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Review of Literature on Quantum Information Science and Technology Programs for High School Students

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***Abstract*—This review of literature critiques recent research (2019-2023) on quantum information science and technology (QIST) programs designed specifically for high school students. Since QIST research and applications are advancing rapidly with an accompanying global demand for QIST workforce development, it is important to understand how high school students may be introduced to QIST concepts and skills early in the academic pipeline. The review identifies best practices for QIST teaching and learning, how prerequisite mathematical skills are addressed, methodological approaches and limitations, as well as QIST practices in high school outreach programs that have not published empirical findings. Implications for practice and future empirical work are discussed.**

Keywords—high school students, outreach, quantum education, quantum information science and engineering, quantum information science and technology, review of literature

I. Introduction and Scope of Review

Rapid quantum information science and technology (QIST) advances and U.S. federal initiatives have resulted in an increased focus on early exposure to QIST knowledge and skills in the science, technology, engineering, and mathematics (STEM) academic pipeline. The U.S. National Science and Technology Council (NSTC) has identified QIST workforce development as a critical component of strengthening the research and discovery of disruptive technologies in quantum sensing, computing, and communication [1]. QIST innovations hold tremendous promise for improving human lives in many ways, for example, by developing environmentally sustainable energy consumption, revolutionizing pharmaceutical care, strengthening cybersecurity, and developing advances in agricultural science [2]. The economic impact has been considerable, with the QIST global economic market reaching $42B in 2023 [3]. Consequently, it is essential to promote QIST learning so students become interested in the many career opportunities in related fields [2].

Part of NSTC's long-term recommendations for expanding and diversifying the QIST talent pool includes outreach and educational approaches that facilitate awareness of QIST principles, skills, and careers for precollege students [1]. Early, consistent engagement with STEM is a critical factor in attracting a diverse talent pool for the workforce [4]. For students developing aspirations for QIST careers, access to advanced mathematics, physics, chemistry, and computer science coursework is important since these courses include disciplinary content and skills closely related to QIST [5]. For example, the National Q-12 Education Partnership has identified *Key Concepts for QIS Learners,* including the mathematics of probability, quantum states, entanglement and superposition, coherence, and quantum measurement [5]. Exposure to these QIST concepts is an additional challenge since many U.S. high schools do not offer the advanced mathematics, physics, chemistry, and computer science courses in which these ideas may be taught [6]-[9]. This has created a need for informal learning opportunities to fill the gap in formalized precollege instruction in QIST concepts and skills [10]. However, many of these programs are relatively new so it is important to evaluate their content, structure, and effectiveness to justify expansion to larger groups of students. This review of literature focuses on recently developed QIST programs for high school students in grades 9-12, which typically includes students of ages 14-18.

There are many informal STEM education programs with a focus on QIST-related topics for high school students, as well as traditional classroom-based approaches, and several have published their disciplinary content and the pedagogical methods that were employed [11]-[20]. However, few researchers have published empirical data on programmatic outcomes [19], [20], making it challenging to learn from their experiences. Therefore, this literature review seeks to examine existing QIST programs for high school students to compile best practices for fostering student interest in and knowledge about QIST topics and careers.

Table I summarizes the publications examined in this literature review, all of which were found by searching in Google Scholar for the terms "high school quantum information science and technology" in October 2023. Google Scholar was set to only include results since 2019, and the phrase "high school" was in quotes for the search to decrease the occurrence of articles about advances in QIST and about college majors and courses. This search yielded ten relevant publications that discussed programs specifically for high school students that varied greatly in pedagogical strategies, content taught, and prior knowledge required for participation. Of these publications, all ten provided a description of the content, eight

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provided a discussion of their findings (quantitative, qualitative, anecdotal), and two provided instruments for assessment [16], [17]. This review is structured to evaluate best practices and disciplinary content, prerequisite skills, measurement of student outcomes, and exploration of well-known programs that have not published empirical findings. Recommendations for policy and practice are also discussed.

