD models for their proposed optimized heat exchangers. During the Spring semester, the students were engaged in creating a prototype of their optimized heat exchanger and were regularly machining parts in one of CU Boulder's instrument shops. This project was an example of an enabling quantum technology, which is a crucial part of the quantum industry [33].

The course was structured to take place 2 days each week. The students met for approximately 1 h each day, during which they were engaged with the course instructor in either lecture or discussion about their project. On one of the days, after these lecture-based sessions, students had scheduled time to work on their project for approximately 3 h. Each week, students also engaged in metacognitive reflection questions and responded to a photovoice prompt (see Sec. IV for more details), both of which were administered via Qualtrics.

Throughout the course, students were exposed to additional activities meant to build their skill sets. The activities were around topics such as error propagation, programming in Python, and project management. Students also visited, and were visited by, various companies in the quantum industry near Boulder, Colorado in an effort to expose them to the local quantum industry landscape. These activities decreased as the year went on so that students could focus on their project.

While not a formal part of the course, students were also given the opportunity to participate in a series of interviews with the researchers. Students could have participated in an interview at the beginning of the course, at the end of the Fall semester, and again at the end of the Spring semester. Students were compensated with a $25 gift card each time they participated in an interview. Students were also given the opportunity to participate in three photovoice focus groups. While there was no formal compensation for participation in the focus groups, breakfast and coffee were provided at each one.

IV. PHOTOVOICE IMPLEMENTATION IN Q-FORGE

In implementing photovoice within this course, we aimed to maintain many aspects of Wang and Burris' initial implementation [3] and PAR in general [9]. While

students were not involved in the development of our original research questions (which were based on the goals of the course), our implementation of photovoice intentionally left space for students to modify the research direction and to change research questions as necessary. While our research questions did not ultimately change throughout the photovoice process, student responses made us aware that we needed to (i) ask more general questions about the course to elicit student thoughts about a wider range of aspects of the course and, (ii) make our prompts broad in order to allow for students to steer the research as a whole.

Students took photos in response to these prompts each week and then participated in three focus groups throughout the year, where they viewed and discussed about the photos taken by one another. Throughout the course, we monitored the student responses to the photovoice prompts and provided feedback to the instructor based on the student responses.

We framed the photovoice activity to students such that they knew that they were to be involved as participant-researchers on the project. We clarified to them that their generation of ideas was important and that we wanted the research to be guided by their thoughts and opinions. We explained that we wanted them to contribute to improving the course and to help us understand their experiences within it.

We also emphasized that creativity was a goal of the photovoice process and that "there is no wrong way to take a photovoice photo." We told students that their photos could be abstract or concrete, and they could also be of the course directly or of something going on in their lives that was related to the prompt. We also provided them with some examples from the literature of photos that had been taken in prior photovoice projects. In this way, we tried to encourage variety and creativity from the students and indicate to them that we valued their honest contributions to the photovoice process.

Each week, students were provided with a photovoice prompt to which they were asked to respond. The research team created this series of prompts using our research questions (see Sec. VI A) to guide their development. Especially during the first semester, the creation of prompts was done on an almost weekly basis so that we could respond to things that the students brought up, as well as the work currently being done in the course. Students took photos with their phones and were asked to submit their photos with a brief caption through a Qualtrics survey. Students had a full week to respond to each photovoice prompt. The photovoice prompts addressed several aspects of the student experience that we were interested in, including teamwork, interest in the quantum industry, and experience with the course as a whole. The photovoice prompts were initially fairly specific; however, we intentionally moved to provide more open-ended prompts as the course went on in an effort to allow students more flexibility in how they responded. During the first semester, a unique prompt was provided each week. Over the second semester, as the students settled into working on their project, we were able to develop photovoice prompts in advance. The intention was to cycle through photovoice prompts related to each research question such that each topic was probed every 3 weeks. The complete list of photovoice prompts can be found in Appendix A.

At the end of the Fall semester, we held our first focus group with the students. It was optional but took place during their usual class time and lasted for one and a half hours. Students who chose to participate signed up for the focus group via Qualtrics and were asked which of their photos they would be comfortable sharing. Students were comfortable sharing the vast majority of their photos, with only one student indicating that we should not share one of their photos with the group. All of these photos were printed prior to the focus group so that students would have them to reference. During this first focus group, seven out of the eight students chose to participate.

The printed photos were grouped based on their prompt according to category (teamwork, interest in quantum industry, and experience with the course as a whole) so that students could view all of the photos of one category together. This allowed students to see and discuss, for instance, all of the photos related to teamwork at the same time and make connections across photos and from week to week. Students did, however, frequently talk about multiple categories at the same time as the distinction between them was vague, and we as facilitators allowed this overlap in discussion to occur naturally. The researchers also asked several open-ended questions of the students, including asking them to identify themes within the photos and how those themes related to their collective experience in the course. The specific questions asked in the focus group can be found in Appendix B.

Two additional focus groups were held in the Spring 2023 semester; the second focus group specifically was a request from the students following the first focus group. One of these focus groups was held in March, halfway through the semester, and the other was held at the end of the semester in May. These focus groups were both structurally similar to the initial one held in the Fall of 2022. All five students enrolled in the course participated in the second and third focus groups. After the first and second focus groups, we printed and framed two to three photos the students collectively selected for them to display in their lab space.

Throughout this process, we sought to maintain the connection of our implementation of photovoice to the values of PAR. We placed value on student contributions to the analysis of the data through focus groups and ensured that there was a mechanism for feedback about the lessons learned from photovoice to reach the course instructor.

Then, at the end of each semester, we consolidated student feedback from photovoice, reflection questions, and interviews into a document that was shared with the course instructor. Students were given the opportunity to provide feedback on this document at the end of the fall semester before it was shared with the course instructor, although none of the students chose to provide feedback on this document.

Implementing photovoice in Q-Forge allowed us to achieve several goals. First, it allowed students to engage in a reflective practice that may have encouraged agency and ownership [40–42]. While there are various types of reflective practices that students can engage in, such as guided reflective writing, learning portfolios, and metacognitive reflection questions [43–45], we chose to use photovoice because, as a form of PAR, it could more easily enable students to have ownership over their experience by changing what is seen as "valuable knowledge," to include student viewpoints and trusting students as the experts of their own experiences [6].

Second, photovoice allowed us to gain in-the-moment feedback from students on their experience in the course. Because the course was brand new, it was important to look at what was occurring on a weekly basis in order to be responsive to the needs of the students. Feedback has also been identified as being the most effective when it is immediate [46], and this methodology allowed for frequent course feedback.

