Challenges and outcomes in remote undergraduate research programs during the COVID-19 pandemic

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In the Summer of 2020, as COVID-19 limited in-person research opportunities and created additional barriers for many students, institutions either canceled or remotely hosted their Research Experience for Undergraduates (REU) programs. The present qualitative phenomenographic study was designed to explore some of the possible limitations, challenges, and outcomes of this remote experience. Overall, 94 interviews were conducted with paired participants; mentees (N=10) and mentors (N=8) from six different REU programs. By drawing on Cultural-Historical Activity Theory (CHAT) as a framework, our study uncovers some of the challenges mentees faced while pursuing their research objectives and academic goals. These challenges included motivation, limited access to technology at home, limited communication among REU students, barriers in mentor-mentee relationships, and differing expectations about doing research. Despite the challenges, all mentees reported that this experience was highly beneficial. Comparisons between the outcomes of these remote REUs and published outcomes of in-person undergraduate research programs reveal many similar benefits, including student integration into STEM culture. Our study suggests that remote research programs could be considered as a means to expand access to undergraduate research experiences even after COVID-19 restrictions have been lifted.

I. INTRODUCTION

Undergraduate research experiences (UREs) affect STEM students' academic pathways and career preparation by providing authentic research-based learning situations [1–5]. A large body of literature has reported both academic and psychosocial benefits as outcomes of in-person UREs. Academically, UREs have been reported to help students achieve a higher level of content knowledge [6], while also improving their eventual career outcomes [7, 8]. Psychosocial benefits refer to the positive growth in a student's perceptions, emotions, attitudes, and social dimensions around their academic experiences. Psychosocially, in-person UREs have been shown to help students increase self-confidence [9–12], develop communication skills [6, 11], improve scientific identity [7, 13, 14], and gain a sense of belonging in the broader community [7, 15–17].

One structure of a URE, which is common in the United States, is the Research Experiences for Undergraduates (REU) program, which is a ten-week summer research experience funded by the U.S. National Science Foundation. Due to the COVID-19 pandemic, some REU programs transitioned to a remote format in the summer of 2020.

Despite differences in the individual goals of each research project and research program, there are several common goals among undergraduate research programs; they all hope to increase retention in STEM career pathways, promote STEM knowledge and practices, and integrate students into STEM culture [18]. While many studies show these goals are often accomplished through UREs, they do not fully describe why UREs lead to increased retention in STEM among participants. In most studies of URE outcomes, data have been derived from self-reported surveys [8, 19] and end-of-program formal evaluations [7, 8, 19, 20], while fewer studies have used in-depth multiple interviews [9, 11]. Furthermore, most studies have exclusively explored the outcomes of in-person undergraduate research experiences, while rarely focusing on remote research experiences [21]. We designed the current study to identify the challenges that students experienced during their remote REU programs, as well as to characterize some of the outcomes of these programs. We used longitudinal semi-structured interviews with mentor-mentee pairs throughout and after the summer research programs. In the current study, we used Cultural-Historical Activity Theory (CHAT) [22–24] analysis to frame the relationships between the challenges and outcomes of the remote research experiences. In particular, mentees' experiences and outcomes within the REU program are modeled as a whole unit, which is called an activity system. Fig. 1 shows a simplified representation of the REU as an activity system in the standard CHAT format developed by Engeström, which represents the system as a triangle that connects a subject to their objectives and outcomes [24]. Section II discusses a more complete description of Activity Theory and section IV discusses the results of our analysis. These results focus on answering the following research questions:

- RQ1: What challenges were observed within the remote goal-directed REU activity?
- RQ2: What are some of the outcomes of the remote REU programs?

This study is part of an in-depth examination of an REU from multiple perspectives, including psychosocial growth [25], challenges and outcomes (this paper), and a more comprehensive description of the tools, communities, norms, and division of labor that occurred with remote REU programs (forthcoming).

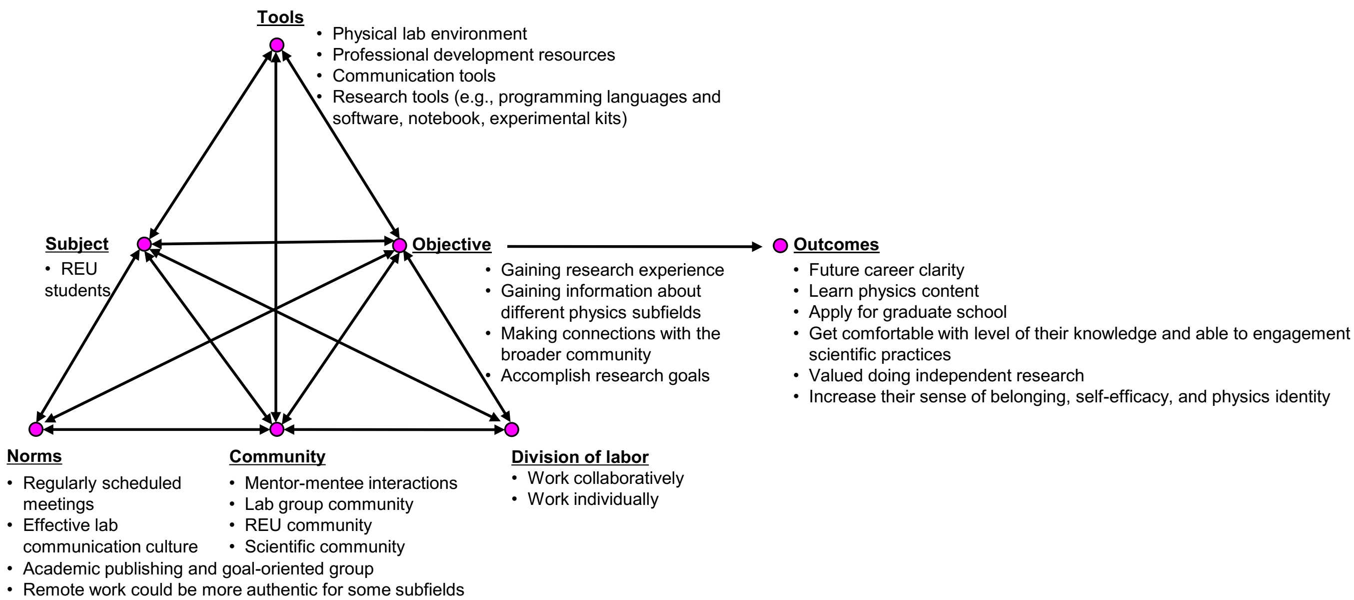

Figure 1. A representation of an REU as an activity system. The triangular model follows Engeström [24]. For each node of the activity system diagram we provide several examples from our data.

II. THEORETICAL BACKGROUND

We applied Cultural-Historical Activity Theory (CHAT or Activity Theory for short) [22–24] as our theoretical framework to help us characterize the challenges and obstacles in the remote REU setting, as well as identify and describe the possible outcomes of research practices in a remote environment. Engeström's third-generation Cultural-Historical Activity Theory (CHAT) argued that every human activity is goal-oriented and mediated by different components, including tools, division of labor, norms, and community. The triangular model of an activity system represented by Engeström's is shown in Fig. 1.

