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Academic and demographic predictors of high school student knowledge of classical physics, quantum physics, and quantum computing in university-based outreach

Robert De La Cruz[1], Angela M. Kelly[2*], Tzu-Chieh Wei[3] and Dominik Schneble[4]

*Correspondence:
angela.kelly@stonybrook.edu
[2]Department of Physics & Astronomy and Institute for STEM Education, Stony Brook University, Stony Brook, NY 11794-5233, USA
Full list of author information is available at the end of the article

Abstract

With the current growth in quantum information science and technology (QIST) industrial innovation, there is an increasing need to prepare precollege students for post-secondary QIST study and careers. This study examined high school student outcomes from a QIST outreach program held at both a research university and an informal science institution in the United States. The pre-/post-research design incorporated a newly developed *QIST Integration Framework* that included elements of science, technology, engineering, and mathematics (STEM) integration frameworks as well as conceptual change theories. The program was structured to address the initially counterintuitive, abstract nature of QIST concepts, and its applications, through multiple representations, career awareness modules, and exposure to role models. The program featured lectures, simulations, demonstrations, and hands-on experiences in classical and quantum physics and quantum computing. Students in grades 10-12 ($N = 209$) attended one of six 25-hour outreach programs over three summers (2023-2025). They improved their overall QIST knowledge as well as knowledge in each subdomain of classical physics, quantum physics, and quantum computing, all with large effect sizes. Analysis of variance and analysis of covariance indicated that there were no differences in QIST knowledge outcomes when considering student gender, ethnicity, grade level, and prior mathematics, physics, chemistry, and computer science course completion. However, students who had completed at least one science research course outperformed those who had not completed this course, with a small effect size. This informal summer outreach program demonstrates promise in promoting QIST subdomain knowledge, skills, and applications, which will prepare students for this critical emerging field that advances technological solutions for immediate and future global challenges.

Keywords: Analysis of covariance; Demographics; Education; Outreach; Quantum computing; Quantum education; Quantum information science and technology; Secondary education; STEM integration

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1 Introduction

In recent years, there have been significant advances in quantum information science and technology (QIST), which requires a new generation of science, technology, engineering, and mathematics (STEM) workers in this transformative industry. Quantum-based devices in development will serve as foundational technologies with the potential to solve major global challenges through quantum computing, communication, and sensing [1]. The emerging quantum industry expects disruptive applications including artificial intelligence, cybersecurity, and biomedical sensing [2–4], with a shift towards commercially available products and "utility-class" quantum computers in the next three to five years [5]. Here, recent reports on advances toward quantum advantage include diminished error rates relative to the number of qubits, reduced cost of quantum error correction, and increased qubit connectivity [1, 6].

The expanding QIST ecosystem and a widening talent gap in quantum technology jobs [7] has led to the U.S. federal government calling for public outreach and education to introduce QIST to a broader audience [8, 9]. Precollege QIST education can provide access to foundational quantum concepts and computing skills, which are largely missing from traditional K-12 science curricula in the United States; for example, Advanced Placement (AP) Physics 2, AP Chemistry, and many college-preparatory science courses lack coverage of QIST concepts and applications [10–13]. At the same time, research has shown that quantum topics are among those that students taking physics find highly engaging [14]. Facilitating quantum literacy among students and teachers in precollege settings may thus serve to promote QIST career aspirations [15, 16], while providing an opportunity to broaden participation in terms of diversity, equity, and inclusion [17]. Here, we define *quantum literacy* as a basic understanding of the core principles of quantum science, extending from foundational concepts in classical and quantum physics to the tenets of quantum information processing, and of how these principles relate to real-world applications.

2 Precollege quantum education

The development of educational programs in emerging fields such as QIST is complex and necessarily interconnected with the workforce needs of the industry [18]. For QIST, an additional challenge is its interdisciplinary nature, which may be cognitively taxing for high school students. Research has identified several challenges that students following a traditional science curriculum encounter when learning classical physics, quantum physics, and quantum computing concepts [19]. For example, students often struggle to connect the mathematical language of quantum physics with tangible physical manifestations [20, 21]; at the same time, a classical deterministic worldview inhibits a shift to a probabilistic understanding of quantum-physical phenomena [22–24], such as those connected to wave-particle duality [25]. These foundational challenges may be exacerbated when learning to design, code, and interpret the function of quantum circuits without knowledge of linear algebra, which is not covered in standard U.S. high school curricula [26]. More large-scale, rigorous empirical research is needed to understand these learning processes for high school students and to measure their outcomes [10, 27].

