Formation of students' interests in quantum technology across STEM majors

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The Quantum Information Science and Technology (QIST) workforce is rapidly expanding as it helps develop transformative technologies used for computing, sensing, and communication. However, exposure to quantum concepts in high school and college is limited for students in many science and engineering degrees, which means many students may lack knowledge about QIST and what the subject entails. This project involved interviews with 22 undergraduate students from varying STEM disciplines. In our analysis, we separate students with high and low interest in QIST across the following factors: awareness and early learning experiences, course-based learning experiences, perceptions of math in quantum, perceptions of the scariness and mystery of quantum, perceptions of a disconnect between QIST and their primary discipline, and perceptions of quantum careers. We examine why quantum may be viewed as "scary" or "mysterious", and how quantum technology may come into contact with their discipline. Many interviewees expressed an interest in quantum, but were reluctant to pursue it as a subject due to a perceived disconnect with their own discipline. Overall, we hope that developing an understanding of students' views of QIST will support ongoing improvements in the development and implementation of introductory QIST courses, minors, and tracks.

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I. INTRODUCTION

Quantum Information Science and Technology (QIST) applies quantum mechanical concepts to develop new approaches to computing, sensing, and networking. For example, quantum computers may speed up the ability to solve certain specialized problems, such as factoring products of large prime numbers (relevant to breaking modern encryption) and simulating chemical and material structures (needed for designing pharmaceuticals and improved batteries).

In recent years, the study of QIST has become relevant for jobs in science and engineering. With its implications for computing, communication, and sensing, QIST education has become a national priority for developing an emerging technology workforce [1]. There has been significant growth in the number of courses and programs about QIST [2] and there are efforts to include QIST topics at the high school level [3]. This project is focused on understanding how science and engineering students form interest in QIST with the goal of identifying ways to increase student interest.

Rosenberg *et al.* [4] studied STEM students at a university and their interests and knowledge about quantum. They found that out of all of the STEM students they interviewed, 56% did not know anything about quantum careers in general. Although there was little prior knowledge about career paths with quantum, 63% of the students showed a high interest in pursuing a career related to quantum.

Through interviews with students from differing STEM programs (e.g., engineering, cybersecurity, physics), we will answer three different questions: (1) How are students with a high or low quantum career interest becoming aware of QIST?, (2) How do they perceive quantum in general and QIST specifically? , and (3) What factors affected their interest in QIST topics and careers?

II. THEORETICAL FRAMEWORK

Social Cognitive Career Theory (SCCT) is a framework designed to explain how career interests are developed in individuals through different choices and backgrounds [5] [6]. Four SCCT constructs were utilized. *Learning experiences* can include classes or personal accomplishments within a certain subject, as well as experiences outside of the classroom, such as undergraduate research or self-directed learning. *Self-efficacy* is an individual's belief about themselves, particularly their confidence to perform specific activities. *Outcome expectations* are beliefs about the activity itself (e.g., it is hands-on, leads to good-paying jobs). These can all change how *interests* form in certain subjects and therefore shift choices for their future [7].

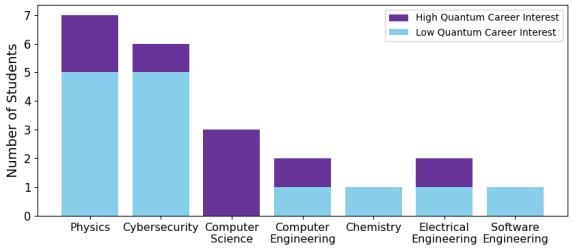

FIG. 1. A plot showing the distribution of interviewees by major. 8 students had shown a high quantum career interest. 14 students had shown a low quantum career interest.

III. METHODS

To investigate how we can increase interest in QIST courses and programs, we conducted semi-structured interviews that probed students' prior experiences with quantum and QIST. The protocol included questions such as "How did you become aware of QIST?", to understand where students encountered QIST or related concepts, either in the media or in their college courses. Diving deeper, we also asked students "How do you distinguish quantum (as a general topic) from QIST, or do you consider them to be the same?". Finally, we want to discover what factors may influence enrollment in courses, a minor, or even pursuing a career in QIST by asking "In what ways might you become disinterested in a quantum course or career?". Many of these questions were written to be aligned with the constructs of SCCT (e.g., self-efficacy) and to answer at least one of the research questions we posed.