The links between the nodes in Fig. 1 demonstrate that they are dynamic and interact with each other, indicating how activity systems can capture unique features of each learning environment [24]. For each node, we provide brief definitions and give a few examples from our data (see Fig. 1). Subject refers to an individual or group whose perspective is considered for analysis. In our analysis, we identify each individual mentee as a subject. Objectives are the goals that are the focus of the activity system. For example, two common objectives for mentees included gaining research experience and accomplishing their research goals. The tools are material, symbolic, and conceptual resources used to mediate a student's pathway toward their goals. Tools can include the physical lab environment, professional development seminars, or programming languages. The community refers to the people who have shared goals with the subject, including research mentors, lab group members, REU participants, and a larger scientific community. The norms include the values, expectations, and guidelines that help the subject participate effectively in the community. Examples of norms within the research group include the frequency of scheduled meetings between mentors and mentees and how members of the community reach out and communicate with each other. Division of labor describes the different roles performed by the community as they work toward a common objective. For an REU, the division of labor includes how different tasks are shared between REU students and their mentors or other lab mates, as well as the degree to which particular tasks are done collaboratively or individually. Lastly, the outcomes are the end results of participating in an activity and could include gaining a clearer idea about future career paths in STEM.

One useful feature of a systems-level Activity Theory analysis is that it can reveal aspects of the system that have conflicting influences on the activity. The observable effects of this misalignment are referred to as tensions that result from an underlying systemic contradiction. A plausible example would be a mentee whose goal is to be recognized by their research mentor for doing a good job at their research. If the mentee believes that asking questions is a sign of ignorance (a norm) then they may avoid asking questions to make it appear they understand more and gain their mentor's approval. However, by not asking questions and communicating with their mentor, they may be less likely to progress in their scientific research, have a successful mentor-mentee relationship, and ultimately receive the recognition they desire. In this example, there is a contradiction between the norms (question-asking indicates ignorance) and the relationship to the community (mentor), which affects the mentee's likelihood of accomplishing their goal (recognition). Generally, tensions, problems, or frustrations that affect the achievement of goals can be interpreted as contradictions within and between elements in the activity system. Identifying contradictions is important because it provides a mechanism that explains why the problem occurred, which can be used to improve remote REU activities in the future.

III. METHODOLOGY

In this article, we explore REU programs from both mentees' and their paired mentors' perspectives. Both mentors and mentees were aware of each other's participation in this study. The interviewer assured students and mentors that their personal perspectives would be confidential and not divulged. We adopted a qualitative longitudinal phenomenographic approach combined with the CHAT framework [24] to collect data throughout the REU program and after it finished. The phenomenographic aspect of our study design aimed to investigate the variation in the ways that the mentees talked about each component of the remote REU activity, including the outcomes [26, 27]. The longitudinal design focused on different features of the activity system at different times. The longitudinal design also captured students' academic and psychosocial growth during the program, which was described in our earlier work [25, 28].

A. Data collection

We sent 64 physics REU program coordinators an email asking if their REU would be offered in a remote format in the summer of 2020. We received eight positive answers. Mentees were recruited into this study by an invitation email from their REU coordinators on behalf of us. After students volunteered to participate in our study, we contacted their mentors. Our overall sample (total N=10 mentees and N=8 mentors) included eight mentees with eight paired mentors and two mentees with no paired mentors. Unfortunately, their mentors (one woman and one man) declined to participate in our study. Demographics of all participants are shown in Table I. The sample of mentees was gender and ethnically mixed, while the mentors were all men. All mentees were physics majors. Additional information about the mentees' projects can be found in Table III in the Appendix (all participant names are pseudonyms). The students were compensated with a $20 gift card for their participation in each separate interview, which was sent weekly.

All participants were individually interviewed at multiple points throughout the REU program in the summer of 2020 and one time after the REU program finished (interview nine with mentees and interview ten with mentors). We video-recorded all interviews via Zoom with the permission of the interviewees. Mentees' interviews took between 60 and 90 minutes, while mentors' interviews took between 30 and 45 minutes. Overall, 94 interviews were conducted. Fig. 2 shows the overall protocol content for each week of the interview and how it was aligned with the CHAT framework.

Mentees' Characteristics		**Number (N=10)**
Gender	Women	4
	Men	6
Race	White	5
	Asian	3
	Mixed	2
Year of college	Rising senior	7
	Rising junior	2
	Rising sophomore	1
Type of home institutions	Ph.D. granting institutions	4
	Master's granting institutions	2
	Bachelor's granting institutions	4
Mentors' Characteristics		**Number (N=8)**
Gender	Men	8
Type of REU institution	Doctoral Universities	6
	Baccalaureate Colleges	2

Table I. Participants' characteristics

B. Data analysis

Each interview was recorded and auto-transcribed with Zoom for analysis. After the interviews were completed, the transcripts were cleaned to fix errors and punctuation. The transcripts became the focus of our phenomenographic analysis. To answer the research questions posed in this article, we focused on the REU activity system as a whole to understand mentees' desired and observed outcomes and their challenges.

Analysis needed for research question 1. Mentees discussed numerous challenges while reflecting on their research experiences. For example, we identified challenges based on mentees' descriptions of things that are "kind of frustrating" or "not working right" and situations where "it's hard to get feedback."

The analysis process occurred in multiple stages, including data immersion and identifying descriptions of CHAT elements (i.e., tools, norms, community, objective, division of labor) using Dedoose software [29]. Then within each CHAT element (e.g., tools) we looked for subcategories that described the different ways that stu-

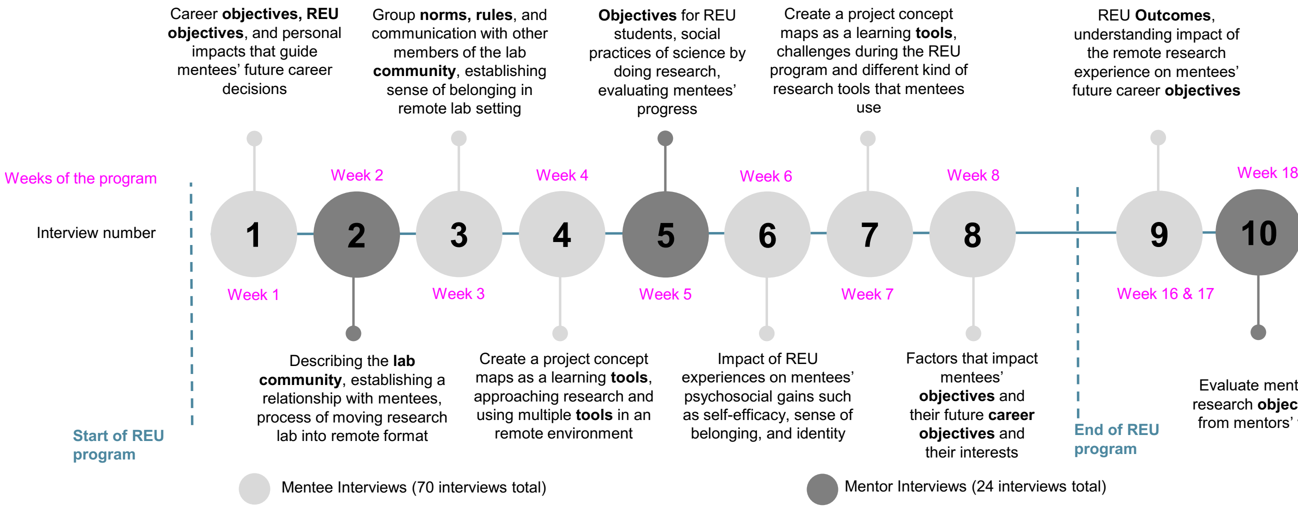

Figure 2. Timeline of the longitudinal study that explored multiple facets of the REU as an activity system. The bold words indicate intentional alignment between the interview protocol and the CHAT framework. The interviews included perspectives from mentees (light gray) and mentors (dark gray). Interviews 9 and 10 occurred after the REU was complete and emphasized many of the outcomes that are discussed in this paper.

dents experienced that CHAT element. As a final step, we constructed activity system diagrams (see Figs. 3-9) to better understand the underlying causes of common challenges that students faced.