Recent quantum education research has identified several effective ways of addressing QIST teaching and learning challenges in high school settings. Student learning may be facilitated by contextualising QIST-related concepts and skills in relevant applications

(e.g., lasers, electron microscopy, BB84 quantum encryption) that directly address technological challenges [28–30]. Effective instruction can promote conceptual understanding through the use of multiple representations, simulations, and "unplugged" activities such as quantum games and building models [31–34]. These hands-on activities and anchoring phenomena may serve as precursors to mathematical formalism [35], including vectors, matrix multiplication, and bra-ket/Dirac notation [36, 37]. IBM Composer and Qiskit are user-friendly platforms that have been used with high school students to incorporate superposition, qubits, multiple-qubit circuits, entanglement, measurement, and probability [34, 38, 39]. QIST workforce expectancy may be communicated to students by exposing them to quantum laboratories, the scientists who engage in this work, and the historical development of quantum ideas [40, 41]; access to role models has been shown to improve high school students' QIST career aspiration formation [16].

3 Research questions

Recent calls for QIST education and workforce development have emphasised the need for a diverse, well-prepared talent pool to accelerate the "second quantum revolution" [8, 42]. This is particularly important given the limited representation of women and ethnic groups traditionally underrepresented in QIST-adjacent fields including physics, engineering, and computer science [43, 44]. These outreach efforts should begin in precollege educational settings, where students often develop QIST interest, motivation, and self-concept [40, 45]. The present study explores the cognitive outcomes of a QIST summer program for high school students in university and informal science institution settings directly addressing this need. This program was offered to a diverse group of high school students (N = 209; approximate ages 15-17 years) in the Northeast United States. The five-day, 25-hour program recruited students from their respective schools and students self-selected to participate in the program. The hands-on summer program focused on disciplinary knowledge and applications in classical physics, quantum physics, and quantum computing. This study investigated student outcomes through three research questions:

1. How have high school students improved their QIST knowledge in a QIST summer outreach program at a research university and an informal science institution?
2. How were student knowledge gains differentiated among classical physics, quantum physics, and quantum computing principles and applications?
3. How did QIST knowledge outcomes relate to students' academic and demographic backgrounds?

4 Conceptual framework

The conceptual framework for the present outreach intervention, which we here define as the *QIST Integration Framework*, was derived from STEM integration and conceptual change frameworks. The QIST field generally is a multidisciplinary combination of physics, mathematics, computer science, materials science, and engineering [46], although background in each of these fields is not required to enter the QIST workforce [47, 48]. QIST as an integrated domain conceptually aligns with efforts to integrate STEM disciplines, where STEM integrated education has been defined as "the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning" [49, p.3]. Other researchers have suggested that STEM-integrated instruction should

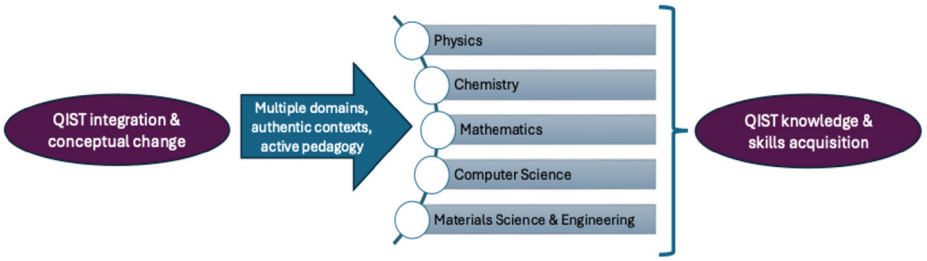


Figure 1 QIST Integration Framework

emphasise making connections with the real world, using multiple pedagogical strategies, addressing connections between disciplines, and articulating societal and ethical research implications and potential career opportunities that relate to each field [49, 50]. There is emerging consensus regarding some essential topics in the quantum education research base, for example, precollege QIST-integrated instruction might include elements of classical physics and electromagnetic wave behavior [40, 51], of quantum physics [19, 52], and of quantum computing [39], supported by sensemaking structures of mathematics [36]. These topics are complemented by exposure to emerging technologies that contextualise actual and as-yet speculative applications ranging from quantum key distribution to supply chain management and transportation control [53, 54]. The National Q-12 Partnership has published *QIS Frameworks* [55] to highlight alignment between core quantum concepts and the *Next Generation Science Standards* [56]. The present *QIST Integration Framework* incorporates a multidisciplinary approach to teaching QIST and QIST-adjacent concepts and skills to promote quantum literacy among high school students.