V. METHODS OF ANALYSIS

By the end of the second semester, we had two types of data to analyze from photovoice: the photos, along with their captions, and the videos of the focus groups. Because one of the main ideas of PAR is using participant ideas as part of the research, we used the themes that the students brought up during the focus groups as the cornerstone of our analysis as described in more detail below. In this paper, we utilize photos and captions from the first semester of Q-Forge, video data from all three focus groups, and responses to some reflection questions from the first semester, which were used as a comparison to the photovoice responses. A goal of this paper is to provide an example of what types of data photovoice photos and captions can provide, for which it is only necessary to look at a subset of the photovoice data. Therefore, data from only the first semester are used in Sec. VI A. However, an understanding of how students experienced the photovoice process throughout the entire year required utilizing data from all three focus groups. These full-year data are included in Sec. VI B.

Our methods for the analysis of these data are as follows: once we conducted our initial focus group, two of the authors (K. A. O. and V. B.) created a content log [47] from the video recording of the focus group. Through this process of creating a content log, K. A. O. and V. B. also created a list of themes that the students had identified in their photos. Then, the two authors applied the list of themes to the photos the students had taken and the associated captions. Furthermore, K. A. O. and V. B. identified several emergent themes that were not discussed by the students in the focus group and coded the photos and captions with those themes as well. These two lists of themes were kept separate so that the researchers could continue to foreground the themes identified by the students, valuing them as members of our PAR. Content logs for both of the Spring focus groups were created and analyzed in a similar manner to the Fall focus group, although the themes presented here are solely from the first focus group.

Once the photos were fully coded with themes, K. A. O. and V. B. engaged in a process of clustering themes that were similar in order to allow the themes to capture the appropriate scope of the photos they were applied to. All of the authors then selected several interesting themes to analyze in greater depth, which are discussed further in Sec. VI A 1. We chose to center many of the themes generated by students in order to continue to value the students' contributions to this research. Further analyzing the data by looking at responses to each photovoice prompt or category (teamwork, quantum industry, or course) proved difficult due to the wide variety of different prompts we asked combined with the small number of students.

Full interrater reliability (IRR) was not conducted for this project, as we are not interested in presenting counts of how many times each theme appears within our data. Instead, we are interested in describing which themes appear at all in order to highlight the span of responses given by students. Instead of conducting IRR, the entire research team examined example data, especially those presented within the paper, and came to an agreement on which themes were present within the data.

VI. EDUCATIONAL AND RESEARCH OUTCOMES

In this section, we share the outcomes of our implementation of photovoice. We begin by sharing themes from our photovoice data that can be used for research purposes in order to investigate students' experiences with various aspects of the course. We then provide details about student experiences with the photovoice process and the pedagogical benefits it provided the students.

A. Research outcomes

In this section, we provide some examples of the types of data we acquired through the use of photovoice. This section is not meant to be a complete presentation of the "results" of our research project but should be interpreted as a sample of some of the types of results one might be able to achieve through the use of photovoice in the context of a physics course.

While our goal here is not to answer any specific research questions, we provide our list of research questions that will be applicable to future work so that readers may put the results we have provided into context. We had two main categories of research questions: those related to student teamwork and those related to student perceptions of the quantum industry.

Teamwork research questions

- What are students' goals and expectations about teamwork in this course and how are those influenced by their past teamwork experiences?
- How do students organize their teamwork and what challenges do they encounter?
- How and to what extent do students solve these challenges?
- How do students perceive the success of their teamwork along different dimensions?

Quantum industry research questions

- What do students think the quantum industry is and how does this understanding change throughout the course?
- Do the students think they are able to participate and be successful in the quantum industry, and how does this change throughout the course?
- Do students want to participate in the quantum industry, and how does this change throughout the course?

1. Takeaways from photos and captions

First, we discuss some themes that showed up in the photos and captions students submitted, emphasizing the themes the students identified in the focus group. We will begin by presenting the list of themes appearing in the students' photos in Table 1. In bold are the themes that appear frequently (in 10 or more photos out of 90 photos overall). The lists are separated based on whether the theme was identified by students as part of the focus group or was identified as an emergent theme by researchers.

We will examine three interesting themes here in detail. One of these themes, *Growth & Accomplishment vs Not Knowing Enough*, was one of the most frequently occurring themes in the photos. The other two themes, *Friendship* and *Locations with Importance*, occurred in a unique way within the photovoice data, as discussed below. These three themes will serve as examples of the type of potential outcomes of photovoice photo data.

The first theme that we will investigate is the theme of *Growth & Accomplishment vs Not Knowing Enough*. Especially early on in the semester, the students submitted many photos that indicated that they felt like they were unsure how to make progress or that they did not know enough to know what they should work on. For instance, in Fig. 1, Nicholas discusses being unsure of how to reconcile the timing of the project with gaining enough information to be successful at it.

FIG. 1. An example of a photo that contained the theme of *Growth & Accomplishment vs Not Knowing Enough*. Nicholas took this photo in response to the prompt "Take a new photo representing how you feel about the project right now." His caption reads, "A picture of a crosswalk with 7 seconds remaining. I am currently in this awkward place where I'm not sure if I should just sprint towards a goal (cross the street) or wait and gather more information before progressing. I don't want to progress without the proper amount of research conducted, but I don't want to waste the team/[company]'s time by taking too long to research".

On the other hand, the students did ultimately feel like they grew and accomplished things throughout the course of the project. In Fig. 2, Jasper discusses feeling like he grew and learned slowly over the course of the semester, but that his progress was still measurable.

FIG. 2. An example of a photo that contained the theme of *Growth & Accomplishment vs Not Knowing Enough*. Jasper took this photo in response to the prompt "Take a new photo representing your experience with this course over the entire semester." His caption reads, "Though bonsai trees grow slowly, with attention and care they still grow. That's a bit how I feel about the class—we definitely grew, but it's been a slow process with lots of unexpected obstacles. Still though, I'm pretty happy with the work we've produced this semester, and am looking forward to seeing what the next semester brings!".

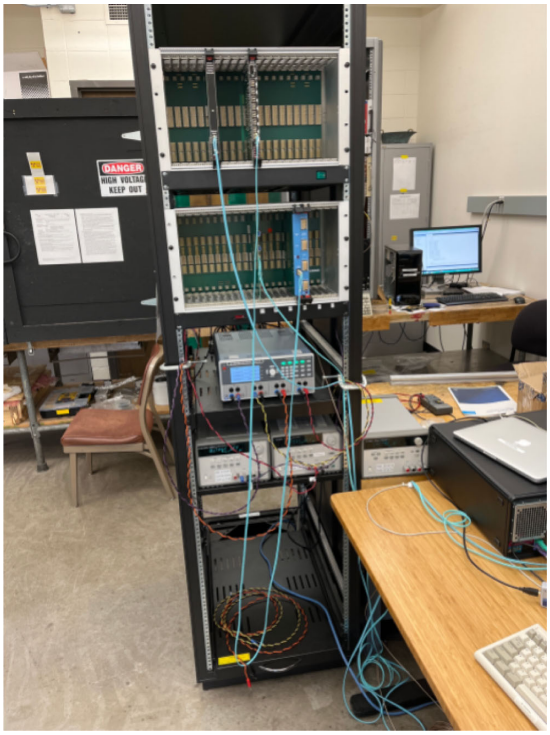

FIG. 3. An example of a photo that contained the theme of friendship. Jasper took this photo in response to the prompt "Take a photo that represents the academic environment/culture you're familiar with here at the University of Colorado Boulder." His caption reads, "This is just a small photo I took from the lab I work in. In an effort to focus on my classwork, I've been pretty much isolated from everyone except the coworkers I've met through labwork, so this photo is pretty representative of how I've spent most of the last 3 years. I'm really excited to get to work with a larger group on something, and maybe make some friends through the process!".