During data analysis, Dr. Dina Zohrabi Alaee (DZ) identified tensions based on what mentees explained to her when they were facing challenges or other difficult situations. After several rounds of discussion between DZ and BMZ, we noticed that tensions could occur both within one element of the activity system, such as a lack of community, or between components of the activity system, such as a lack of connection between tools and objectives. We used the theoretical lens of CHAT to reconstruct the features that led to the particular challenge. CHAT helped us to examine the interactions between the elements that participants mentioned during their research experience.

Analysis needed for Research question 2. Mentees were asked directly about the outcomes of the REU experience at multiple points during the REU program and after it finished. Most of the results from this research question emerged from interviews 9 (mentees) and 10 (mentors), which focused on the impact of the REU experience on mentees' academic goals. To address research question 2, DZ identified moments when participants talked about the outcomes of the REU program based on what they learned and how they thought this remote research experience would impact their professional and academic decisions. DZ then applied a phenomenographic analysis process by reviewing every excerpt related to outcomes and searching for variation. Next, DZ sorted them into themes based on similarities. Our main goal when using phenomenographic methods was to gain insights into our participants' perspectives regarding REU outcomes. DZ met regularly with BMZ to discuss the coding process. In the discussion (Sec. VI), we compare the outcomes of these remote experiences with previous research on the outcomes of in-person research experiences.

IV. RESULTS ON RESEARCH QUESTION 1

What challenges were observed within the remote goal-directed REU activity?
The COVID-19 pandemic impacted both mentors and mentees who participated in the remote REU program. They all joined this program with their own expectations, concerns, and emotions about the new remote research format. Although some challenges arose uniquely due to COVID-19 and the REU's remote format, we also observed challenges that could have occurred in any research opportunity. For instance, Grace said, "We were very delayed in getting our access to the supercomputers at the beginning, which was a little frustrating"– Interview 9, (Solid State Physics). This challenge was not unique to the remote REU format because the supercomputer is always accessed remotely (though COVID-19 likely disrupted employees who were responsible for helping Grace obtain supercomputer access). This section provides examples of ways in which the remote format both created unique challenges for students and exacerbated difficulties that might have occurred anyway

during in-person REUs.

Working from home introduced technical challenges. Several mentees mentioned they had a hard time accessing the right technologies, partly due to the lack of resources and partly due to the lack of in-person contacts who could provide technical support. This phenomenon is demonstrated in Fig. 3, a diagrammatic representation of the challenge showing that tools were not able to mediate the research goals due to a lack of access to the proper tools and community support to use those tools. For instance, Helen, who simulated the decay process of short-lived isotopes, had some difficulty trying to compile different software. She said, "I think the actual processes aren't that difficult, but where I've struggled is downloading the different software and trying to become familiar with this new software well. I think [I] understand what the general approach should be, but... Downloading it and trying to compile it was challenging... It's hard to do it remotely"–Interview 4, (Nuclear Physics). This struggle with software issues persisted most of the weeks during the REU program. David used his less powerful personal computer to do research. He described in addition to "getting used to the way the software works" he also needed to do it on his personal computer, " involving a lot more processing time,...as opposed to a more powerful computer. In the beginning, I was able to do things more by trial and error because it would only take a few seconds or a few minutes to run a simulation. Now, it takes a few hours. I have to make sure that I understand beforehand how to get the software working right because it takes a long time and wastes a lot of time if I'm trying to do it just by trial and error"–Interview 4, (Acoustic).

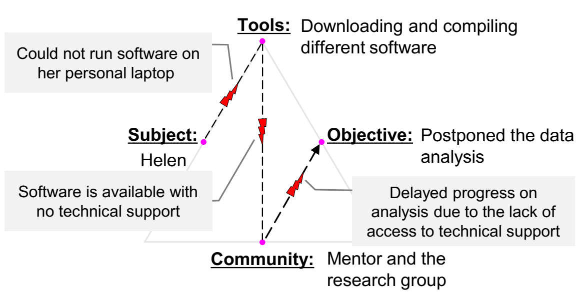

Figure 3. Example showing how working from home introduced technical challenges. The dashed lines represent tension between elements of CHAT.

Working from home introduced motivational challenges. The sudden transition from working in a lab environment to working at home in pajama pants and hanging out with family members introduced several motivational challenges. A lack of social interaction (working from home in isolation) and lack of communication with other members of their research lab also made some mentees feel discouraged about their research work. This

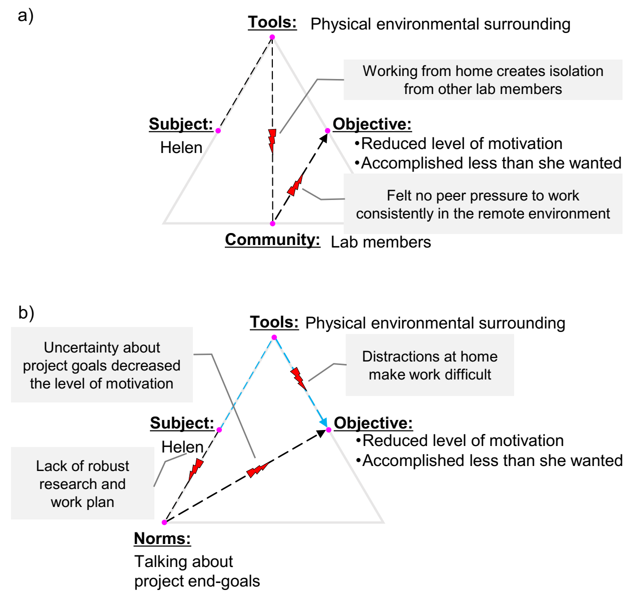

Figure 4. Example showing the different motivational challenges that working from home created. The different dashed paths represent tensions between different elements of CHAT. a) Dashed lines represent tension in mentees' level of motivation and productivity due to a working environment that creates isolation and no sense of peer community. b) Dashed lines represent tension in mentees' level of motivation and productivity due to the lack of a robust research plan (black dashes) and due to distractions created by working from home (light blue dashes).

isolation impacted mentees' motivation and performance at a time when they needed to feel more connected to and recognized by their research lab community.

Fig. 4 represents different tensions created by working from home. Because of their separation from a physical research lab, mentees' had less understanding of the research lab norms and less communication, which reduced their level of motivation and negatively impacted their progress. Mentees were usually asked by their mentors to conform to the work norms of the research lab (e.g., staying on task and reaching out for help). However, conforming to these norms was harder in a remote format without seeing other members of their lab adhere to the same norms and feeling some of the "peer pressure" to work consistently.