The *QIST Integration Framework* is also derived from theories of conceptual change. Posner et al. [57] defined conceptual change as "the process by which people's central, organising concepts change from one set of concepts to another set, incompatible with the first" (p. 211). The authors suggested that students accept new concepts when they believe them to be comprehensible, plausible, and relevant [57]. Faletič et al. [58] posited that students may expect quantum physics to be consistent with their classical view of the world. One strategy for addressing this cognitive dissonance is to first introduce classical concepts so students may compare and contrast new quantum concepts with what they already know, for example, through model-based reasoning that builds upon and revises prior knowledge [58, 59]. In the context of the present study, this was exemplified when diffraction and polarization were introduced as classical wave behaviors, prior to exploring them in the context of single photon behavior. Furthermore, knowledge and skills acquisition may be considered as important as understanding relevant applications and societal impacts [60]. When students are exposed to QIST principles and skills, whether in formal or informal settings, they may gain an appreciation of quantum computing and strengthen their knowledge of foundational quantum concepts [34]. The *QIST Integration Framework* (Fig. 1) provides a mechanism for understanding how quantum outreach might be structured to optimise students' cognitive outcomes.

5 Research design

This quantitative study measured outcomes of a QIST summer outreach intervention for students entering grades 10-12 [51] using a pre-test/post-test design with paired data

analysis [61]. The research design was selected to analyse quantitative survey data that measured QIST and QIST-adjacent knowledge, skills, and applications with descriptive and inferential statistics, including paired-samples t-tests, analysis of variance (ANOVA) with post hoc Tukey tests, and analysis of covariance (ANCOVA). The covariates were pre-intervention scores and school-level poverty as measured by the percentage of students classified as economically disadvantaged. The newly developed survey included 19 items measuring content knowledge of QIST concepts, applications, and computing. Each question had four multiple choice responses. The survey was developed and validated by quantum physicists and physics education researchers, along with 19 secondary STEM teachers, who provided feedback on question structure and language. The pre-survey was administered on the first day of the program as soon as students arrived, and the post-survey was administered at the end of the last day. The survey had adequate reliability (Cronbach's $\alpha = 0.70$). Permission for research with human subjects was secured and students and parents provided voluntary assent and consent, respectively.

6 QIST outreach structure

The QIST outreach programs were 25 hours over five days, and co-taught by a quantum theorist, a quantum experimentalist, a physics education researcher, several graduate students in physics and STEM education, and a postdoctoral researcher. The set of core instructors was consistent throughout each iteration of the program, with some variation only in the last two sessions (when a postdoctoral researcher and visiting scientist taught a few modules). The disciplinary content included three main areas of QIST conceptual progressions, applications, and career awareness, described below with more comprehensive detail in Schneble et al. [51]:

1. *Pre-Quantum Notions and Quantum Principles* (eight hours of instruction): Topics included the electromagnetic spectrum; classical wave and quantum behavior of light (superposition, interference, diffraction, polarization; photoelectric effect); the quantum basis of the physical world, including wave-particle duality and single-particle superpositions for atoms and photons, the modern perspective of "which way information" when analysing quantum interference, quantum coherence in macroscopic objects, the notion of entanglement in Schrödinger's cat and its extension to Wigner's friend, as well as connections to measurement, decoherence; and the broader nature of physical reality. Students engaged in the following activities: observing and predicting wave interference and diffraction simulations with PhET simulations [62]; creating slit interference devices with a human hair; measuring light intensity with two to three polarizing filters and interpreting Malus's law graphically; comparing diffraction and polarization for classical waves and quantum particles (photons); and making predictions of, and experimentally observing, interference patterns with a Mach-Zehnder interferometer. Students also observed "quantum" at work in an atomic, molecular, optical (AMO) research laboratory at the university or visited interactive light exhibits at the informal science institution.
2. *Foundations of Quantum Computing* (ten hours of instruction): Topics included superposition and entanglement; the Poincaré and Bloch spheres; basic quantum gates; connections between quantum concepts and the mathematics of vectors and matrices; single and multiple qubit circuits (including circuits describing

Table 1 Sample Quantum Science Activities

Scope and select NGSS alignment	Sample activities
Classical and single-photon wave diffraction, superposition, interference, polarization. "HS-PS4-3: Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other" [56].	Young's double slit experiment; Malus's law; Mach-Zehnder interferometer; photon counting in diffraction.
Modern applications in AMO laboratories (e.g., macroscopic coherence, quantum gases, quantum simulations); quantum science careers. "HS-PS2-6: Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials" [56].	Quantum simulations v. quantum computations; AMO laboratory visits; QIST career panels with scientists.
Quantum information communication, producing entangled photons, quantum repeaters and internet. "HS-PS2-6: Investigating or designing new systems or structures requires a detailed examination of the properties of different materials, the structures of different components, and connections of components to reveal its function and/or solve a problem" [56].	Quantum measurements; polarization manipulation and measurement; Bell's inequality test with IBM Composer; quantum key distribution.