TABLE I. SUMMARY OF QIST-RELATED INTERVENTIONS WITH PUBLICATIONS

Author(s), Year	Program Summary	Publication Content
Akdemir at al, 2021 [11]	A three-period (55 minutes each) in-school quantum cryptography lesson outline (formal) with no testing or assessment provided.	☑ QIST Content ☐ Findings ☐ Assessment data
Angara at al., 2020* [12]	A one- or two-day quantum computing workshop (informal) outline; tested the one-day workshop on 25 high school students; discussion of outcomes was based only on student feedback (no content assessment was given).	☑ QIST Content ☑ Findings ☐ Assessment data
Angara et al., 2022* [13]	(a) *HighTechU* – A one-day quantum computing workshop (informal); tested on 18 high school students and assessed by a post-survey asking students to evaluate their own understanding of topics covered. (b) *Quantum Week* – A one-day online quantum computing workshop (informal); tested on 6 students in grades 8-12 and assessed by a post-survey asking students to evaluate their own understanding of topics covered.	☑ QIST Content ☑ Findings ☑ Assessment data
Economou et al., 2020 [14]	A two-day quantum computing workshop (informal) outline with no testing or assessment provided.	☑ QIST Content ☐ Findings ☐ Assessment data
Hughes et al., 2022 [15]	A week-long in-school quantum computing workshop (informal) developed by national lab staff and high school teachers; tested on 2 cohorts of 20-25 students (ages 15-18), each in a classroom setting; assessed by descriptive statistics from a pre-/post-survey on interest level, content knowledge, and importance of learning quantum computing.	☑ QIST Content ☑ Findings ☑ Assessment data
Ivory et al. 2023 [16]	A week-long QIST summer program (informal) developed by staff from national labs, academia, industry, and educational non-profits; tested on 32 students in 10th-12th grade; assessed by a post-survey about program impact (20 of the 32 students completed this survey).	☑ QIST Content ☑ Findings ☑ Assessment data
Salehi et al., 2022 [17]	Includes data from 22 two- or three-day quantum computing workshops; tested on 430 students with complete data from 317 students (only 19 of these were high school students); assessed by pre-/post-surveys on content knowledge and satisfaction with the program (this is the only publication to include quantitative inferential analysis of the data in addition to providing descriptive data).	☑ QIST Content ☑ Findings ☑ Assessment data
Satanassi et al., 2021 [18]	A six-day (3 hours each day) extracurricular quantum computing workshop (informal) as part of the ISEE Erasmus+ project; tested on 25 students in grades 11-12 and assessed by observations of students during the program.	☑ QIST Content ☑ Findings ☐ Assessment data
Tappert et al., 2019 [19]	A five-day in-school quantum computing workshop (informal) designed by a PhD candidate; tested on a 12th grade class (size not stated) in a classroom setting; assessed by a post-survey that asked students to rank the topics covered by their level of interest in them.	☑ QIST Content ☑ Findings ☑ Assessment data
Walsh et al., 2022 [20]	A full-year in-school quantum computing course (formal); tested twice—once on a class that moved from an in-person format to an online format starting in March 2020 due to the COVID-19 pandemic and once fully virtual the following year; assessed by end-of-year focus groups and observations.	☑ QIST Content ☑ Findings ☐ Assessment data

**Publication from 2022 describes the findings of the program described in publication from 2020, plus an additional program.*

II. Best Practices for QIST Teaching and Learning

Because of the relatively high difficulty level of the topics taught in QIST interventions, all publications analyzed in this review included several different strategies for easing the students' transitions into quantum concepts. There were many similarities among the ten publications, particularly in the pedagogical strategies used, topics covered, and prerequisites for participation, although notable differences are identified.

A. Pedagogical Strategies

The ten publications included many pedagogical strategies for providing an in-depth learning experience for students that was also approachable and age-appropriate for high school (Figure 1). These strategies fell into five major categories: (1) using multiple teaching modalities for each topic; (2) including hands-on activities to represent abstract concepts; (3) having students play games to reinforce concepts; (4) giving students experiences using quantum circuits and other advanced computational tools; and (5) providing opportunities for students to meet role models in QIST fields.

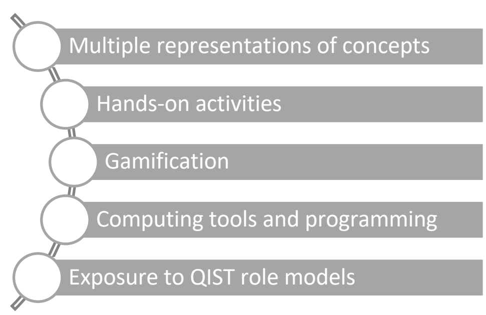

Fig. 1. Pedagogical approaches for teaching QIST concepts and skills.