For instance, Helen stated that doing research in the remote setting was "harder when you're not around everyone else doing the research... It's kind of harder because different things are happening in your house. You just don't have that same motivation sometimes from your environment." She also said, "I haven't really necessarily seen [the end goal of the project]. Sometimes that's been hard since I feel like I need to know what I'm doing is on the right track. But I think also I'm doing less than what I want to do. It's kind of hard to know what point you should be working on. Like, what other people are up to in their programs because you don't get to see them every day and have the subtle interaction" –Interview 6, (Nuclear Physics).

Lack of social interaction with other lab members made Bruce feel isolated, which reduced his productivity. He said, "Being personally motivated was kind of difficult...because I was living at home. There are currently five people at home. Most of the rooms are taken up by other people's activities... There were certainly some things that were distractions. Now that I'm looking back I wished I had gone outside more. Because I really kind of got clumped inside and that probably wasn't great for me. I felt like my mind got stuck sometimes because of that"–Interview 3 & 9, (Quantum Optics). Fig. 5 graphically depicts how the lack of a physical and social lab environment for Bruce impacted his motivation.

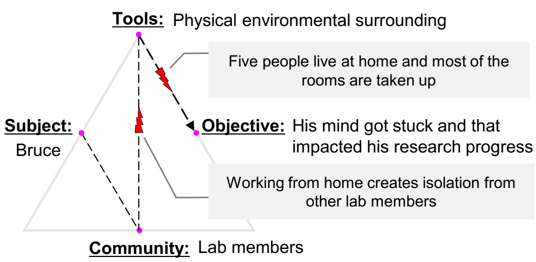

Figure 5. A second example showing how working from home introduced motivational challenges. The dashed lines represent tension between elements of CHAT.

Information overload and lack of time introduced challenges. Many new researchers experience difficulties learning the background material required for their work. However, these difficulties were exacerbated in the remote setting, as students were unable to take part in the informal learning interactions that happen when immersed in an in-person research group. Even the most motivated and organized mentees were frustrated by the amount of new knowledge that they had to learn during the limited time of the REU program.

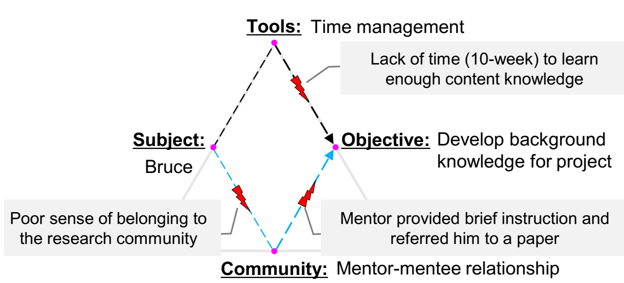

Figure 6. Example showing how information overload and lack of time introduced challenges. Black dashed lines represent tension in the REU activity system due to the lack of time, and the blue dashed lines show the tension in the mentor-mentee relationship due to the lack of sufficient instruction.

As one example, during most of the weeks of the REU program, Bruce felt quite frustrated. He said, "I certainly feel overwhelmed at some points in time. There's just a lot of reading, I feel like there [are] a lot of things I need to understand just to be able to get to the point where I could start doing research"–Interview 3 (Quantum Optics). Fig. 6 shows an example of a mentee (Bruce) with limited background knowledge who hoped to gain more knowledge during his meetings with his mentor and complete his research project. Bruce's frustrations arose from a lack of time to learn enough and a poor sense of belonging to the research community due to a lack of good mentor-mentee relationships. He said, "There were times when [my mentor] starts talking [about his research, his past students, and conferences he went to], and I kind of just have to sit back and listen to him. I don't feel great about it because it ends up just being a long period of time where I'm just being lectured... If I have an issue, he would briefly talk me through that, but he will refer me to a paper that would answer it, or a section of a textbook that would answer that question." A lack of background knowledge on the project may lead a mentee to feel like an outsider in the lab because they can't participate in, or even understand, the conversations in the lab. Overall, a lack of background knowledge and limited time are general features of any REU program. However, in a remote setting, it is more difficult for mentors to determine when mentees feel frustration. Mentors do not see mentees most of the time and they receive fewer indications from body language, facial expressions, and tone of voice during Zoom meetings.

In comparison with Bruce, Frieda's situation provides a good example of how mentors can effectively support their mentees. Frieda talked about the efforts her mentor made to identify and teach the essential knowledge and how he asked her to join their big research group meetings with all the other researchers in the field. She recalled her mentor telling her, "You're going to come to these group meetings and you're not going to understand most of what they say, but that's okay. You're going to get there." She continued "Mostly I've been listening because I don't know that much yet... I think that he is just preparing me, so hopefully, I will [know] eventually and be able to contribute as well. After each of those meetings, my mentor met with another REU student and me and worked through some of the terminology and stuff [that they talked about in a big group meeting]. He's doing a really good job of making us feel like we can understand it"–Interview 3, (High Energy Physics). Her mentor also said, "We also have a real working research meeting and I've invited her and my other student to that. I [told them] it's important for you to see how these meetings run... and seeing the scientific process at work. Then what we will often do after those meetings where they said they don't understand anything, we'll go back in line by line go through what was discussed... and a lot of terminologies"–Interview 5. As Frieda's example shows, engaging mentees in reflective thinking and scientific conversations around their projects can develop positive relationships, support learning, and improve research productivity.

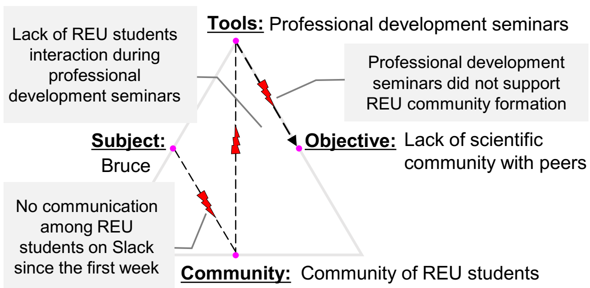

Figure 7. Example showing how lack of communication opportunities among REU students introduced challenges. The dashed lines represent tension between elements of CHAT.

Lack of communication opportunities among REU students introduced challenges. A lack of a community of peers that provides mutual support during the REU program might be one barrier to integrating students into the STEM and retention in STEM. For example, many REU programs hope to create professional development seminars and form experiences that integrate students into the STEM culture and particular STEM fields, while also improving collaboration and peer community. However, in those online professional development seminars, students had no opportunities for collaboration and quietly listened to the faculty member who explained their field of research. Our data indicate that the remote REU participants persistently lacked community throughout the REU program.

Fig. 7 shows how two goals (community and career preparation) were in tension. We observed that although REU coordinators aimed to provide career preparation and advice during the professional development seminars, these seminars were primarily information delivery rather than peer discussions and interactions between mentees. The professional development seminar brought everyone into the same Zoom room but adversely affected the community among students. According to Bruce, "[Having a community] really has kind of fallen by the wayside, to the point where there has not been a single chat in the group chat since the first week." He continued that during social events and seminars, the REU students did not interact because they were listening to lectures, and he wished they had some sort of 'all groups meeting' where they could present their work to each other.