Schrödinger's cat and Wigner's friend discussed earlier); unitary evolution and measurement; quantum key distribution; Moore's law and the limitations of classical computing; Bell's inequality and the 2022 Nobel Prize (Aspect, Clauser, Zeilinger). Students built a Bloch sphere model; performed Mathematica simulations of a single qubit in various orientations; played Qubit Touchdown [63]; compared classical and quantum gates; built single and multiple qubit circuits with IBM Composer and observed probabilities of outcomes; sent coded messages to each other as an illustration of cryptography; and performed tests of Bell's inequality in hands-on activities using computation and IBM Composer.

3. *Transitions to QIST Academic Pathways and Careers* (two hours of instruction): Topics included the four pillars of quantum information science (computing, simulation, sensing, communication) as career guidelines; academic pathways to pursue QIST careers (panels/discussions with graduate students, career scientists, university admissions staff); potential quantum computing scenarios and future applications and use cases.

The instructional modules and activities were aligned with the *Next Generation Science Standards* [56], with the National Q-12 Partnership's *QIS Frameworks* [55] providing further suggestions for standards-based alignment (see examples in Table 1). The conceptual complexity was scaffolded through vertical, grade-level curricular alignment with integrated STEM principles. The sessions were accompanied by age-appropriate hands-on activities, simulations, demonstrations, games, model building, and group discussions. Students worked in groups of three to five to prepare presentations on a topic of their choice (five hours for preparation and delivery). The program was run six times in 2023-2025, three times at a research university and three times at an urban informal science institution.

7 Study participants

Participants in the QIST outreach program included $N = 209$ self-selected students entering grades 10-12 (approximately 15-17 years old) from both urban and suburban schools. These included $n = 62$ students in 10th grade, $n = 74$ in 11th grade, and $n = 79$ in 12th

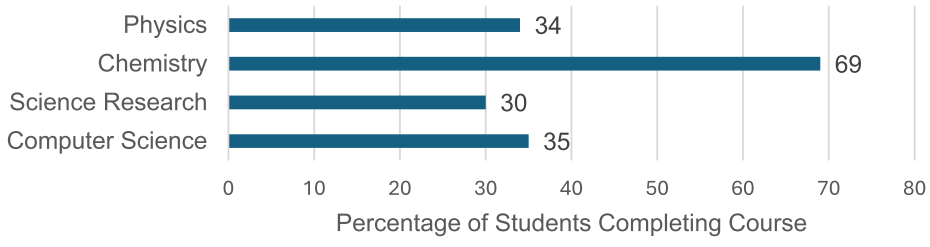


Figure 2 Percentage of Students with Prior Science and Computer Science Coursework ($N = 209$)

grade. The participants' self-reported demographics indicated that $n = 81$ were women (39%), $n = 128$ were men (61%), and none were non-binary; 21% of students belonged to ethnic groups traditionally underrepresented in STEM (Black, Hispanic, or Native American). Approximately 50% of the students attended a school where 30% or more of the students were entitled to free or reduced lunch, a measure of socioeconomic status and economic disadvantage in U.S. schools as reported by the National Center for Education Statistics [64]. A long-term goal of the program was to increase participation in QIST careers, particularly for those from underrepresented backgrounds who might not have considered these options due to limited exposure or guidance [11].

Data on prior course taking was collected to determine whether QIST knowledge gains were differentiated by STEM preparation. The courses considered included college-preparatory physics and chemistry, which were elective courses for high school students that typically aligned with a state-standardised curriculum (students traveled from several U.S. states). Computer science could include a variety of high school coursework, including basic programming, computer-aided design, and Advanced Placement (AP) Computer Science Principles and AP Computer Science A. Science research was an elective course that was typically repeated with increased expectations over four years. This course focused on developing students' capacity to design and conduct independent research projects through a variety of methodologies. Many students in science research courses worked with university or industry researchers in STEM fields, with the goal of participating in science research competitions by their final year of secondary school. In terms of science coursework, $n = 71$ students (34%) had taken physics, $n = 145$ (69%) had taken chemistry, and $n = 61$ (29%) had taken science research. There were $n = 74$ students (35%) who had taken a computer science course. In terms of mathematics preparation, students were identified by the highest level of prior course completion for further analysis: Level 1 students ($n = 53$, 25%) had taken Algebra 1 and/or Geometry; Level 2 students ($n = 133$, 64%) had completed Algebra II/Trigonometry; and Level 3 students ($n = 23$, 11%) had completed at least Precalculus and in some cases AP Calculus AB or BC. Science and computer science course enrollment data are summarised in Fig. 2, and mathematics course enrollment data are summarized in Fig. 3.