These two sentiments of growing and not knowing enough were both present in the photovoice data from these students, indicating that there was a dichotomy for the students between needing to know more and also feeling like the learning process was occurring throughout the course. While the project was at times confusing and students were not sure how to proceed, by the end of the first semester, they felt that they had accomplished something important with respect to their project and that they were excited to continue working on the project in the next semester.

Friendship was an important theme that came up in the photos and captions throughout this course, appearing several times in photos, but less often in the reflection questions. It was clear from these photos that friendship was an important aspect of this team project. For instance, in Fig. 3, Jasper indicates that making friends through this course was one of the things that excited him about taking this class, as he had felt isolated in his past research experiences.

The photos and captions also showed that the students did ultimately become friends with their teammates. In Fig. 4, we can see Owen was excited about his relationships with the other students, enough to take a photo, and write about it in response to a prompt that did not specifically ask about his experience with his teammates.

Finally, we discovered through photovoice that the friendships students developed with one another sometimes led to concerns about focus and distraction. As Jasper photographed and wrote in Fig. 5, the fact that they became friends with one another made it hard for him to believe that the team would be able to focus enough to finish their project and meet the industry sponsor's expectations.

All of these photos emphasize that friendships between group members were a key part of the students' time in Q-Forge. It was something students looked forward to, something that ultimately happened and that students were excited about, and something that had the potential to disrupt their work within the project. Nevertheless, all of these photos highlight the nature of friendship within this group and its importance to the students' experience.

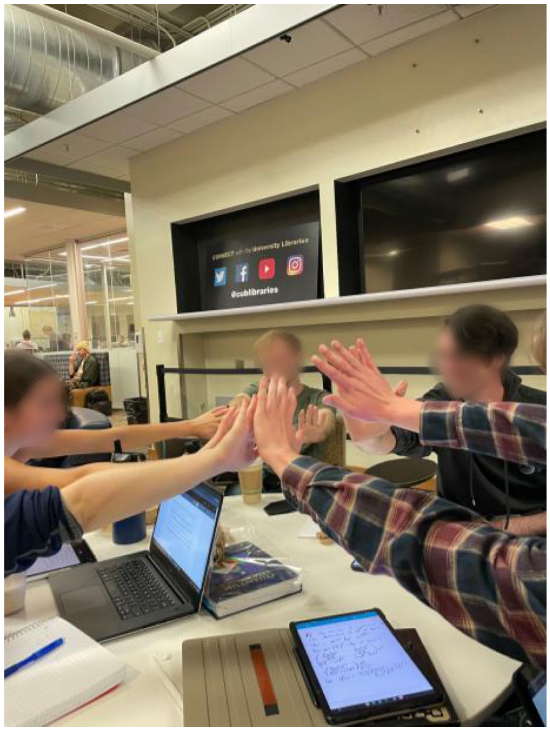

FIG. 4. An example of a photo that contained the theme of *Friendship*. Owen took this photo in response to the prompt "Take a photo that represents the environment/culture of a company in the quantum industry." His caption reads, "We are collaborative besties".

FIG. 5. An example of a photo that contained the theme of *Friendship*. Jasper took this photo in response to the prompt "Now that you have your group roles, take a new photo representing how you are feeling about the team working together in the coming weeks." His caption reads, "To be honest I'm a bit nervous about the next few weeks, I think it'll be difficult to win [the industry sponsor] back over again, based on the last meeting. The project has such an enormous space to work in and optimize that it feels impossible to find a foothold, especially under deadline pressure from [the industry sponsor] who's expecting progress more quickly than we're able to deliver it. Everyone in the group has quickly become friends, but I honestly worry that this will make it more difficult to keep everyone on task, and repair [the industry sponsor]'s opinions of our abilities".

Finally, through the photovoice photos and captions, we were able to understand a location, coffee shops, that held importance to the students. This theme, *Locations with Importance*, appeared several times within the student photos and captions but only appeared once in the written reflection questions.

The appearance of coffee shops in many of the students' photos and captions reflected that they felt that coffee shops were important to their work habits and gave them a place to come together as a group. For example, in Fig. 6, Reese took a photo of a coffee shop on campus and wrote a caption about the fact that the team gets coffee together at least once a week, indicating that they feel that the coffee shop is an important place to them as a team.

Another location that came up in the photovoice photos and captions as important to the team was their shared lab space and, specifically, the whiteboard, which will be discussed further in Sec. VI A 2.

The photovoice photos allowed us as researchers to identify coffee shops as location that held special importance to the students. Because this theme did not appear with the same frequency in our other data, this highlights the potential for photovoice to provide researchers with access to different conclusions than those that might be made without photovoice as a data source.

Beyond *Growth & Accomplishment vs Not Knowing Enough*, *Friendship*, and *Locations with Importance*, the Q-Forge students brought up many important themes that were present in their photos and captions, and the ones highlighted here are simply examples of those themes and what we learned about them from the photos and captions.

2. Discussion of photos in focus group

Next, we present some student discussions during the focus groups about the photos themselves that changed the way we looked at the photos. Based on these discussions, the students highlighted a new way of looking at a common type of photo that was taken during photovoice, and we gained a new perspective on one of the goals of the students. These takeaways highlight the value of the focus group as a part of the photovoice process, as well as the value of the student voice in co-creating the research.