Barriers in mentor-mentee relationships introduced challenges. A good mentor-mentee relationship is key to having a successful research experience. Analysis of the data identified that most mentees maintained a positive relationship with their mentors. However, a lack of adequate communication tools and lack of physical proximity in a remote lab setting made it harder to form this relationship. Over the course of the COVID-19 pandemic, meeting over instant communication apps such as Zoom became the norm for communicating remotely. However, these tools have limitations and shortcomings. For example, the Zoom platform was blocked or had a bad connection in China. Joshua's mentor said, "We use Zoom. But, we also use WeChat. Because sometimes Zoom does not work very well, we lost connection"–Interview 10. Having group meetings more than once a

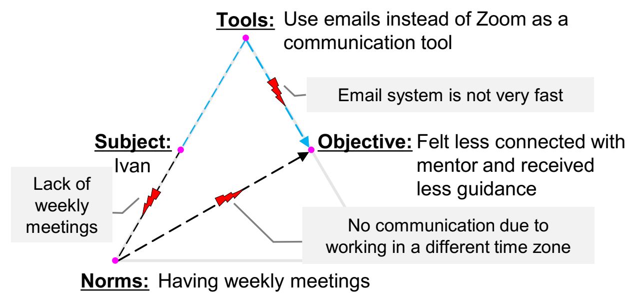

Figure 8. Example showing how barriers in mentor-mentee relationships introduced challenges. Black dashed lines represent tension in the mentor-mentee relationship due to the lack of weekly meetings and the blue dashed lines show the tension in the mentor-mentee relationship due to the use of emails instead of Zoom.

week was one of the productive norms among some REU groups in a remote lab setting. Weekly check-ins were vital for supporting mentees' research goals and helping them develop more open communication with their mentors. However, some mentees felt that they were not a priority for their mentors and that they primarily communicated with their mentors via email. For instance, Helen said, "We zoomed in the beginning, and I've talked about what my role would be. Then we've just been emailing out the next plan for what I'm doing. I know he has two kids. I think that it's just been like a little hard for him to stay in touch as much"–Interview 3, (Nuclear Physics). This challenge was probably unique to COVID-19 due to the juggling of childcare, school, and full-time work responsibilities with children at home. Fig. 8 shows how the lack of communication tools and physical proximity can impact both the mentor's and mentee's contribution to the new norm of weekly check-ins in the online setting. Ivan also did not have many weekly meetings over Zoom, but for a different reason. Ivan lived in a very different time zone from his mentor. He said, "We do not have virtual meetings. We send emails... [He] looks very busy with other people and I think the email system is not very fast. I want more guidance from him"–Interview 3, (High Energy Physics). Ivan's mentor described challenges when collaborating with him, saying, "I should have told the REU director that I couldn't manage a student who is in a 14-hour different time zone. Unfortunately, the only available hours for me to meet with Ivan overlapped with my meeting hours with people at CERN. In the past, I had always managed the REU time commitments by meeting with people in CERN in the morning and the REU students in the afternoon. Because they were local. And that was just not an option [this summer] and there just weren't enough hours in the day for me to meet with Ivan"–Interview 10.

Differing expectations between mentors and mentees introduced challenges. Barriers also arose when mentees' expectations differed from their mentors' expectations. Ivan, who was also enrolled in summer courses at his home institution, said, "I had to take lots of courses and I did not have too much time to do research... My mentor gives me lots of information that I can read on my own. I have to use lots of time to do it. He treats me as a researcher and a physicist and he gave me lots of raw materials and I have to do it on my own"–Interview 6, (High Energy Physics). Meanwhile, his mentor believed that "It was hard to really get his attention and get him working on the projects as a remote student...and apparently a miscommunication about the amount of time that he was supposed to have budgeted for the REU experience... I don't really know that he has a good idea of what it's like to be a researcher and to work in high energy physics because the ability to pursue a research question fairly independently is a pretty central aspect of that experience and I don't think he got there"–Interview 10.

Interestingly, differences in expectations between Ivan and his mentor were about more than how time was used on the project. Ivan thought his research group was not serious and formal, which affected the time and effort he dedicated to his REU. He said his lab members were "Very kind and funny, [but] it is just different from my expectations"–Interview 3, (High Energy Physics). He said, "My mentor just sent me some instructions and if I am working along those directions, I get the work done"–Interview 3 & 6. He wished his mentor asked him to bring "some ideas about doing some research." His feeling about his project did not change over the duration of the REU program. After the REU program finished, he said, "I just followed some things just have been done before. So maybe not very big [research], it is maybe just a little part"–Interview 9, (High Energy Physics). Meanwhile, his mentor thought "He might have been a little bit disappointed with the research project he had because I think he wanted to look at big overarching questions, and we wanted him to look at the data that came out and some checks... We all have dreams of sitting in a room and dreaming up some theory that explains everything. However, you have to learn a certain amount of discipline and commitment to seeing through the tedious part so you can get to the fun parts of having a discovery or learning something"–Interview 10. The representation for this tension in Fig. 9 shows that both the mentor and mentee did not speak regarding their expectations and did not communicate properly as a group to consider each other's goals. For Ivan, he expected to do a bigger project and explore his own ideas rather than follow instructions and solve smaller problems. On the other hand, his mentor assigned him tasks that were matched to his prior experience and effort level. The mismatched expectations and norms between mentors and mentees were not a very common theme across the sample of 10 students. However, when this issue does arise, it can significantly diminish the quality of the outcomes.

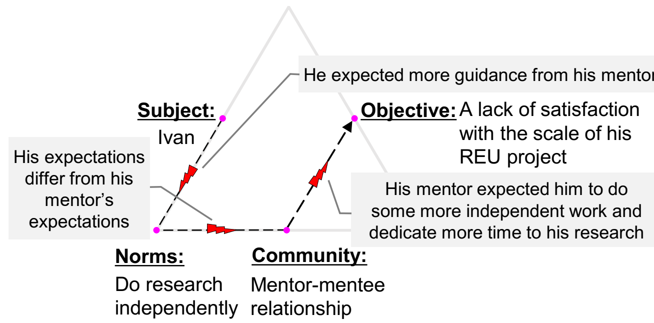

Figure 9. Example showing how differing expectations between mentors and mentees introduced challenges. The dashed lines represent tension between elements of CHAT.

V. RESULTS ON RESEARCH QUESTION 2

What are some of the outcomes of remote REU programs?

Outcomes are the final part of the goal-oriented REU activity system. A few weeks after the program finished, in the 9$^{\text{th}}$ interview, we asked all mentees to describe the outcomes of their REU experience. We found that almost every mentee, despite their different projects, challenges faced, and different circumstances during COVID-19, described having achieved many of their goals to some degree as a result of their research experience. When mentees talked about the challenges and benefits of their programs, they all expressed satisfaction to some extent and all stated that attending the REU program was the right decision in their academic journey. The following subsections explain several of the specific outcomes of the remote research experience.

Mentees described learning physics content. All mentees expressed that their remote research experience deepened their knowledge of discipline-specific project content and also introduced them to new areas of science. An example is Grace, who said, "I am learning a lot about chemistry and biology and just how much physics intersects with everything, and how it is fundamental science. Overall, I am definitely enjoying learning how to use the program, learning the chemistry and physics involved has been really interesting and enlightening"–Interview 7, (Solid State Physics).