1) Multiple modalities: To help students gain an understanding of topics that were completely new for most program participants, researchers provided several different ways of representing each concept to students [12]-[14], [18], [20]. Angara et al. [12], [13] utilized a combination of four types of activities to encourage student learning: (1) hands-on "unplugged" activities; (2) pencil and paper practice sheets; (3) programming activities via partly pre-filled Jupyter Notebooks; and (4) a board game that reinforces topics covered. Economou et al. [14] used a combination of lecture, pen and paper exercises, and computer-based simulations, all of which contained both visual representations and statistical representations. Satanassi et al. [18] also combined introductory lectures with activities, in this case teamwork activities focusing on problem solving and the societal implications of quantum computing, and epistemological whole-group discussions. In addition, to increase the potential for student understanding, they described each topic by relating the mathematical or logical explanation with experiments and/or equipment and also provided students with a narrative, including the characters and tasks involved, to give them motivation and context to solve problems [18]. Walsh et al. [20] also provided multiple approaches by examining conceptual, experimental, and mathematical representations, but they always introduced a topic and had students conduct relevant, inquiry-based experiments or simulations before providing the mathematics behind them. They also only introduced students to new skills, such as computer programming, immediately before they were required [20].

Hughes et al. [15] took this a step further and created three difficulty levels of activities for their quantum computing course to accommodate students entering the program with varying backgrounds and skillsets. Though Akdemir et al. [11] provided little information about using multiple learning modalities, unlike the other publications, they described strategies for differentiation, such as color-coding notes, adjusting he types of questions asked (e.g., matching instead of multiple-choice), and presenting reference videos or slides to help students with additional learning needs. Another approach for varying skill levels was presented in Hughes et al. [15], in which one of the cohorts assigned groups of students based on pre-survey data collected about their content knowledge, such that groups contained varying ability levels and complementary skillsets.

2) Hands-on analogues: In addition to providing multiple learning modalities, Angara et al. [2]-[3] described several "unplugged activities" that included physical hands-on models to provide students with an opportunity to interact with something they would otherwise not be able to experience directly. It is worth noting that the descriptions are similar in these publications because Angara et al. [13] is an update to Angara et al. [12] that included an additional workshop, as well as assessment data. These "unplugged activities" included (1) qubit doughnuts, in which a stuffed doughnut toy was used to show that a qubit can be in state |0> (sprinkles), state |1> (no sprinkles), or in superposition (spinning doughnut that can land on either side), as well as to discuss entanglement; (2) find your quantum partner, in which colored balls with numbers were used to represent amplitudes of different quantum states and students matched them to another student such that the two values squared add up to one; (3) Bloch sphere – drawing on a balloon, in which a balloon was used as model of a Bloch sphere and students drew lines to represent the change in state as a gate is applied; and (4) measurement and probability, in which probability was demonstrated by picking objects from a box randomly and looking at the total of each color chosen [12]-[13]. These hands-on analogs were all rated highly by students when asked how much each activity aided their understanding of the topic [13]. Economou et al. [14], Hughes et al. [15], Ivory et al. [16], and Tappert et al. [19] also discussed using hands-on activities, but in these cases, the authors were referring to simulations and other computer-based activities rather than manipulating physical objects.

3) Gamification: As a method to reinforce QIST concepts, Angara et al. [12]-[13], Economou et al. [14], and Hughes et al. [15] included playing quantum-themed games in their curricula. Hughes et al. [15] used a game called quantum "tic-tac-toe" to provide practice with quantum encryption, and this activity was highly rated by the students in the program. In Angara et al. [12]-[13], Entanglion, a cooperative board game that includes the quantum computing topics found in many of the programs discussed in this review, was used as a concluding activity that reinforced the topics learned. Economou et al. [14] also concluded their workshop with a game as a test of quantum computing skills; in this pencil-and-paper game, known as the Money or Tiger, students had to choose the correct series of quantum gates to determine which of two doors is safe (money) or unsafe (tiger).

4) Advanced computational tools: With the exception of Akdemir et al. [11] and Satanassi et al. [18], all of the publications examined in this review included information about the computational tools used in the workshop. The workshops in these publications included training in the use of IBM Quantum Composer [21], an online application that can both simulate the results of quantum algorithms and run the algorithms on real quantum computers [12]-[17], [19], [20]. In addition, Angara et al. [12], [13], and Salehi et al. [17] added Jupyter Notebooks and Qiskit as a way to enhance the computer coding experiences for students in their workshops.