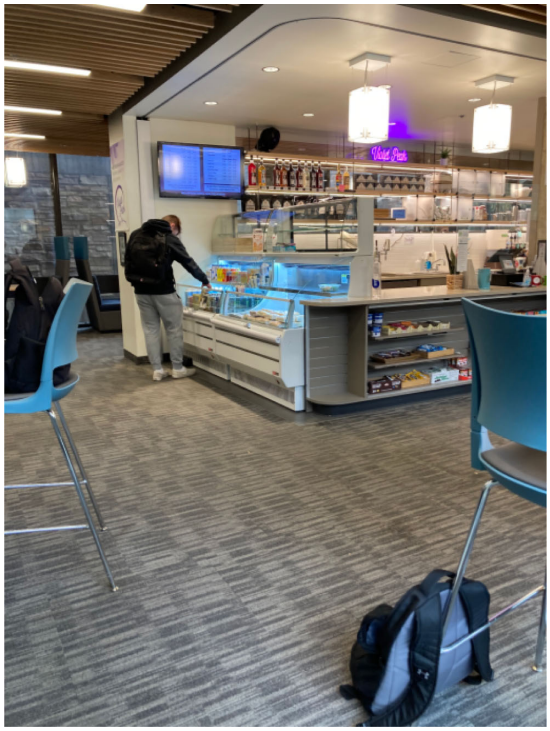

FIG. 6. An example of a photo that contained the theme of *Locations with Importance*. Reese took this photo in response to the prompt "Take a new photo that represents the environment/culture of a company in the quantum industry." His caption reads, "I feel coffee shops are the heart of any physics industry. Our team gets coffee at least once a week and we take that time to talk about whatever is on our minds wether [sic] that be personal or professional. I think a coffee shop is the best environment to get to better know your colleagues sharing a common activity talking in a neutral environment. I did also notice a very nice expresso [sic] machine at [the company] so one could assume those guys drink a ton of coffee".

Throughout the course of the first semester, we noticed that many students had taken photos of the whiteboard in their lab space. These photos mostly included lists of who was going to take on each task, but also included other types of project-related work. For an example of one of these whiteboard photos, see Fig. 7. Initially, both the students and researchers thought of these photos as something that students submitted when they did not know what else to photograph. For instance, in the focus group, the students noticed that there were a lot of photos of the whiteboard when Owen said,

> Like last time, I think there's a—a very obvious 'I was lazy this week' sort of picture, which happens to be the whiteboard this time around.

Later on, however, the students realized that these whiteboard photos likely had more meaning and significance to them than they had initially suggested. Stella began another discussion about the whiteboard photos by saying,

> Yeah, I do like that the whiteboard ones are all completely different prompts. It's kinda funny. They all have that vibe of teamwork, but every single prompt of the whiteboard photos is different. Which goes to show that I'm not sure if we took pictures of it because it's just something familiar and that's immediately what we go to when we think of this class is 'Oh, the whiteboard. Cause that's where I'm with everyone.' I don't know, I just think it's kinda nice.

Reese replied,

> Yeah, I would say they all kind of fit pretty well. I would say the whiteboard is a good scapegoat but that's if they weren't good fits for the prompt and whatnot. They all were different photos I think for different prompts, they all fit pretty well. You know, your experience with teamwork… 80 percent or 90 percent is in that room around the whiteboard.

Later on, Owen added to the discussion about the whiteboard photos by saying,

> I think it's interesting that out of all the tools that we have at our disposal in the lab, we've got all this high-tech stuff… the one we actually do use, and basically did the whole project on, is the whiteboard. That's been doing the heavy lifting.

Reese replied, "I agree. That's why it should be in four different prompts, you know?"

Throughout this discussion, the students convinced themselves, and us as researchers, that the whiteboard photos were valuable contributions to the photovoice process, regardless of if the students were taking them out of "laziness." Through these photos, we learned that the whiteboard was an important shared space for the students where they accomplished a great deal of the work that needed to get done over the course of the semester. This discussion within the focus group helped provide much needed context to these photos so that we could more accurately interpret their meaning.

There were also important ideas that we learned about the students' attitudes toward one another from the focus group experience that we might not have otherwise known. For instance, the focus group allowed us to understand that the students were deeply invested in the well-being of their teammates and wanted to ensure that they were happy and fulfilled. We discovered this because Owen brought up the prevalence of people within his photos,

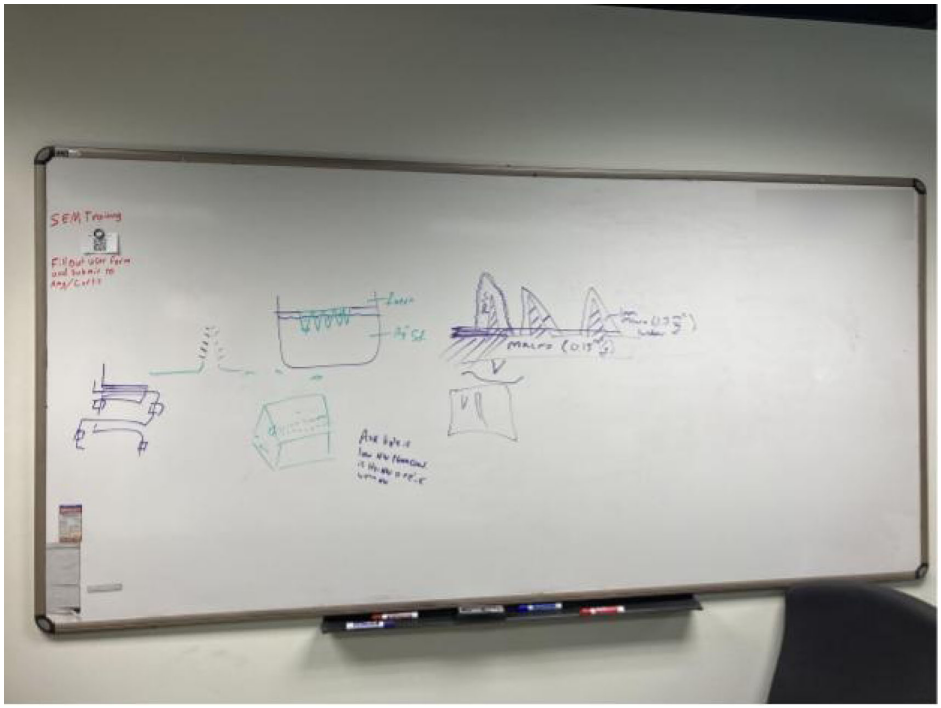

FIG. 7. An example of a photo that Charlie took of the whiteboard in response to the prompt "Take a new photo representing how you feel about the project right now". His caption read: "This photo represents how I feel about the project: confused. Right now the project is still a collection of ideas where no one knows if they will work. Doing all the reading required to understand the needs of the project has been a tall task and while I have a good grasp of what our goals are, the project is still confusing. I feel like it is a collection of scattered ideas with not a lot of direction right now, which is represented by the drawings on our lab's whiteboard".

> I do think it's interesting how my photos all have pictures of people. It kind of speaks to the way that I've approached the project–I absolutely care most about the people. The progress doesn't matter so much to me, if you guys are unhappy then I don't care how far along we are, you know? … I think the prettiest photos are the ones that have happy people in them.

Reese followed up by saying,

> No, I appreciate that. I have a positive outlook in that regard of, like, I don't really care if we're not on the–getting what we want done. If everybody's not firing on every cylinder then we're not gonna get it done to begin with. So it's like we've gotta focus on ourselves before we can focus on the project.

This interaction allowed us to understand the value that the students placed on the happiness and well being of the team, even putting it before the success of the project in terms of importance. The focus group provided us with additional context about the team, even beyond what we learned from the photos alone.