Joshua, an international student, talked about how much he learned from extracurricular activities during the REU program; "In GRE preparation courses, I learned some required physics concepts in English... These are important for my future career. In seminars, I broaden my horizons, such as I learned some new physics knowledge in other physical areas"–Interview 7, (Nuclear Physics).

Mentees gained information about future career paths. The remote REU experience positively impacted most mentees' interest in graduate school. Most of the mentees (N=8) said the REU experience helped them understand the nature of research work and think about their future careers in one of the subfields of physics. David stated, "Not only I was able to learn more about the software and about the research going on in one of the fields that I am interested in, but also because I was able just to get a better understanding of how research works and that sort of dynamic. I got a better feel for what doing research with a professor looks like so that I have a better understanding of how that will work when I am, for example, in graduate school doing research"–Interview 9, (Acoustic). Caleb learned that he might prefer a balance of hands-on and computer-based work. He explained he enjoys computational and theoretical research, but "I would like to be in a lab-type setting; some days, I am doing hands-on research, and other days, I am doing computational stuff. My biggest takeaway from the REU program is that I do not think I could just be on a computer for eight hours a day"–Interview 6, (Atomic Physics). Due to a lack of knowledge about different career options, some mentees were initially uncertain about their interests, but developed clearer plans during the experience. For instance, Joshua said that he is interested in studying nuclear physics in graduate school now, but "Before the REU program, I did not even know what I was interested in because there were too many fields"–Interview 9, (Nuclear Physics).

Our data show that most of the REU programs offered a variety of seminars on topics such as GRE exam preparation, Python programming, science writing, ethics, graduate school preparation, and different subfields of physics. However, seminars about career options outside of graduate school were not mentioned in the interviews.

Mentees intended to apply for graduate school. After finishing the REU program, most mentees (N=9) were sure that they would like to apply to graduate programs. Frieda said, "It was really good for where I was in my education and made me seriously consider this field as a graduate school field, which, not that I was not considering it, but I am much more serious about considering it now"–Interview 9, (High Energy Physics). Similarly, Andrew describes how the REU contributed to his desire to do research in graduate school. Andrew said the REU program "has influenced me in the fact that it makes me want to do graduate school and research more. Because beforehand, I do not know if that is going to be a lifestyle I want to get into. I have not done research before, so I did not know if it [would] be something I enjoyed or something I [would] absolutely hate. So after doing this REU, I enjoyed this. I can see myself doing that"–Interview 9, (Nuclear Physics).

Bruce was unsure about his future career during most weeks of the REU program. However, in the last interview, he said that his mentor provided him with a new perspective and insight on doing research. He said, "I definitely think that [my REU mentor] had a strong influence on making my decision about graduate school"–Interview 9, (Quantum Optics). Bruce explained that this influence came from stories that his mentor told him about his previous students' career decisions and also from giving him a sense of how he does research. He said, "There [are] just so many different ways that they're either the professors or they're working in research labs or in different things... It's just stuff that I really would like to be doing in the future as a career... I think another [influence] is just he's giving me a sense of how he does research... He's not always super stressed about everything. He's not overworking himself. This idea that you can be a researcher and not overwork yourself all the time is also quite enticing"–Interview 9, (Quantum Optics).

Mentees planned new learning opportunities in STEM fields. Some mentees explained how they planned to tailor their activities toward their future career goals by choosing elective classes, attending seminars, or reading related articles and books after the REU finished. One example was Joshua who decided to take some elective courses in astrophysics and nuclear physics the following semester to narrow down his interests. Other mentees tried to read and search through the literature related to their summer research experience. For instance, Helen said, "I am part of the American Nuclear Society and get updates and stay informed, especially around medical physics. I always have liked reading Physics World news about medical physics, listening to podcasts, and connecting with people. So I have definitely been more interested in learning more in that area after that REU"–Interview 9, (Nuclear Physics). Similarly, Andrew said, "What I did over the summer made me want to learn more about that... I got a book on nuclear physics, and I was kind of reading that as the program went along"–Interview 9, (Nuclear Physics).

Mentees valued doing independent research. Due to the lack of in-person interaction between mentees and other members of the lab community, mentees had to engage in substantial independent learning. For instance, Caleb said, "[The remote format] makes [the research] a lot more independent. Because you are still able to reach out via email, Zoom, or whatever platform you use, but there is that added step of composing the email asking for Zoom chat. Whereas in in-person, you just like walked out to the office, or they are in the room with you, and just like look over your shoulder. So, it adds a lot more independence”–Interview 7, (Atomic Physics). Likewise, David explained that he became more independent in his learning since, “I will be in the middle of a project, trying to figure something out in the middle of the day. Then I will just go look it up and try to figure it out. I usually use it as a resource on my own, and I think that might be a bit different if I was working with the professor, more closely in a physical environment”–Interview 7, (Acoustic). Although independence is an important factor in any research work, some mentees were hoping to be less reliant on their mentors, such as Ivan. As described in section IV, Ivan wished his mentor had let him explore his ideas about the direction of his research. Instead, Ivan lamented that “I am just a follower in this program.”

Mentees were comfortable with their knowledge and ability to engage in the scientific community. Regardless of the project area, every REU program aims to provide opportunities for students to develop research practices and become lab community members through collaborative work. During interview nine after the REU program finished, eight mentees described feeling more comfortable with their ability to get involved in their community (e.g., by asking questions and learning new concepts) and became more comfortable with the level of their knowledge. For instance, Grace said, “[I can] ask a question and not feel like I am asking a stupid question. It is very hard to look back on my near past self and reflect because... It is hard to see [how much I] changed”–Interview 9, (Solid State Physics). David said, “I had a better understanding of what was going on. So I was able to contribute a lot more”–Interview 9, (Acoustic).

Increase in sense of ownership of research projects. In our previously published study, some mentees talked about a sense of ownership as a factor that linked to their sense of belonging [25]. We found that students developed a sense of ownership of their project when they recognized their own accomplishments and produced potentially new results for their project. In addition, giving students the freedom and autonomy to make some decisions about their research activities was linked to a sense of project ownership. For example, Caleb said, “I really liked [my mentor] and his style of mentorship. He makes sure you’re doing your stuff, but he also gives you the freedom to do your stuff. He’s not overbearing so it’s a good balance... His approach of giving you enough freedom, but enough like a good balance of freedom and guidance. [For example], you get a model or you get a graph and data, and you feel a good sense of accomplishment. Like I really did this instead of kind of like he’s telling me what to do the entire time”–Interview 3. On the other hand, his mentor said he is supporting him “By respecting and giving him great freedom. If he had ideas on how to do things, I would say, ‘Do it and show me.’ I did not have to tell him, this is how you do it step by step. In the beginning, yes, but it did not take long to get going on his own and then come up with his own improvements and extensions and search. I certainly think that encouraged him”–Interview 10. Overall, five mentors described how they intentionally helped mentees’ sense of ownership by offering them responsibility in their projects. These mentors explained that their mentoring philosophy includes helping mentees increase their sense of ownership. Two other mentors cultivated ownership by providing a bigger picture of the project and giving students responsibilities. As Frieda’s mentor explained, “She had a project, and it was very well specified that this was her project. There was no one else working on it... So, it was hers and hers alone”–Interview 10. No one else would do what Frieda was working on, so the team needed her to get her part done.