5) Role models: In addition to addressing the curriculum delivered in the workshops, several of the publications described the inclusion of role models for the students to be able to see themselves in a QIST-related career in the future [15, [16], [19]. In Tappert et al. [19], two assistant teachers that captured student questions for the instructor to answer during breaks and were available as a resource for the students, but there was little description of the interactions between the assistants and the students. One of the cohorts described in Hughes et al. [15] had two teaching assistants that were senior high school students with internship experience that were described as integral in explaining key concepts to a less experienced audience. Ivory et al. [16] described the most interactions between role models and students, as they included talks by QSIT professionals and tours of QIST-related facilities to grow the students' STEM network and provide them with exposure to potential careers. They also included a session with a post-doctoral researcher, who was closer in age to the students than many of the QIST professionals, so that students could ask questions about academic pathways to post-secondary QIST study and careers [16].

B. QIST Topics Addressed

There was variation in the topics covered in workshops among the publications examined for this literature review, in that most included quantum physics topics [11], [14], [16], [17], [20], all included quantum computing [11]-[20], and some also spent time on emphasizing the importance of QIST to society [15], [16], [18] (Figure 2).

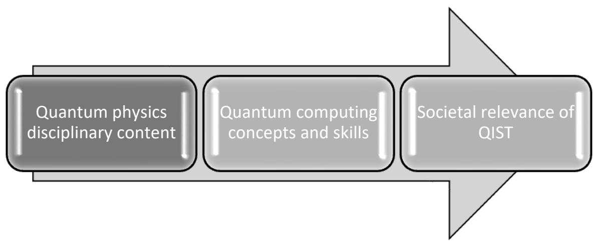

Fig. 2. Topics commonly addressed in QIST teaching and learning.

1) Quantum physics topics: Some programs included minimal quantum physics content as a means to introduce quantum computing concepts [11], [15], [19], while some purposely did not include it at all so they could spend more time on quantum computing activities [12], [13], [17], [18]. However, Economou et al. [14] started with an introduction to the history of quantum mechanics, which included a comparison of classical and quantum mechanics. In this same lecture, they subsequently explained emission spectroscopy, wave-particle duality, superposition in terms of electron locations, and an overview of technologies that use quantum mechanics [14]. The quantum physics content in Walsh et al. [20] was more extensive, providing students with a more comprehensive introduction to quantum mechanics. To make this approachable to all levels of high school students, there was a focus on linear polarization to explain many quantum phenomena [20]. Ivory et al. [16] also included quantum mechanics, with an entire day of the workshop dedicated to exploration of light, wave-particle duality, and polarization in order to prepare students to learn about superposition and the measurement of qubits.

2) Quantum computing topics: Most publications related to QIST programming for high school students described interventions that were focused on quantum computing specifically. Because of this, all of the publications examined in this review included quantum computing topics in their programs [11]-[20]; however, Walsh et al. [20] was not clear about the exact quantum computing topics covered in their year-long course. Despite having different lengths of time with students, from a single day workshop to an entire year course, these programs all introduced qubits, superposition, entanglement, measurement, and gates/operations. As a way to help students understand quantum algorithms, Satanassi et al. [18] dedicated time for students to practice following an algorithm using classical computer and logic gates first. However, some went into more depth and included common quantum computing algorithms, such as Grover's algorithm [17], [19] and Deutsch's algorithm [11]-[13], while Angara et al. [12], [13] also provided an introduction to Superdense Coding and the Deutsch-Jozsa algorithm. Many also included activities related to quantum teleportation [12], [13], [15], [17]-[19].

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There were also differences in how quantum states were represented: Angara et al. [12], [13], Economou et al. [14], Salehi et al. [17], Satanassi et al. [18], and Tappert et al. [19] specifically referred to using bra-ket or Dirac notation with students, while Akdemir et al. [11] and Ivory et al. [16] only specified using 0 and 1 to represent states. There were also three programs that included quantum encryption [11], [15], [18], which has been identified as a highly important skill in the quantum workforce [2], [22]. Another topic of importance that was not directly specified, except in Akdemir et al. [11], Economou et al. [14], and Ivory et al. [16], was error when using quantum computers, but it should be noted that this topic may have been covered in other workshops without referring to it by name in their publications.