8 Results

The first and second research questions were addressed by examining whether students demonstrated QIST interdisciplinary knowledge gains after attending the summer outreach program. Composite scores were calculated based on the number of correct answers on 19 items. Paired samples t-tests were utilised to compare mean scores from before the

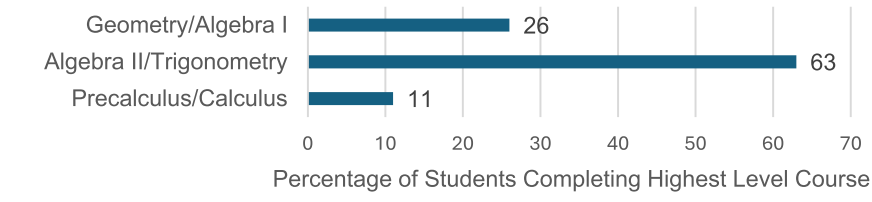


Figure 3 Percentage of Students with Highest Level Prior Mathematics Coursework ($N = 209$)

program to immediately afterwards, and missing data were deleted listwise. The remaining data were normally distributed as indicated by skewness (<0.58) and kurtosis (<0.72) values. Students demonstrated significant learning gains ($t(199) = 23.31$, $p < .001$) from pre-test ($M = 36.7\%$, $SD = 15.2\%$) to post-test ($M = 62.9\%$, $SD = 17.5\%$) with a large effect size (Cohen's $d = 1.65$) [65].

Knowledge gains were also analysed by disaggregating the 19 items by conceptual focus. This included five items on classical physics, six items on quantum physics, and eight items on quantum computing. Students demonstrated significant learning gains for classical physics ($t(199) = 13.18$, $p < .001$, $d = 0.93$, large effect); quantum physics ($t(199) = 10.98$, $p < .001$, $d = 0.78$, large effect); and quantum computing ($t(199) = 19.76$, $p < .001$, $d = 1.40$, large effect). Survey questions (with the multiple-choice answers) and descriptive data are shown in Table 2, and inferential statistics are summarised in Table 3.

Since students had attended the QIST outreach programs at both the research university and the informal science institution over three years, their outcomes were compared to see whether there were differences depending on when and where they attended the program (Table 4). A one-way ANOVA with post-hoc Tukey tests were run, with 15 between-group comparisons for overall QIST knowledge. Levene's test indicated homogeneity of variance among groups ($p = .066$). QIST knowledge outcomes were largely consistent over three years, with one exception. The students in session five outperformed students in session four in the overall composite score ($F(5,200) = 3.01$, $p = .012$) with a medium effect ($\eta^2 = .070$). Effect sizes (η^2) were interpreted as: .01–.06 (small effect), .06–.13 (medium effect), and $\geq$.14 (large effect) [66]. Instructional methods were consistent in each iteration of the program, which was reflected in the single identified difference between groups. Notably, the students in session five were the only group who learned about quantum tunnelling as an advanced topic.

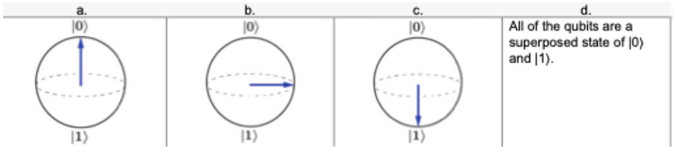
To answer the third research question, QIST knowledge outcomes were analysed by examining potential differential outcomes related student characteristics including gender, ethnicity, and academic background. One-way ANCOVA was performed using the post-test scores as the dependent variable and the pre-test and school-level economic disadvantage as covariates. Levene's test showed homogeneity of variance when considering groups designated by gender ($p = .914$) and ethnicity ($p = .648$). Results indicated that there was no significant difference between the performance of women and men ($F(3,176) = 2.80$, $p = .091$). There was also no difference when comparing underrepresented ethnic minority students in STEM and the rest of the student sample ($F(3,170) = 2.02$, $p = 0.157$). Descriptive and inferential statistics are summarised in Table 5.