The 22 participants in this study ranged from first- to fifth-year college students and came from seven different STEM disciplines. Students were recruited from a quantum computing course, a Discord channel for physics students, and through flyers posted around campus. All students had varying levels of quantum knowledge and interest. Figure 1 shows a graph with the distribution of all interviewees by major. Students were separated into two categories. Eight students (7 men, 1 did not provide gender) had a high quantum career interest (i.e., expressed interest in pursuing quantum-related jobs). Fourteen students (11 men, 2 women, 1 transgender) expressed low quantum career interest (i.e., interested in other fields and had no intention to pursue a quantum-related job after college). We hoped that this distinction would reveal the experiences and attitudes that differentiated high- and low-interest students. Interviews were conducted and recorded either in person or over Zoom.

The analysis of interview transcripts used Dedoose qualitative data analysis software. This program allowed for highlighting specific excerpts and tagging them as a parent code (see Table I), which was named after either a construct of SCCT or a concept that answered one of the research questions. Child codes were created to summarize each high-

lighted quote. In total, 9 parent codes were used with 805 child codes being applied.

A codebook was created for each parent code with the code description, inclusion criteria, and an example excerpt. An abbreviated version of this codebook is shown in Table I.

After completing the interview analysis, the parent and child code data were then brought into the diagramming software tool Lucidchart. Within Lucidchart, child codes were grouped into common subsets or subthemes. For example, the parent code "View idea of quantum" included 11 subthemes, such as "Math in quantum" and "Disconnect of quantum". Every child code underneath the subtheme "Math in quantum" had an excerpt that mentioned math being involved in quantum. Across the 9 parent codes, 34 subthemes were created to group most of the 805 excerpts. 60 excerpts that were not added to subthemes either did not fit in a common category or did not have certainty on where they belonged within the results.

IV. RESULTS

The results are separated based on whether students had a high quantum career interest (N=8) or a low quantum career interest (N=14). Within each results subsection, we describe 6 categories, each corresponding to one subtheme: quantum awareness and learning experiences, course learning experiences and self-efficacy, math perceptions of quantum, scariness and mystery of quantum, quantum disconnect, and quantum career perceptions. When referencing the word "quantum" in comparison to QIST, we refer to any ideas that students may have, including scientific ideas from quantum physics, quantum mechanics, and quantum technology, but also other associations they may have with the term.

A. Students with high interest in QIST careers

Quantum awareness and learning experiences: Three students mentioned their awareness before college, while two others had said that they became aware of quantum through the introduction of a quantum minor at their university, as well as conversations in a computing course. When asked about alternate resources students looked to for information about quantum, 4 high-interest students noted that they watch YouTube videos regarding the topic. Another popular resource to learn about quantum was the use of IBMs Qiskit [8], which is an online open-source software for users to learn about quantum programs and algorithms. One student mentioned they started a quantum journal club at their institution. Ted, a computer science major, said, "...I run a club, which I started to kind of teach me more about quantum. I'd say that is one place. We just read research papers and talk about them. It's not that crazy, but that is one place..." All of these sources are ways for students to learn about quantum outside of their college classes.

Course learning experiences and self-efficacy: Out of the eight high-interest students, three were taking classes within the quantum information science minor, one of whom had already obtained the minor. The rest of the students in this section had not taken any minor courses but were currently in a quantum course or had taken one in the past. Quantum mechanics was more common for physics majors, while a quantum technology course was more common for computing-related majors. Beyond quantum courses, one student created a quantum video game in collaboration with a professor.

Five students in the high-interest group noted increased self-confidence and confidence to solve physics problems after taking a quantum course. Gabriel, a computer science student, said, "...the whole experience was really good, definitely beneficial to myself, like I kind of, it did give me confidence to be, like, okay, like, no matter how hard something is, like, I am confident in my ability to figure stuff out." Other students mentioned that they would be reluctant to take more quantum courses if it had a possibility of taking away from other course topics that they may be more interested in.

Math perceptions of quantum: Most high-interest students mentioned that the amount of math and linear algebra that appears in quantum courses may be unexpected for students. Matthew, a computer engineering student, expressed their struggles with math in quantum physics. He said, "So the topics that I struggled with was keeping track of very long calculations... I can see why to get to quantum through the physics path takes a while." This follows Meyer *et al.* [9] who studied instructors and how quantum is taught across different environments. Students may have a harder time connecting to the content if it strays further away from their main discipline's curriculum.