C. Importance of QIST to Society

Though all publications examined in this review mentioned the importance of QIST or QIST-related topics in their introduction, this topic was not often mentioned as part of the content to be taught. In fact, only three of the publications specified that their programs included time dedicated to the importance of QIST in solving global technological problems. After each topic, Satanssi et al. [18] set aside time for student teams to reflect on the societal impact of each quantum technology discussed in the workshop. Ivory et al. [16] highlighted the importance of QIST through talks and tours given to students that provided information about QIST applications. In Hughes et al. [15], the final module in the course included information about how quantum computing can provide protection from hacking, a real-world application about which students particularly enjoyed learning.

III. Prerequisite Skills

Many QIST-related programs were designed to require no specific science, mathematics, or coding skills for participation [12], [13], [14], [16], [17] or did not list any prerequisites [11, [19]. To help with the potential lack of prior knowledge, Salehi et al. [17] provided students with a Jupyter Notebook with a review of linear algebra and Python that had to be completed before participating. Unlike programs with no prerequisites, Hughes et al. [15] assumed that students had already taken high school physics, and therefore had a basic understanding of electricity, magnetism, and waves. They also suggested that students would benefit from knowing some modern physics, but this was not required for participation [15]. Despite this physics prerequisite, Hughes et al. [15] did not require specific mathematics or coding skills, as those were taught as needed throughout the program. The only other program with a prerequisite was in Walsh et al. [20], which for a full-year course in quantum computing required that students had completed their second year of high school algebra before taking the course.

A. Approaches to Minimal Mathematics Preparation

Because all the publications examined in this review, except Walsh et al. [20], had no mathematics prerequisites, there were several approaches to teaching QIST topics, which often require complex mathematical applications. The first strategy was to purposefully avoid using linear algebra, at least when first introducing quantum states and gates/operations [14], [16]. This was done with Economou et al. [14] and Ivory et al. [16] using the method described in the book *Q is for Quantum* [23], which represents potential quantum states as black and white marbles that are shown in misty clouds until measurements are made. However, Ivory et al. [16] chose to continue using models for calculations instead of linear algebra, while Economou et al. [14] used the marble representation as an introduction to linear algebra for calculating the results of quantum operations.

The second strategy was to represent quantum states using vectors (bra-ket/Dirac notation) but to avoid using linear algebra to calculate the change in state when using quantum gates [12], [16], [18]-[20]. Angara et al. [12], Satanassi et al. [18], and Walsh et al. [20] were still able to show changes in state, but they did so with matrix representations and calculations rather than using linear algebra.

The final strategy was to provide students with an introductory Jupyter Notebook activity with a review of linear algebra and Python coding to be completed before the start of the workshop to ease students into the use of linear algebra and vector calculations throughout the program [17]. After this introduction, Salehi et al. [17] were able to teach students the linear algebra they needed during the workshops or complete more challenging calculations using Python code. It is also worth noting that only Angara et al. [12], [13] described using complex numbers with students when calculating quantum operations, while Economou et al. [14], Salehi et al. [17], and Walsh et al. [20] specifically stated that complex numbers were avoided to make the content more accessible to all students.

IV. Measuring Student Outcomes

The assessment of student outcomes is an important metric for evaluating the most promising interventions for implementing high school QIST instruction, however, most publications did not include rigorous analysis of gains in cognitive and affective domains. Student outcomes were described in eight of the manuscripts, with two sharing assessment instruments [16], [17]. Akdemir et al. [11] and Economou et al. [14] did not report assessment data in their publications, however, it should be noted that many of these articles were written for practitioner journals that described novel interventions that typically did not report empirical findings. Outcomes are described in terms of quantitative and qualitative analyses, along with anecdotal findings that supported the use of specific pedagogical strategies.

A. Quantitative Measures

Five of the manuscripts reported quantitative results to substantiate positive student outcomes. Salehi et al. [17] examined the impacts of their QIST intervention, which had been implemented in ten countries, with 19 high school students (from a total sample N=317, which also included undergraduate and graduate students). Their pre-/post-survey consisted of seven questions related to quantum computing. High school students improved their knowledge (p<.001) with a large effect size (Cohen's d=2.44). Participants also reported high levels of satisfaction with the workshop but these data were not disaggregated by the age/level of students. This was the only study to report an inferential analysis along with descriptive statistics.