Similarly, QIST knowledge outcomes were analysed by examining students' prior course taking. One-way ANCOVA was again generated using the post-test scores as the dependent variable and the pre-test and school-level economic disadvantage as covariates. Lev-

Table 2 QIST Concept Inventory Results by QIST Knowledge Classifications

Survey items		Pre-test mean % (SD)	Post-test mean % (SD)
CLASSICAL PHYSICS (5 questions)			
1.	A student shines a red laser at the center of two small slits, and a pattern of bright spots appears on the wall. What causes this pattern? ***Answer:*** The light waves diffract and interfere constructively and destructively. ***Distractors:*** (a) The light waves are reflected from external objects. (b) Some light waves enter one slit and some enter the other. (c) Light waves deflect from the edges of the slits.	70.1 (45.9)	88.6 (31.9)
2.	For a beam of light, the direction of polarization is defined as: ***Answer:*** The direction of the electric field's oscillations. ***Distractors:*** (a) The beam's direction of travel. (b) The direction of the magnetic field's oscillations. (c) The direction that is perpendicular to both the magnetic and the electric field vectors.	15.9 (36.7)	39.3 (49.0)
3.	In Young's double slit experiment, you observe a pattern with a red laser light source. What will happen to the interference pattern if you use a green laser instead of a red one? ***Answer:*** The dark fringes are closer together. ***Distractors:*** (a) The pattern will oscillate from side to side. (b) The bright fringes are further apart. (c) The bright fringes become brighter.	39.6 (49.0)	46.8 (50.0)
4.	Two transparent plastic films are placed on top of one another, and they appear black. If one is rotated 90°, they appear almost transparent. What phenomenon does this demonstrate? ***Answer:*** Polarization. ***Distractors:*** (a) Refraction. (b) Interference. (c) Diffraction.	37.8 (48.6)	86.1 (34.7)
5.	How are the interference patterns in single- and double-slit interference different? ***Answer:*** Single slits produce a wide central maximum, while double slits produce a central maximum the same width as other bright fringes. ***Distractors:*** (a) Single slits produce equal spacings between constructive and destructive interference bands. (b) Only double slit patterns vary if the frequency of the source is changed. (c) Double slit interference patterns have a wide central maximum.	44.3 (49.8)	68.2 (46.7)
Classical Physics Composite		39.1 (22.0)	65.8 (22.5)
QUANTUM PHYSICS (6 questions)			
6.	If you measure the momentum of an electron exactly, which is true about its simultaneous position measurement? ***Answer:*** Measurements of position will be inaccurate. ***Distractors:*** (a) Position can be determined directly using an equation. (b) Position can be measured accurately. (c) Measurement depends on electron spin.	39.8 (49.1)	41.8 (49.4)
7.	A quantum object can exhibit properties of both waves and particles. In double slit diffraction, which of the following can result in particle effects?[a] ***Answer:*** Placing a detector near one of the slits. ***Distractors:*** (a) Changing the frequency of the source. (b) Changing the distance from the slits to the screen. (c) Changing the medium through which the light travels.	20.4 (40.4)	41.8 (49.4)
8.	When multiple qubits are entangled, which Einstein called "spooky action at a distance," the following is always true: ***Answer:*** The measurement of one qubit is correlated with the measurement of another qubit. ***Distractors:*** (a) The qubits cannot be measured. (b) The qubits experience decoherence. (c) The states of the qubits may be duplicated.	39.8 (49.1)	62.2 (48.6)
9.	In a thought experiment inspired by Schrödinger, a single photon with polarization D enters a box with a cat through a polarizing beam splitter. A polarized $\|H\rangle$ photon will trigger the release of a poison and a polarized $\|V\rangle$ photon does nothing. The state of the system, including the photon and the cat, for the outside observer before looking inside may be expressed as: ***Answer***: $\frac{1}{\sqrt{2}}(\|H,\ \textbf{cat dead}\rangle + \|V,\ \textbf{cat alive}\rangle)$. ***Distractors:*** (a) $\frac{1}{2}\|V\rangle\ \|\text{cat alive}\rangle$. (b) $\frac{1}{2}\|H\rangle\ \|\text{cat dead}\rangle$. (c) $\|H\rangle\ \|\text{cat dead}\rangle$	61.7 (48.7)	96.5 (18.4)
10.	Which of the following statements is incorrect? ***Answer:*** Any quantum state can be cloned, just like a paper can be copied. ***Distractors:*** (a) Superposition can happen for classical waves. (b) Entanglement does not happen for classical objects that follow classical mechanics. (c) Violation of Bell's inequality demonstrates quantum mechanics is a more correct theory than classical mechanics.	30.3 (46.1)	43.0 (49.5)