3. Comparison to reflection questions

In order to give an idea of the themes one might see in photovoice responses compared with other metacognitive activities, we provide here a comparison with more typical written reflection questions. Both photovoice and written reflection questions were assigned weekly to the students, although the specific prompts for each were different. A complete list of reflection question prompts can be found in Appendix C. The same list of themes that were developed to describe the photovoice data was also applied to the responses to the reflection questions.

The five most common themes appearing in the photovoice responses (see Table I) also frequently appeared in the reflection questions. Nearly, all of the students brought up all five of these themes in both photovoice and reflection questions.

There were also several themes that occurred almost exclusively, though rarely, in the photovoice responses but showed up not at all or only once in the reflection questions. These were *Team Accomplishments*, *Friendship*, and *Locations with Importance*. We hypothesize that some themes may have been easier to capture in photovoice because of the visual element of the response. For instance, *Locations with Importance* may have been something that appeared in photovoice responses because students could physically take a picture of the location that was important to them rather than having to think of it in response to a reflection question prompt, which cues a much more abstract, verbal response.

TABLE I. Table of themes identified in the photos and captions by students and researchers and their definitions. Themes in bold appeared in 10 or more photos out of 90 photos overall in order to provide an idea of the most common themes. However, as the purpose of these results is to describe the presence of themes rather than to make an argument for their prevalence, we do not provide the specific frequencies of the individual themes.

Themes identified by students	Definition of theme
Friendship	Students talk about feeling like they have made friends with their teammates or are excited to
Divide and Conquer vs Everyone Coming Together	Students talk about dividing work among themselves or about coming together to share work or being in the same physical location together
Excitement and Novelty	Students talk about being excited about anything or about feeling like something is new, undiscovered, or on the cutting edge
Collaboration vs Individuality	Students talk about working together or working alone
Money and Jobs	Students talk about their plans for future jobs, current jobs, past jobs, or money
Differing Strengths	Students talk about team members having different skills, different strengths, or each being good at different things
Team Accomplishments	Students talk about having accomplished or hoping to accomplish something together
Taking a Step Back vs Pushing Forward	Students talk about taking a step back when they are overwhelmed or stuck or about moving through challenges without stopping
Locations with Importance	Students talk about spaces or types of spaces that are important to one or more of the students
People behind Technology	Students talk about the importance of people involved in creating quantum technologies
Optimism and Frustration	Students talk about feeling optimistic or looking forward to new things in the future or about being frustrated with the course or project
Overwhelming	Students talk about being overwhelmed or intimidated by something
Faster Progress vs People being Happy	Students talk about making faster progress on the project or about slowing down so that people can be happy
Productivity	Students talk about being efficient or productive
Taking Care of Self and Others	Students talk about taking care of themselves or other people
Pressure	Students talk about feeling under pressure
Themes identified by researchers	
Change	Students talk about change or lack thereof, whether in the past or in the future.
Organization	Students talk about organization of work or their physical space
Growth & Accomplishment vs not Knowing Enough	Students talk about learning or growing, including both in one moment or across the semester or about feeling like they do not know enough to make progress on the project or need to learn more
Uncertainty	Students talk about instances where they felt unsure or uncertain.
Relationship with Industry Sponsor	Students talk about interacting with their industry sponsor
Feeling Stuck	Students talk about feeling like they are unable to make progress on the project or feeling stuck
Timing	Students talk about the timing of the project or timing being a challenge
Respect	Students talk about the importance of having respect for one another

However, the differences may also be due in part to the types of prompts used for the two assignments. Our reflection questions were much more pointed and specific than our photovoice prompts. This meant that photovoice allowed students more of an opportunity to bring up things that were important to them without being asked, such as the way they became friends with their classmates. This is an asset of photovoice since it allows participants to drive the research with their own ideas rather than those of the research team.

B. Student experiences with photovoice

When implementing photovoice in Q-Forge, it was important to us to not only gain research results but also for photovoice to have pedagogical value to the students.

Here, we will show that the students had a positive experience with photovoice in this course and felt like it was a valuable experience for them and their learning regardless of the research outcomes. We discuss both Q-Forge students' experiences with the photovoice process and their suggestions about changes to it, indicating how the process itself affected the student experience.

The students were asked explicitly for their thoughts about the photovoice process in two reflection questions and in the three focus groups, so students were provided opportunities to share their experiences with the process both individually and collectively.

Student views about the photovoice process progressed throughout the year. In the following subsections, we will demonstrate how these views changed at different points. At the beginning of the first semester, students had mixed views about the benefits of photovoice and how enjoyable it was. As the year went on and they participated in photovoice focus groups, many students began to appreciate the photovoice process more, feeling that it brought them together as a group, allowed for creativity and reflection, and was fun, but challenging.

1. Student experiences early in the course

During the fourth week of the Fall 2022 semester, we asked students a reflection question that read, "How have the photovoice assignments been going for you so far? Have they helped you reflect on topics relevant for this class?". The students responded generally positively, but some students found the photovoice prompts to be too frequent or somewhat irrelevant to the rest of the class.

One student who felt particularly positively about the photovoice experience, Charlie, wrote,

> The photovoice assignments have gone well so far. I have enjoyed being able to get creative with the photos and think critically about the prompts. They have helped me reflect on topics relevant for this class in a way that would probably be different if I just had to type out a response. So, I appreciate them for giving me a new perspective on the prompts and topics discussed in this class.

On the other hand, a different student, Nina, wrote,

> I don't find them very effective. Because they are weekly, they feel too often to be a photo that I thoughtfully take myself, and more thinking of my response and searching for a photo either online or in my past camera roll that fits what I think.

While this reflection question was asked after the students had a few weeks of experience with the photovoice process, it was still early in the semester and the project that the students were working on was still ill defined. Partially because of this, we were interested in finding out how the students felt about the photovoice process at the end of the semester and, therefore, we asked them during each focus group.

2. Student experiences from the first and second focus groups

The focus groups in particular seemed to be an important aspect of the photovoice process for students. The students were able to see the potential for photovoice to bring them together as a group and provide the opportunity to share their photos with each other in a meaningful way.

In the first focus group, when asked about how the photovoice process had gone for them, the students discussed not understanding the value of photovoice prior to the focus group. Reese said,

> It [photovoice] kinda seemed like, I wouldn't say pointless, but a little like busy work until the end where we're like 'oh, okay.' You know?

During this first focus group, the students ultimately ended up suggesting that having a focus group earlier in the semester would have resolved this issue of photovoice feeling like busy work and would have allowed them to see the value in the activity earlier on. It is for this reason that we decided to hold two focus groups in the Spring 2023 semester.