Angara et al. [13] reported survey findings from six students with an average age of 16 years. The majority of students reported the QIST activities were helpful in improving their understanding of quantum ideas, although they self-reported lower levels of comprehension of entanglement, teleportation, and Qiskit tools. Hughes et al. [15] reported "students demonstrated their understanding when completing the activities and answering the questions," and "they were particularly engaged, delegated questions to each other, asked for clarification from each other, and brainstormed conceptual understanding" (p. 188). Their quantitative data from 45 students indicated improved student familiarity with quantum mechanics and quantum computing concepts; however, students did not improve their understanding of the importance of quantum computing and their interest in learning more about quantum computing (the median reported value was the same before and after taking the module).

Tappert et al. [19] reported survey findings from a class of 12th grade students although the sample size was not indicated. Students ranked the topics they learned during a five-day curricular unit, with entanglement and measurement ranked as the most interesting topics. The authors also shared that students' questions indicated "a remarkable understanding of quantum computing in a very short amount of time," yet there were "misunderstandings caused by an awkward use of an analogy of sound waves and quantum mechanics waves" (p. 54). The data supporting these inferences were not reported. Finally, Ivory et al. [16] administered a 17-item evaluation post-survey to N=20 high school students. Data indicated students self-reported improved knowledge of quantum science and technologies, greater understanding of failure as part of the scientific process, and greater likelihood of taking quantum or STEM-related courses in high school.

Quantitative results revealed overall positive outcomes for students participating in QIST programs, although the sample sizes tended to be low (20 or fewer students) and only one paper provided an inferential statistical analysis. Future research should explore more robust instrument development with pre-/post-designs that include control group data. Once programs move beyond pilot phases, larger sample sizes would provide more statistical power to generalize findings to other populations of high school students.

B) Qualitative Measures

One publication reported qualitative data to assess student outcomes, although there was little information on data collection and coding methods. Walsh et al. [20] conducted focus groups from a two-year pilot of quantum computing course, and found that students self-reported greater understanding of matrix algebra operations, classical computing, and the physical nature of encoded information. Observational data indicated that student engagement was higher during in-person instruction than in the second-year remote iteration of the project (necessitated by the global pandemic). Highly engaged students furthered communication with student-initiated social media such as Discord and

Snapchat. This has been shown to be a common strategy for students exercising agency in expanding their social networks to facilitate the attainment of academic goals [24].

C) Anecdotal Measures

Two publications reported anecdotal data that indicated the positive outcomes of their interventions, which seemed to be based upon the general observations of the authors. For example, Angara et al. [12] described students in their two-day workshop as "highly motivated and eager to engage in quantum computing," while their learning strategies "nicely stimulated interaction" and "generated synergy and fostered collaboration" (p. 328); however, the authors also noted that students reached cognitive overload at the end of a full day of quantum activities and they had difficulty remembering some concepts. Satenassi et al. [18] reported a general impression of their approach to quantum computing with high school students, stating "from the first glance at students' reaction, it seems to us that the interaction between the narrative, logical, and technical/mechanical levels has a special potential to stress, from an epistemological point of view, the meaning of quantum computers" (p. 10). They indicated future plans to collect data to test their hypotheses regarding these learning levels.

V. Best Practices in QIST Learning from Other Programs

The same search term that was used in Google Scholar to find publications about QIST programming for high school students was then also used in a general Google search to identify additional QIST educational programs that had not published empirical results. This resulted in finding four programs that had provided some information about the audience and/or what topics the program contained but did not have peer reviewed publications associated with them. Details about these programs are summarized in Table II.

TABLE II. SUMMARY OF QIST-RELATED INTERVENTIONS WITHOUT PUBLICATIONS

Title	Type	Program Dates	Summary
Introduction to Quantum Computing [25]-[27]	Quantum Computing Course	Annually since 2020	A year-long online quantum computing course for high school students that has reached over 7,500 students; part of the *Qubit by Qubit* initiative.
Quantum Computing Summer Camp [25]-[27]	Quantum Computing Workshop	Annually since 2020	An online quantum computing workshop (program length unavailable) for high school students that has reached over 300 students; part of the *Qubit by Qubit* initiative.
UC Davis Quantum Computing Workshop for High School Seniors [28]	Quantum Computing Workshop	October 2023	A one-day in-person quantum computing workshop for high school students in grade 12 with a focus on cryptography; part of the *QuIST* initiative at University of California, Davis.
Quantum for All Students [29]	Quantum Workshop	Summer 2022, 2023, 2024	A four-day in-person quantum technology workshop for high school students (grades 9-12) offered at various locations; students participated in a research study about the program funded by the National Science Foundation.