Table 2 (*Continued*)

Survey items		Pre-test mean % (SD)	Post-test mean % (SD)
11.	By 1900, most physicists were convinced that light phenomena were best explained by the wave model. Which of the following can only be explained by the particle model of light? ***Answer:*** Photoelectric effect. ***Distractors:*** (a) Interference. (b) Diffraction. (c) Polarization.	37.8 (48.6)	56.7 (49.7)
Quantum Physics Composite		38.3 (21.2)	57.0 (23.5)
QUANTUM COMPUTING (8 questions)			
12.	Alice sends a 5-qubit message to Bob with the quantum key 01101. Bob receives the 5-qubit message 10101. What is the original message? ***Answer:*** 11000. ***Distractors:*** (a) 11011. (b) 01001. (c) 01010.	21.9 (41.5)	86.6 (34.2)
13.	A qubit is prepared in an unknown state. It is then measured with the outcome $\|1\rangle$. Which of the following could not be its initial state before measuring? ***Answer:*** $\|0\rangle$. ***Distractors:*** (a) $\frac{1}{\sqrt{10}}\|0\rangle + \frac{3}{\sqrt{10}}\|1\rangle$. (b) $\frac{1}{2}\|0\rangle + \frac{\sqrt{3}}{2}\|1\rangle$. (c) $\frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle)$.	41.3 (49.4)	49.8 (50.1)
14.	The Bloch sphere is used to visually represent a qubit. The qubit can be in a superposition of: ***Answer:*** All of the above. ***Distractors:*** (a) $\|0\rangle$ and $\|1\rangle$ states. (b) $\|i\rangle$ and $\|-i\rangle$ states. (c) $\|+\rangle$ and $\|-\rangle$ states.	64.7 (47.9)	92.5 (26.3)
15.	Which of the following gates does not result in a 90° rotation of the qubit? ***Answer:*** Y. ***Distractors:*** (a) S. (b) $\sqrt{Z}$. (c) $\sqrt{X}$.	15.4 (36.2)	54.2 (49.9)
16.	Which of the following qubits is in a superposed state of both $\|0\rangle$ and $\|1\rangle$? ***Answer:*** b. 	43.8 (49.7)	57.2 (49.6)
17.	A qubit is initialized $\|0\rangle$ and a NOT gate is added to the quantum circuit. What is the expected probability distribution of the computational basis state? ***Answer:*** 100% $\|1\rangle$. ***Distractors:*** (a) 100% $\|0\rangle$. (b) 50% $\|0\rangle$ and 50% $\|1\rangle$. (c) 25% $\|00\rangle$, 25% $\|01\rangle$, 25% $\|10\rangle$, and 25% $\|11\rangle$.	22.4 (41.8)	49.3 (50.1)
18.	Two qubits in an entangled state may be represented by which of the following quantum circuits: ***Answer:*** (a). 	24.9 (43.3)	71.6 (45.2)
19.	Classical gates can do the following: ***Answer:*** Perform binary operations. ***Distractors:*** (a) Create superposition. (b) Entangle qubits. (c) Rotate polarization by 90°.	37.3 (48.5)	64.7 (47.9)
Quantum Computing Composite		33.9 (20.5)	65.7 (21.5)
TOTAL SCORE		36.7 (15.2)	62.9 (17.5)

[a] An earlier iteration of this question stated: "… which of the following *will* result in particle effects?"

Table 3 Descriptive and Inferential Statistics for QIST Knowledge Classifications

Knowledge band	*Pre-score*	*SD*	*Post-score*	*SD*	*t*	Cohen's *d*	95% Confidence interval of difference	
							Lower	Upper
Classical physics***	1.95	1.10	3.29	1.13	13.18	0.93	1.13	1.53
Quantum physics***	2.30	1.28	3.42	1.41	10.98	0.78	0.92	1.32
Quantum computing***	2.73	1.63	5.26	1.72	19.76	1.40	2.29	2.80
Overall composite***	6.98	2.91	11.96	3.32	23.31	1.65	4.56	5.40