Also during the first focus group, the students had a discussion about how the photovoice process, and the focus group specifically, allowed them to compare their and their teammates' progress throughout the course. They discussed how they had all been excited at the start of the project and then became frustrated later on in the semester when the project sponsor decided the initial project goal was not feasible, and how they could see this progression throughout their photos. Reese went on to mention how it was a lot easier for him to remember when a photo was taken versus when he filled out a survey response, which meant that photovoice allowed him to better track his progress throughout the semester than a reflection process without photos.

The students additionally realized that photovoice had the power to allow them to see the similarities in their experiences and bring them together over these shared experiences. During the exchange about how looking at the photos allowed them to see a progression of emotion throughout the semester, Owen said,

> We were definitely thinking about a lot of similar things and this really brought that to life. I wouldn't have otherwise known.

Stella agreed,

> I do think it's really nice to see how everyone is, like, we're all on the same boat. And it's just nice to see what everyone took photos of, honestly.

Throughout the second and third focus groups, the students reiterated that the first focus group was the first time they felt this sense of shared experience.

In the second focus group, students indicated that they continued to think about the way the first focus group brought them together and that experience also informed the photos that they took in the second semester. Nina said,

> I think while I'm taking the pictures I remember that we did [the focus group] and how it kind of brought us all together in like talking about the project and the things we can do better next semester. So I kind of take it more seriously.

Other students echoed that they had begun taking photos while thinking about sharing them with the group, demonstrating how the focus group was a valuable part of the Q-Forge students' experience with photovoice and changed the way they viewed their photography going forward.

3. Student experiences from the end of the course

By the end of the year, the students overall felt like they had a positive experience with photovoice. During the third focus group, Stella said,

> I think it's been pretty good—the photovoices. And I know all of us have always enjoyed these sessions to look back. And I think having two of them was really useful this semester, like, I think that was pretty meaningful.

This statement suggests that, while students enjoyed the photovoice process as a whole, the focus groups were an incredibly important aspect of the photovoice experience that should be valued and upheld by researchers. At least for these students, the photovoice process seemed to have been brought together by the focus groups, allowing them to gain the most from the activity as a whole.

One student also brought up the fact that they thought the photovoice process was valuable beyond its use as a research tool. During the third focus group, Jasper said,

> But, honestly, I felt like the photovoice, I guess, was kind of something that it's—in the moment you're like, 'oh I don't know what photo I'm going to do'. But afterwards, when you're looking back, it's really great to reflect on it. So even if it wasn't—even if it was just part of the class and not for research stuff, I think it would still be super valuable… I think it's a great way to reflect on what we're doing and have a great little collage or library of photos at the end of the semester to really see the journey.

Several students agreed with this sentiment, with Owen pointing out how much he enjoyed being creative during the photovoice activity. He said,

> I loved the creative aspect. I think as physicists we're just doing math. We're just doing concrete stuff all the time. Doing something that's a little bit—yeah, using the other side of your brain. I just find it so refreshing and you get some interesting angles on the project that you maybe wouldn't otherwise.

These two comments highlight the valuable role that photovoice played in their course experience and even how it positively impacted their progress on the project.

Finally, we asked students a second reflection question about their experience with photovoice at the end of the second semester. The question read, "how has the photovoice process gone for you over the course of the semester?". Overall, the student responses were more positive than during the first semester. Stella, who felt particularly positively about the process by the end of the course wrote,

> It's been really fun! I love the photo voice sessions and getting to look back on the journey we've had together.

This student is one of the ones who felt like photovoice was "busy work" before the first focus group. Nevertheless, by the end of the second semester, this student felt extremely positive about engaging in photovoice and seemed to really enjoy the process.

Nina, who felt less positively about the process, wrote,

> It's gone okay. I'm not someone who usually takes photos of things so it's been hard to take a picture that really represents my ideas.

While Nina felt less positive about the overall experience than Stella did, the fact that the experience was challenging is not necessarily a negative outcome for the students.

Overall, the students' experiences with, and perception of, photovoice changed over the course of the year, particularly due to their experiences in the focus groups and the power these focus groups had to bring them together as a cohort. While the photovoice data acquired before the first focus group was still valuable to the research, the additional buy-in from students in the form of focus group participation was extremely beneficial, especially given our reliance on student participation in developing themes associated with the photos. Notably, despite the students' mixed feelings about photovoice at the beginning of the year, all but one student in the first

semester still chose to attend the first focus group, suggesting that they were still at least somewhat invested in the process. As the year went on, students' perceptions of photovoice improved and, while at least one student still found the process challenging, the overall impression was that the students found photovoice to be valuable to them.

4. Student suggestions for photovoice implementation

The focus groups allowed us to gain feedback from the students about how the logistics of the photovoice process could be tailored to best work for them. During the first focus group, the students made two suggestions. First, they suggested changing the day of the week that the photovoice responses were due so they would have the weekend to take photos, thereby allowing them to take photos that required more time or required them to be at a different location. Second, they requested that the instructor give reminders about what the photovoice prompt was well before the due date, thereby allowing the students to be aware of the prompt earlier and have more time to think about their responses. We ensured that the instructor was aware of both of these suggestions and he worked to implement them during the second semester.

Students in the second focus group also echoed the importance of receiving reminders about the photovoice prompt earlier. Jasper commented,

> I do feel like the notifications and the reminders and everything have helped me kind of try to remember to capture moments for the photovoices, and so I feel like more of the photos I've brought have actually been authentic answers to the question rather than rushed, last minute answers to the question.

This comment helped us realize the importance of making sure the photovoice prompt was easily accessible to students and that they were reminded of it well before the due date. The students seemed to value these reminders, as they allowed the students to capture more authentic moments in their photos, which is of value both to the students and to us as researchers.

During the final focus group, we also asked students how they felt about having a unique prompt every week versus having repeated prompts throughout the semester. Overall, the students enjoyed the repeated, more open-ended prompts with the exception of one student who preferred the initial, more specific prompts. There was, however, some consensus that the cycling through prompts felt repetitive, which was seen as both a positive and a negative by the students. Nina began by saying,

> It was good but it'd come up and I'd be like, 'is this the right prompt for this week? Didn't I just answer this?' and then I'd be like, 'shoot, now I have to think about it again'.

As the discussion continued, the students came to the conclusion that adding a fourth prompt to the cycle would have helped it feel less repetitive. Stella stated,

> I wouldn't know a fourth question, but I think that might somehow be beneficial. Cause like Nina said it was kind of, a little bit, not in a negative way, but it was noticeable that we had just answered that question and I'm like 'well, I feel the same as I did last time!'

At the same time, Reese said,

> I think I'm in kind of a similar boat because, you know, over the course of a week maybe not much would change but then we'd come back in sessions like this and we'd look at the progression. Week to week it feels like we didn't come very far, but that's why looking back, I think, is so valuable.

These quotes exemplify how students felt about the cycling of prompts. The repetition felt challenging to them because they felt like they had just answered the prompt or did not feel any differently about it, but, at the same time, it allowed them to look back at the end of the semester and see the progress that they had made.