A. Qubit by Qubit Programs

Of the four QIST-related programs found, two were run annually by *Qubit by Qubit*, an initiative developed by *The Coding School* to train a workforce in quantum topics in collaboration with the University of Maryland, Caltech, IBM, and Microsoft [25], [26]. Although there were no peer reviewed publications about these programs at the time of this literature review, the *Qubit by Qubit* website reported descriptive statistics about their success [27]. They stated that "100% of students know more about quantum computing now than they did before" and that "88% of students feel like they've developed tangible skills in the field of quantum" and "are interested in participating in future quantum programming" [27]. In a description of the full-year quantum computing course, the strategies appeared similar to those in the workshops with publications; most notably, this course also used IBM Quantum Composer and Qiskit to teach quantum computing concepts [25].

B. Other Programs

The *UC Davis Quantum Computing Workshop for High School Seniors* provided an outline of activities on their website, and this outline showed similarities with the publications examined in this review, in that it included many of the same methods and topics, including quantum cryptography taught with lectures and hands-on experiments, meeting role models with similar ages and experiences, and visiting QIST laboratories to meet professionals who also served as role models [28]. Unlike the UC Davis workshop, the summer camps offered by *Quantum for All*, a National Science Foundation funded project, differed from all the others examined in this review because their main focus was quantum mechanics rather than quantum computing [29]. These *Quantum for All* summer camps asked students if they would like to opt in to participate in a study, so assessment data may become available in the future for review and would contribute to advancing the field of quantum education research [28]. To date, this project has disseminated detailed descriptions of their professional development workshops for high school teachers, which preceded their summer camp offerings for students that included many of the same topics [30],[31].

VI. Summary of Recommendations

Based on the information gathered from ten publications and four websites about QIST-related programs, the best practices for QIST learning include the use of multiple teaching modalities, the inclusion of hands-on experiences, the playing of quantum-themed games, the use of advanced computational tools, and the introduction of QIST role models. To provide an in-depth understanding of QIST, students should be exposed to a combination of quantum physics, quantum computing, and the societal importance of quantum advances. It is also helpful to include experiences involving linear algebra and/or matrices without complex numbers. QIST-related programs available to high school students employed varying pedagogical strategies, but the main goal, as suggested by the National Q-12 Education Partnership [5], is to make students feel comfortable with and interested in the many challenging topics found in QIST.

Part of the challenge of developing QIST curriculum and instruction is achieving consensus on what should be taught as global industries are rapidly advancing new technologies and applications. As is the case for many Kuhnian scientific revolutions [32], emerging QIST educational paradigms will take time to coalesce around the essential concepts, skills, and applications that are most beneficial for students in precollege STEM settings. This requires consistent coordination among key stakeholders to inform K-12 educational reforms to meet QIST workforce readiness demands. The U.S. National Quantum Coordination Office is one such entity that coordinates the National Quantum Initiative and the synergistic relationship among the many stakeholders in QIST innovations and expertise [33]. Coordinated efforts are essential for identifying the best practices for students to acquire QIST knowledge and skills while increasing interest in pursuing QIST post-secondary study and careers.

Future research on QIST high school interventions should explore student outcomes with a variety of quantitative, qualitative, and mixed methods approaches. There is a need for robust instruments to measure gains in QIST knowledge and skills, as well as student attitudes towards QIST study and career aspiration development. Larger sample sizes will provide greater statistical power for inferential analyses of student outcomes – this is needed to generate evidence for scaling promising programs to more diverse populations. Qualitative research that evaluates data from several sources (e.g., observations, student artifacts, interviews and focus groups) with rigorous techniques will provide explanatory frameworks for analyzing student experiences. In the current landscape of rapidly advancing QIST knowledge acquisition, it is essential to collect evidence for promising interventions that promote QIST literacy and workforce development.

VII. Acknowledgment

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