Mentees described growth in their sense of belonging, self-efficacy, and physics identity. A higher level of sense of belonging and identity is associated with improved academic performance and possibly enhanced persistence in the field of physics. Sense of belonging (to a physics lab or broader community) and physics identity both describe the degree of personal attachment to the field. For example, physics identity can be defined as the self-recognition of being a physics kind of person or a physicist. Many mentees reported growth in their sense of belonging, self-efficacy, and physics identity. We have already described the psychosocial benefits of these remote REU experiences in more detail in another paper [25]. However, for completeness, we summarize these benefits here because they were an important outcome of the remote REU experience. We found that a supportive lab research community and mentor-mentee relationship helped most mentees to exhibit psychosocial growth. Findings for the self-efficacy construct indicated that self-efficacy stemmed from various sources, such as getting more physics content knowledge, doing independent research, producing new results, and communicating with other members of the scientific community.

Almost all mentees reported a higher level of belonging to their lab community and possibly to the disciplinary community at the end of the REU program. David said he had a “place in the field now”. He said, “Just because I have been able to experience [research] and contribute as well as being able to look through the work that other people have done in the field a lot more in-depth and having done my little bit of work in the field helps me to understand better the work that others have done in it... Even now that I am not doing that research full time, I feel much more in part of that than when I was only taking classes before”–Interview 9, (Acoustic). Likewise, Frieda considered herself to be part of the physics community because of the growth she recognizes in herself. She said, “Now I feel I know a lot about it, I have gotten a lot done, I am informed, and I feel more in it, like I am more submerged in it personally. Maybe you could say my physics identity has gone from like an amateur to like a beginner to intermediate now. I feel like I am actually part of the field"–Interview 9, (High Energy Physics).

VI. DISCUSSION

We used the combination of phenomenography and the CHAT framework to understand the challenges in remote REU programs. Based on our semi-structured interviews, mentees shared with us different types of challenges they faced during the remote REU program. As we outlined in section IV, COVID-19 and the remote format impacted students' learning. Essential components of effective learning, such as readily available feedback and having a good mentor-mentee relationship, were harder in a remote format.

Although the first research question identified some challenges, our data still showed that the outcomes of the remote REU program broadly align with the generally accepted benefits of an in-person undergraduate research experience. Table II compares the primary goals for UREs described in the literature [18] (left column) with outcomes of the remote research experience from our findings (right column). It should be noted that mentees described outcomes that are short-term (e.g., preparing graduate school application materials) and long-term (e.g., future career decisions). When outcomes are viewed more generally or at a coarser grain size (e.g., getting research experience), the remote and in-person formats often seem similar. However, if we examine more specific outcomes with a smaller grain size there are clearly differences. For example, remote experiences lacked the experimental and hands-on elements and were largely confined to theory and computational projects. However, because most literature describes outcomes more generally, we will focus on this comparison at a coarser grain size.

Most previous studies of in-person UREs have identified outcomes that fall into three major categories [18]: increasing retention and persistence in STEM, promoting STEM disciplinary knowledge and practices, and integrating students into STEM culture [14, 30, 31]. We use these same three categories in Table II and link our findings (Sec. V) to each of these categories.

Increasing mentees' retention in STEM fields. Undergraduate research experiences can impact students' retention in STEM degree programs and provide them with a new way of thinking about their future career paths in STEM fields. In-person UREs often aim to help mentees understand what it means to do research and what a science career might look like [18]. The outcomes associated with this goal across our data included: clarifying future career interests; applying for graduate school; and engaging in new learning opportunities in the STEM field. Mentees reported gains in their knowledge around specific subfields of physics. They described how weekly meetings, doing research, and talking informally with their mentors about their future career options enhanced their career preparation. This result is consistent with prior research that has examined the influence of UREs on students' long-term outcomes, such as clarifying future career goals [9–11].

Promoting STEM disciplinary knowledge and practices. UREs can help students to develop new skills, learn new knowledge, and engage in the practices of their STEM discipline, such as using computational models or analyzing and interpreting data. The outcomes associated with this goal in our data included learning content knowledge through the REU experience, gaining independence as a researcher, and developing questioning skills. In terms of the activity system CHAT triangle, the disciplinary knowledge and practices would be considered research *tools* that support the research objectives of a student's project. Several previous studies on URE outcomes indicated that meaningful research practices could facilitate students' learning and development of their technical knowledge in addition to promoting their communication skills [6, 11, 18, 32]. Similarly, in our data, multiple mentees said they felt like they better understood physics concepts and what was going on in their lab research group. They reported an increased understanding of physics knowledge due to their contributions to scientific work and discussions among their lab group. Additionally, many reported becoming more active and independent learners due to the remote aspect of the program.

Integrating students into STEM culture. Other studies of in-person UREs mentioned that undergraduate research experiences could strengthen students' motivation and interest in STEM culture. Integration into STEM can be thought of as a psychosocial growth process (e.g., a gain in physics identity [11, 12, 16], self-efficacy [13, 20, 33], and a sense of professional belonging [16, 17]) as students learn the knowledge, practices, and values of the discipline. Although integrating students into STEM culture seems a hard goal for remote UREs to achieve due to the absence of face-to-face interaction between community members, our results indicated that students felt growth in terms of their performance, competence, and how the other members of the research community recognized mentees as physics people and trusted them as researchers.

VII. CONCLUSIONS AND RECOMMENDATIONS

Prior to 2020, the vast majority of articles about online education debated whether such methods were effective and whether academia should more broadly use remote learning. In a perfect world, sometimes! However, when the COVID-19 pandemic began in early 2020, many institutions rapidly experienced a remote learning transi-

Goals expressed in literature for students participating in in-person UREs [18]	**Short term outcomes of the remote Research Experiences for Undergraduates based on our data**
Increase mentee's retention	· Clarifying future career interest
in STEM fields	· Applying for graduate school
	· Engaging to new learning opportunities in the STEM field
Promote STEM disciplinary	· Learning physics content
knowledge	· Appreciating value of doing research independently
	· Utilizing disciplinary research practices by asking questions and directing projects
Integrate students into STEM	· Finding interest in physics field
culture	· Expressing higher level of sense of ownership of their project during REU experience
	· Becoming enculturated in the physics community and expressing a stronger sense of belonging, self-efficacy, and physics identity as a result of the remote REU experience [25]

Table II. Comparison between the primary goals for in-person UREs and the actual outcomes for the remote REU program.

tion. In this study, We attempted to elucidate some of the challenges and outcomes associated with remote research experiences. Our data shows that all participants described their remote experience as a "real" research opportunity that achieved desirable outcomes. The remote format still allowed mentees to meet their personal goals by the end of the program.

Although there were many positive outcomes, here we discuss five recommendations to address some of the challenges we noticed (see Sec. (IV)). There is not necessarily one "right" way to run a research program, and institutional context will influence each individual program's solutions. Nevertheless, we hope these ideas spur on innovation and increase the quality of remote research opportunities in the future.