The students also suggested adding another category of prompt about their individual contribution to the project so that we would be cycling through four categories of prompts instead of three. This would allow for more spacing between the prompts from the same category and, therefore, allow the prompts to feel less repetitive.

Finally, the students suggested that the photovoice prompts could ask about their experience over a broader range of time. We specifically asked students to respond to the prompts based on how they were feeling in the past week, and the students suggested changing this so that each photovoice submission reflected their experiences with one of the categories over the past month while still responding to one prompt each week. While we agree that this would be an interesting and useful change to implement, the success of changing the prompts in this manner likely depends deeply on the length of the course or project where photovoice is being implemented, as well as the research questions and goals.

VII. RECOMMENDATIONS FOR RESEARCHERS AND INSTRUCTORS

Throughout the process of implementing photovoice over the course of the year, we learned several lessons that may be important for researchers using photovoice to study a physics class or for instructors looking to

implement photovoice within their classes. In this section, we will detail some recommendations for implementing photovoice in other courses based on our experience with Q-Forge.

We recommend that instructors and researchers use broad prompts. To begin, we experimented with several different types of prompts, both highly specific and very broad. We found that the broader prompts were more effective because these types of prompts allow students to bring up things that are important to them that researchers and instructors might not otherwise know to ask about. Furthermore, almost all of our students indicated that they preferred responding to the broader prompts when they were asked about it in the focus group with only one student preferring the more specific prompts.

We recommend specifying to students that the goal of the photovoice activity is for them to take their own, new photos rather than using old photos or photos from the Internet. At the beginning of the Fall 2022 semester, while we were asking students to respond to more specific prompts, we encountered challenges with students submitting either photos they found online or old photos from their phones. We quickly realized that we needed to specify in each prompt that the students should take a new photo, which the students indicated was challenging for them.

We recommend that instructors ensure that they provide regular reminders about photovoice to the students. The students indicated to us during the focus groups that it was incredibly important for them to receive reminders about the photovoice prompt several days to a week before the photos were due rather than being required to seek it out on their own. This allowed them to begin thinking about the photovoice prompt early in the week rather than remembering it at the last moment. The students also suggested that having a reminder about the prompt and therefore having more time to be thoughtful about their response to the prompt made it easier for them to avoid using old photos or images from the Internet since they were not rushing to submit any photo when they remembered that it was due.

We recommend placing value on the focus group portion of the photovoice process and holding focus groups early on in the photovoice process. The focus group experience ended up being valuable for students and researchers alike in a way that we did not anticipate. While we understood the importance of holding a focus group to allow students to participate in co-creating the research, there were many benefits of the focus group beyond this that are important to keep in mind when implementing photovoice within a class.

For instance, our first focus group showed us the importance of having a focus group on the students' feelings about photovoice. When asked how the focus group experience contributed to their feelings about photovoice as a whole, one student replied, "it's the voice" indicating that photovoice would not have felt complete without the focus group. For this reason, and because the focus group impacted how the students responded to later photovoice prompts, we encourage others to hold a focus group before the end of a semester-long course so that students get to have this positive experience earlier on in the process.

Another option in lieu of having an earlier focus group could be to allow the students to share photos with one another outside of a focus group setting. For example, instructors or researchers could allow students to opt in to having their photos displayed on a website for other students to view or have students share their weekly photo with a partner or a small group of students at the start of class. This would allow students to engage with one another's photos in advance of a focus group, allowing them to get some of the benefits of a focus group type experience. The Q-Forge students enjoyed seeing each other's photos, making this one of the important aspects of our focus group experience that could be replicated in a different way.

The focus group was also important for researchers, as it allowed us to begin analyzing the photos with a list of student-developed themes. While we understood the importance of allowing students to co-create the research prior to the focus group, we were able to gain an understanding of the meaning behind the photos that we would not have been able to gain from the photos alone. An example of this is the significance of the whiteboard photos in Sec. VI A.

VIII. CONCLUSIONS AND FUTURE WORK

Through this work, we provided examples of both the educational and research outcomes of our implementation of photovoice in a senior capstone physics course. We detailed student experiences with the photovoice process throughout the year, sharing how their thoughts on the photovoice process overall became more positive following the first focus group. We followed this discussion with some example takeaways from the photos and captions that our students submitted, providing a detailed analysis of several themes that appeared in the photos including *Growth & Accomplishment vs Not Knowing Enough*, *Friendship*, and *Locations with Importance*. We also provided examples of how the student discussions in the focus groups allowed the students to convey new ideas that were important to them, such as the way they prioritized their team's happiness and the importance of their lab space. Additionally, we compared the responses to photovoice prompts to student responses to reflection questions, showing that some themes appeared with similar frequency in both reflection question responses and photovoice, and some appeared in photovoice responses, but not reflection question responses. Finally, we provided some recommendations for future researchers and instructors looking to implement photovoice.

Throughout our implementation of photovoice, we met the original goals of photovoice (allowing people to document their community, critical dialogue through discussion of photographs, and reaching policymakers in several ways). First, the students were taking weekly photos of what was actively affecting their lives in relation to this course, allowing them to document the intersection of Q-Forge with their everyday lives. Then, the students engaged in focus groups where they were able to discuss their experiences in the course together. The students really enjoyed these discussions and found that they had similar experiences, both positive and negative, with the course. Finally, these outcomes of photovoice were shared with the course instructor (the "policymaker" in this scenario), in order to improve instruction.

As we demonstrated through our implementation, photovoice is a way to potentially elicit unique information from students, while allowing them to participate in the research process by developing themes, providing feedback, and taking unique photos that drive the research in directions that may not have been predicted by researchers. Photovoice is also a methodology that can elicit positive student affect from participating in the research and allow students to feel like they have a voice within a physics course. The students in this physics capstone course indicated that they appreciated having the opportunity to be creative in a unique way as a part of their course.

The process of engaging in photovoice may be especially useful in smaller classes like Q-Forge, where the size of the class is not prohibitive of full group discussions like a focus group. While there are many positives to the use of the photovoice methodology, we do have concerns about the scalability of this methodology for use in larger courses. Because a larger course may not allow for the use of a focus group, another similar method of engagement for eliciting student thoughts on the photovoice photos would need to be developed in order for photovoice to be effective at a larger scale.

Future work focusing on the photovoice methodology could include investigating the affordances of photovoice in other types of physics courses. For instance, photovoice might provide different types of results in a project-based course versus a traditional lab course or a lecture course, and first-year students might get different benefits from the process than seniors. Furthermore, it would be interesting to investigate the benefits of the photovoice process as a whole versus the process of taking photos alone or holding a focus group alone. Finally, further research into the scaffolding required to successfully implement photovoice at a variety of levels would likely benefit the community as a whole.