Scariness and mystery of quantum: When high-interest students thought about quantum, they mentioned the scariness of it in reference to other students who were not as educated on the topic. Aside from mentioning the scariness of quantum, other students noted that the "mystery" and "strange nature" of quantum can be a positive idea. Mark, a computer science student, noted, "...to me, it's a hop and jump away from real magic in a way. So to me, quantum is very much like real world wizardry, in a sense." The quantum mystique may be scary and off-putting to some students, but is a source of motivation for others, particularly students in the high-interest group.

Quantum disconnect: The disconnect expressed by most of the high-interest students was how learning quantum in the classroom may be different than what you encounter in the real world, such as in a career in quantum. Students said that classroom material on quantum revolves heavily around theory, while a career in quantum would require more hands-on work. Another common disconnect is that QIST can be separated from general quantum mechanics theory in many courses. Alex, a physics major, said, "I kind of separate, like, you know, the foundations of quantum mechanics from, like, quantum information science. I think in general...quantum information science is kind of like a thing that's either a sepa-

TABLE I. Parent codes and their descriptions

Learning Experience	A course, interaction, or action/activity that taught the student a new topic that they had previously not known about or wanted to learn more about.
Self-Efficacy	A student's confidence or sense of belonging regarding any aspect of their college career.
Quantum Career	What is expected in a career in quantum; why a student would/wouldn't want to go into a quantum career.
Quantum Education Resource	A resource used outside of college and classes to learn more about quantum concepts (e.g., YouTube, Wikipedia, Scholarly articles, etc.)
View Idea of Quantum/Overall Interest	How a student views quantum in general, what concepts they think of when they hear the word "quantum", and what aspects may affect their view of quantum.
Increase Quantum Interest	A suggestion or idea towards how to increase overall quantum interest to the students or general public.
Quantum Awareness	When the student first heard about or became aware of the word quantum.

rate class or kind of tacked on to the end of stuff." In physics, students were expected to learn the basics of quantum mechanics as a required course. However, QIST was rarely discussed in required physics courses. On the other hand, some computing and engineering students were exposed to ideas of QIST within their required classes, even though quantum mechanics was not one of their required courses.

Quantum career perceptions: When asked about ideas of what a quantum career may look like, the most common answer was the expectation to be constantly creating new discoveries. The high-interest students also mentioned the need for a higher degree in order to get into the field of QIST. Gabriel, a computer science student, noted this regarding a quantum career: "I think it's very, like, cool, very stimulating, working on all these, like, fancy, cutting-edge things... it's just a very interesting career, and... it probably pays well, yeah, I guess it would check a lot of those boxes." Overall, these students thought QIST careers would be meaningful and they had a positive outlook for future work.

B. Students with low interest in QIST careers

Quantum awareness and learning experiences: All fourteen low-interest students expressed awareness of quantum before college through mentions in high school courses or through television and other media. Similar to the high-interest students, eight of the low-interest students mentioned YouTube and Wikipedia as alternate education resources outside of classes. Other students mentioned that they read science articles or magazines or listened to podcasts about quantum topics. In comparison to the high-interest students, some low-interest students spent time learning quantum because it was interesting but not to further their education. Burt, an electrical engineering major, said, "I hear a lot through [various sources], and it's always super interesting to read about. But I don't really know what they're talking about a lot of the time, but I just still read it anyway, because I'm just like, this is cool."

Course learning experiences and self-efficacy: In the low-interest group, it was noted that three out of fourteen of the students were currently taking classes within the quantum minor. Two students noted that they had not taken any quantum or quantum-related course during their time in college at the time of the interview. The rest of the 9 students in the low-interest group had taken a quantum-related course, with the most common being Modern Physics. Most physics students within this group had plans to take a required Quantum Mechanics course at some later point in their college career. Many of the students who hadn't yet taken a quantum course, such as early-stage physics majors who typically take quantum mechanics in year four, noted that they would feel more confident in solving quantum problems after taking a course. These students also mentioned that they would have a positive sense of belonging within a quantum course, although they expected it would come as a "challenge".

Math perceptions of quantum: The outcome expectation that quantum requires a significant amount of math was a factor in determining students' interest. Math in quantum was also a concept that some students found confusing. The low-interest students, whether they had already taken a quantum course or not, had an expectation of heavy math. Gerald, a physics major who had not yet encountered any quantum courses, said "I think quantum entails a lot of math. Looking in my head, I think back to the early 20th century physicists that were working on it. And the next thing that pops in my head is the loss of sanity." Regardless of the quantum course experience, there was a perception of heavy math involved in quantum. This idea is expressed by Burt, who says, "...it feels... as if it's like a too-smart-for-you kind of concept where they hear the word quantum and they get scared immediately because they go, Holy crap, that's a lot of math. And that's, that's math I don't want to do."