Recommendation 1: Provide technical support for students working from home. One finding from our study dealt with technical challenges that mentees faced while working at home due to a lack of resources and support. However, some students did not face this kind of challenge due to the nature of their project or because their mentor overcame this challenge by providing them with additional support from graduate students. To address this challenge, first, we suggest that programs should ensure that all of their students have access to adequate technology. In addition, because REUs occur over a period of approximately ten weeks, it is important to get students off to a quick start. To facilitate REU students' engagement with technology immediately upon entry into the REU program, it would be beneficial to have a point of contact who can respond quickly with technical-related help (e.g., software installation). For example, this could be a graduate student or a technology support staff. Second, mentors can provide more training in using technology in order to fulfill students' project goals. The training documentation including manuals, software handouts, and resources could be available online before the program starts.

Our findings indicate that working from home is likely to reduce motivation. We identified a lack of a robust research plan, a lack of interaction between REU students, and a lack of interaction between students and their mentors as specific issues that negatively impacted students' motivation. In Recommendations 2, 3, and 4 we suggest a few ways to address these challenges.

Recommendation 2: Support students learning and develop learning plans. We noticed that students often struggled and felt overwhelmed by the amount of knowledge they had to acquire during a 10-week program. This challenge is probably common to both in-person and remote REU programs. In particular, it can be difficult for many students to differentiate between essential versus interesting background knowledge in order to prioritize what they should learn by themselves. Literature searches and textbook resources will likely contain more new terms, concepts, and mathematics than students can learn over the summer. Not all students faced this challenge. For example, as described earlier, Frieda's mentor provided support to his students learning by talking about topics, ideas, and concepts after each meeting. It is important to have scaffolding and structure in the learning process. Mentors can help mentees to organize their learning materials. For example, mentors could differentiate between articles and content knowledge that are essential to achieve the project goals and those that are optional to read. They can also help mentees better understand how to read them (skim versus in detail) and how to find good resources if they need to. This guide will help students not get overwhelmed by the extensive amount of new knowledge and what they have to learn.

On top of that, for some students, understanding how their project fit into a bigger research effort helped them to engage more deeply and feel less aimless about what they should be doing in their project. We suggest that mentors and mentees could co-develop a detailed learning plan including: a timeline of the project, different resources and references, steps to get to that goal, and possible results and outcomes. Furthermore, the plan could make explicit what depth of knowledge and what concepts are required to accomplish particular aspects of the project. Some aspects may require procedural knowledge (e.g., for an experimental process that is rigidly fixed) while other areas require deeper and more flexible concepts and mathematics (e.g., for developing or improving a computational model). Such a plan could guide students' decisions about balancing effort between learning background knowledge and making concrete progress toward research goals. These planning steps could raise motivation and productivity.

Recommendation 3: Provide regular interactions between REU students. One challenge discussed in our data was the lack of communication opportunities among REU students during the REU program and the lack of motivation due to isolation. We noticed that some students had social engagement activities such as online movie nights and informal discussions that helped them to feel connected with their REU and lab community and to feel less isolated. We that online REU programs can plan social activities outside of their research projects such as an online movie night, a book discussion club, an online yoga class, an online game night, or other events so students can share their daily life together as a part of a community.

In addition, mentors and REU coordinators can create fun activities to facilitate social interactions among REU students. For instance, we recommend students work toward a non-research common goal through informal, creative, and collaborative activities, such as designing an REU T-shirt. These activities may help students to build their interpersonal skills and friendships. Mentors and coordinators could also offer peer check-in opportunities or schedule times that REU students can work together in the same Zoom room. Students need to support and encourage each other when facing similar challenges. These professional interactions may make students feel connected to their research community and become more motivated to do research.

Recommendation 4: Provide regular weekly check-ins between mentors and students. Our results indicate that most students reported experiencing quality mentorship. However, a few students mentioned that their mentorship experiences fell short of meeting their expectations and resulted in challenges. Offering one or more weekly meetings with the mentor and/or lab group will help mentees to understand the norms and expectations of doing remote research and support better mentor-mentee relationships. In addition, meetings create opportunities for students to get engage in their community and feel more included and motivated. Also, choosing communication platforms that are easy to use may help students feel more connected to their research group and know that their mentor is easy to approach and available throughout the research process.

Recommendation 5: Developing shared expectations. This recommendation addresses challenges around mentor-mentee relationships, including differing expectations between mentors and mentees. As we mentioned above, having weekly meetings provides the opportunity for students to ask questions and to build a stronger understanding of their research project. Additionally, this creates a culture of communication where mentors and mentees can discuss what they are looking for during the REU program and be clear about their expectations around doing research. Mentors could establish open communication early on, even before the REU begins, to talk about the nature and time commitment of the work. Additionally, mentoring contracts could be used to articulate shared expectations, provide a foundation for the mentor-mentee relationship, and support the mentee's growth [34]. These efforts can be used to address questions such as: How often can the student meet with their mentors? How often can the student expect to receive feedback about their progress? How long will meetings be? How should mentees document their progress?

VIII. FUTURE WORK

While COVID-19 was an unwelcome crisis, it caused us to rethink our standard practices and gave us insight into possible improvements in undergraduate research opportunities. As stated earlier, one of the main goals of undergraduate research programs is to increase the retention of students in STEM fields. Future studies may consider exploring students' career outcomes a few years after experiencing remote undergraduate research programs. Another issue to be addressed in future studies is how physics identity and sense of belonging to various levels of the physics community (e.g., peers, professors, and community of scientists) form during research experiences. Students' motivation and engagement in remote settings is another issue that could be addressed in future work. We found evidence that without face-to-face interaction (e.g., direct conversation over Zoom) in a remote learning setting, students experience lower levels of motivation. Furthermore, our study was conducted to explore challenges during the early stage of the COVID-19 pandemic with the most restrictions, which was a particularly challenging time. Similar studies could examine remote research experiences now that most restrictions are lifted and life is more similar to pre-pandemic conditions. This new research could better determine which challenges are more general features of remote research experiences and which were pandemic related.

Overall, the outcomes of these remote undergraduate research experiences were sufficiently positive that similar programs could be organized in the future. Remote UREs have the potential to provide wider access to research opportunities, and they would provide education researchers with additional opportunities to study learning in a unique educational environment.

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APPENDIX: REU PROJECTS' CHARACTERISTICS

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Name	Area of research	Description of project
Andrew	Nuclear Physics	Understand the efficiency of detector, learn about details of the old nuclear reaction simulations, and refine the new simulation
Bruce	Quantum Optics	Numerically model quantum optical devices, learn PyBoard coding, use digital time delay and construct the circuit with equipment that shipped to his home
Caleb	Atomic Physics	Examine at the atomic structure and different spectroscopies and make a model for specific properties
David	Acoustic	Make a basic resonator model to learn the modeling program and then make an acoustic model of a reed instrument
Emma	Physics Education	Science outreach and build a 3D-printed particle and Particle Physics trap and work with electronics that shipped to her home to make circuits
Frieda	High Energy Physics	Use different models in high energy physics to predict the probability of different decay modes in collisions
Grace	Solid State Physics	Learn the density functional theory and model certain molecules and look at the dynamics of the system
Helen	Nuclear Physics	Simulate the decay process of short lived isotopes, learn about different isotopes and different spectra fields, and literature half lives
Ivan	High Energy Physics	Gain knowledge about CMS and LHC and use simulations and experimental data to refine the codes for detection of the charged particles in a large collider experiment
Joshua	Nuclear Physics	Understand neutron mirror model and add new equations into the old code to solve problems related to nuclear physics

Table III. Projects' characteristics.

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