While in this paper we address our results only as an example of what type of results photovoice may elicit, our future work will contain a more detailed analysis of these photovoice responses in the context of specific research questions. We plan to conduct future studies also utilizing interview data and reflection questions from these students in order to investigate their experiences with teamwork (what their goals were, what challenges they encountered, and how they resolved those challenges) and their interest in, and knowledge about, quantum industry.

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APPENDIX A: PHOTOVOICE PROMPTS

The following were all of the photovoice prompts used throughout the Q-Forge course. The prompts followed by an asterisk were cycled through every 3 weeks (3-4 times total) in the second semester after we assessed how the first semester went:

First semester

- Take a photo of something that motivated you to take this course.
- Take a photo that represents what you think good communication would look like in the context of working on a team.
- Take a photo that represents the academic environment/culture you're familiar with here at the University of Colorado Boulder.
- Take a photo of something representing what you anticipate finding most challenging about any aspect of the [industry] project.
- Take a photo that represents how your team has decided to divide up tasks so far. The key aspect of this prompt is how your team decided to divide the tasks, not what each person did.
- Take a photo that represents the environment/culture of a company in the quantum industry.
- Take a photo representing how you feel about the project right now.
- Take a photo that represents how you deal with situations where you feel stuck.
- Now that you have your group roles, take a photo about how you are feeling about the team working together in the coming weeks.
- Take a photo representing what you find most interesting at the moment about pursuing a career in quantum industry.
- Take a photo of something with respect to the [industry] project that you are proud of.

- Take a photo representing your experience with teamwork as a whole during this project.
- Take a photo representing your experience with this course over the entire semester.

Second semester

- Take a photo that represents something you're excited or concerned about in Q-Forge for this upcoming semester.
- Take a photo representing your level of interest at the moment about pursuing a career in quantum industry.*
- Take a photo that embodies the ways your team worked together this week.*
- Take a photo representing how you feel about the project right now.*
- Take a photo that represents the journey you've taken in Q-Forge from last August until now.

APPENDIX B: PHOTOVOICE FOCUS GROUP PROTOCOL

The following questions were asked of the students with respect to each category of photos:

- What themes do you notice in these photos?
- How do these themes represent your collective experience with teamwork/quantum industry/the course as a whole?
- Do any of the comments other people made about your photos resonate with you? Were there any comments that surprised you?
- After hearing from the photographers, are there any changes you want to make to the list of themes you noticed in the photos?

We also asked the students several general questions about the photovoice process as a whole at the end of the focus group:

- To what extent did participating in the focus group activity change your perception of the photovoice activity as a whole?
- Are there ways that we could make the experience of participating in photovoice better for you?
- Is there any other feedback you haven't already given us about how the photovoice process has been for you?

APPENDIX C: REFLECTION QUESTION PROMPTS

The following are the reflection questions that were asked of students throughout the course of the year. The prompts followed by an asterisk cycled through in the second semester every three weeks (3-4 times total) after we assessed how the first semester went:

First semester

- What are you excited about with respect to the Q-Forge course?
- What are you nervous about with respect to the Q-Forge course?
- What are you expecting to get out of the Q-Forge course?
- For your Project Preference assignment, you entered a list of parts of the project you're interested in. Why did you choose those parts?
- Please explain how [the Python coding activity] affected your confidence in your coding ability.
- Was there anything surprising you learned during the discussion about intellectual property and nondisclosure agreements? Briefly describe what it was, why you found it surprising, and how it compares with the way ideas were discussed in your prior research and/or industry experiences, if you have any.
- How have the photovoice assignments been going for you so far? Have they helped you reflect on topics relevant for this class?
- In class this week, you've discussed some industry specific roles (e.g., project manager). How are these roles similar or different than what you or other team members have taken on during group projects in prior courses?
- After doing the essential skills modules [project management modules] this week, how comfortable do you feel using industry-standard terminology to communicate what are the necessary inputs and potential outputs of your project?
- At the moment, how confident are you about your ability to contribute to the [industry] project and why?
- What did you learn from the field trip both with respect to the quantum industry and with respect to your project?
- What is one challenge your team encountered while organizing the work for your project in the Project Scheduling activity due Friday?
- Did you and your team overcome the challenge you discussed above? If so, briefly describe how.
- After starting to work on the project, has your interest in pursuing a job in the quantum industry increased, decreased, or remained the same? Please explain.
- How are you taking into account the fact that your team size is going to change at the end of the semester in terms of your planning, team roles, and other work on the project?
- How have your interactions with the industry partners been? What has gone well? What could be done better?
- Give an example of a decision your team had to make together this week. How did your team collaborate in order to come to this decision?
- Describe one thing you did this week that you think is authentic to a real industry experience.
- Thinking about your experience giving peer feedback, which parts of it were hard and which were easy?

- Describe one thing you did this week related to Q-Forge that you do not think is part of an authentic industry experience.
- Think about one specific challenge with teamwork you had in the last week. Describe what happened.
- What strategies did you use to respond to the challenge you described above?
- To what extent do you feel that the support you've received from the course instructors and [the industry partner] has been adequate to ensure that you make progress on the project? Please explain.
- How are you feeling about your team's ability to make progress on the project given the updated expectations and project goals?
- You have now visited or had visitors from Atom Computing, Vescent, SRI, and Cold Quanta. What have you gotten out of your interactions with various quantum industry companies aside from [the industry partner]?
- How much time this past week did you spend on your assigned project role versus other parts of the project? Explain your decisions about how you allocated your time.
- How has working on this industry project impacted your interest in pursuing a career in industry?
- After participating in this industry project, how confident do you feel in your ability to successfully work in industry? Please explain.
- Are there any other comments or suggestions you want to make about any aspect of this course?

Second semester

- What goals do you have related to teamwork for this semester?
- What are you expecting to get out of Q-Forge this semester?
- Think about one specific challenge with teamwork you had in the last week. Describe what happened. If you can't think of any examples of challenges, tell us about a time when the team worked well together instead.*
- What strategies did you use to respond to the challenge you described above? If you wrote about a success above, what strategies did your team use to realize that success?*
- How did you feel about your team's communication with the industry sponsor this week?*
- Did you do anything in the past week that helped prepare you for a job in quantum industry? If so, what was it? If not, was there anything else you did for Q-Forge that you found valuable?*
- Give an example of a decision your team (or some subset of your team) had to make together this week. How did your team collaborate in order to come to this decision?*
- Did you have any experiences in the course this week that changed your level of interest in entering the quantum industry? Why or why not?*
- Describe how your teammates' differing levels of prior knowledge and skills have impacted how each team member has contributed to the project this semester.
- What skills do you feel like you didn't gain from this course that are important to being successful in quantum industry?
- Are you planning to enter the quantum industry after graduating? Why or why not?
- What goals related to teamwork did you accomplish this semester?
- How has the photovoice process gone for you over the course of the semester?

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