Scariness and mystery of quantum: With a major con-

trast from the high-interest students, the low-interest students expressed the scariness of quantum as something that pushed them away from pursuing the topic. The negative stigma around the topic gave way to possibly untrue beliefs about what quantum courses entail. Bonnie, a physics major, expressed this idea by saying, "Quantum sounds scary. Quantum is just like one of those things where it's like, quantum, ugh!". For some students, the scariness and mystery of quantum were a negative idea that pulled students away from further pursuing the topic. Gerald mentions this by saying, "I definitely did struggle [with quantum]. And I think here's the issue, because I might have blocked that out of my brain."

Quantum disconnect: For low-interest students, the largest disconnect of quantum with the most comments came from physics students, with some mentions that the physics curriculum lacked a "lead-up" to the required quantum mechanics course, even though there is a required modern physics course. This left some students feeling unprepared for the quantum mechanics course. Another aspect of the disconnect was described by Patrick, a cybersecurity major, who expressed how quantum felt so distinct that there was not much benefit to go into it, considering their discipline. Patrick noted, "I mean, quantum is so isolated, and any kind of technology involving using any kind of quantum mechanics is so specialized that it's just like having experience in it, but not having a large amount of knowledge and experience in it, is it really beneficial?". Patrick, as well as 2 other students, noted that the idea that quantum mechanics felt unrelated to a major or career lowered interest in furthering education on the topic.

Quantum career perceptions: Students in the low-interest group had varied answers compared to the high-interest group. While they thought that a quantum career would require a PhD, they also leaned heavily towards the implication that a career would involve many computational simulations and requirements. Gerald, a physics major, expresses this by saying, "...I could see it being like computational, you could probably run simulations of what this would be like, so you could find either a noise in the system or the effectiveness of the system, how fast it's going to run like, I feel like there's a lot of simulations that you can do specifically for quantum computing." Four students in this group noted that they did not have any idea of what a quantum career would entail, either due to not looking into the idea or not being educated in quantum courses about it. Clara, a physics major, mentioned, "Aside from quantum computing, it's really hard to fathom what a career in quantum would look like outside of academia..."

V. DISCUSSION

The results suggest several ways to increase interest and enrollment in quantum courses, as well as build up quantum programs for undergraduates. One significant implication of this research is that students, even physics majors, have very little knowledge about quantum careers and how QIST connects to their own field of study, echoing results from Rosenberg *et al.* [4]. Outreach about how QIST can be incorporated into different disciplines could increase awareness and relevance to students.

Looking at quantum awareness, both high- and low-interest students sought resources outside of their coursework. However, there were differences in how these students went about searching for more information about quantum and QIST. The high-interest students tended to look deeper into the topic, with an eagerness to learn more, while the low-interest students learned more by simply coming across the topic in media sources. In other words, students who have a higher interest in quantum will actively search for more information. We also note that many popular science descriptions of quantum emphasize the weirdness and strangeness [10]. For higher interest students, the mystery and complexity leads to curiosity, but for others it makes quantum topics seem distant, inaccessible, and intimidating. Instructors should carefully use the "weirdness" of quantum to avoid alienating students.

This research also affirms the idea that many students may benefit from simpler QIST courses that develop an introductory interest first [11]. Both high- and low-interest students who had taken a quantum course noted how they enjoyed it and felt more confident after taking one, and those who had not taken one felt a need for a lower-level course to feel more comfortable. Such a QIST course would be suitable for first-year students and would show connections between quantum-related topics and a variety of undergraduate majors. This would increase relevance, encourage future learning, and relieve the scariness and mysteriousness that both high- and low-interest students felt.

Finally, it is important to recognize the similarities and differences between those with a high and low quantum career interest. Both groups of students see a quantum career as either a job with the need for higher education, a research position, or a computational environment. High-interest students tend to have more knowledge of what they see themselves personally doing in a quantum career, while some low-interest students are not able to envision a quantum career. Creating more outreach on what a quantum career entails, as well as how certain disciplines can apply their knowledge to a quantum career, can personalize interest in a future career and create a new possibility for students who were not aware of how they could contribute to quantum technologies in the future.

Students' reactions to quantum and QIST topics varied depending on their prior academic knowledge, which sheds light on possible roadblocks that prevent some students from pursuing additional QIST-related opportunities. We hope this work and future research on students' QIST career interests can help guide changes to curricula that improve access and appeal to a wider range of students.

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