*** $p < .001$

Table 4 Student Outcomes Disaggregated by Program Year and Location

Session	Year	Students *n*	Location	Composite *mean (SD)* max score = 19	Group comparisons
1	2023	31	University	11.52 (3.01)	1 → 2 $p = .788$ 1 → 3 $p = 1.00$ 1 → 4 $p = .943$ 1 → 5 $p = .135$ 1 → 6 $p = .998$
2	2023	11	Informal Science Institution	13.00 (3.38)	2 → 3 $p = .877$ 2 → 4 $p = .358$ 2 → 5 $p = .997$ 2 → 6 $p = .890$
3	2024	31	University	11.73 (3.41)	3 → 4 $p = .844$ 3 → 5 $p = .232$ 3 → 6 $p = 1.00$
4	2024	44	Informal Science Institution	10.82 (2.88)	4 → 5 $p = .005^{**}$ 4 → 6 $p = .639$
5	2025	34	University	13.53 (2.88)	5 → 6 $p = .170$
6	2025	55	Informal Science Institution	11.84 (3.78)	

$^{**}p < .01$

Table 5 ANCOVA Results Comparing Students by Demographic Groups

Demographic variable	*Estimated marginal pre-mean*	*SE*	*Estimated marginal post-mean*	*SE*	*F*	*p*
Women ($n = 77$)	6.27	0.27	11.38	0.33	2.89	.091
Men ($n = 122$)	7.46	0.27	12.11	0.27		
Underrepresented minorities in STEM ($n = 38$)	7.28	0.22	11.97	0.24		
Non-underrepresented minorities in STEM ($n = 136$)	6.05	0.47	11.22	0.46	2.02	.157

ene's test showed homogeneity of variance when considering prior course taking in chemistry ($p = .357$), computer science ($p = .526$), and science research ($p = .343$). Results indicated there were no significant differences between the performance of students based on prior chemistry enrollment ($F(3,176) = 0.25$, $p = .622$), and computer science enrollment ($F(3,176) = 0.80$, $p = .371$). However, students who had completed a science research course outperformed those who had not ($F(3,176) = 4.75$, $p = .031$, adjusted $\eta_p^2 = .026$, a small effect). When considering physics, Levene's test indicated heterogeneity of variance ($p = .009$), consequently, outcomes were compared using the nonparametric Welch's ANCOVA test [67]. Student performance did not depend upon whether they had previously taken a physics course ($F(3,176) = 0.25$, $p = .620$). Descriptive and inferential statistics are summarised in Table 6.

The final analysis explored QIST knowledge outcomes by student grade level (10, 11, 12) and prior mathematics course taking. One-way ANOVA with post hoc Tukey tests were run with post-treatment QIST knowledge composite as the dependent variable. Levene's test indicated homogeneity of variance for grade level ($p = .319$) and prior mathematics course taking ($p = .472$). Results indicated no significant differences between student outcomes when comparing students by grade level ($F(2,202) = 0.036$, $p = .965$). Prior mathe-

Table 6 ANCOVA Results Comparing Students by Prior Course Enrollment

Academic variable	*Estimated marginal pre-mean*	*SE*	*Estimated marginal post-mean*	*SE*	*F*	*p*
Completed Physics ($n = 62$)	7.24	0.34	11.66	0.34	0.25	.620
Did Not Complete Physics ($n = 118$)	6.87	0.25	11.88	0.26		
Completed Chemistry ($n = 123$)	6.96	0.24	11.88	0.25	0.25	.622
Did Not Complete Chemistry ($n = 57$)	7.08	0.37	11.65	0.37		
Completed Computer Science ($n = 63$)	7.64	0.34	12.06	0.35	0.80	.371
Did Not Complete Computer Science ($n = 117$)	6.64	0.24	11.67	0.26		
Completed Science Research ($n = 54$)*	6.69	0.34	12.49	0.37	4.75	.031
Did Not Complete Science Research ($n = 126$)*	7.12	0.24	11.51	0.24		

*$p < .05$

Table 7 ANOVA Results Comparing Students by Grade Level and Mathematics Course Taking

Academic variable	*Pre-mean*	*SD*	*Post-mean*	*SD*	*F*	*p*
Grade 10 ($n = 60$)	6.90	2.81	11.94	3.16	0.036	.965
Grade 11 ($n = 69$)	6.94	2.94	11.97	3.50		
Grade 12 ($n = 76$)	7.19	2.82	11.91	3.35		
Math Level 1 ($n = 53$)	6.58	3.05	11.62	3.21	2.92	.056
Math Level 2 ($n = 124$)	6.92	2.75	11.77	3.39		
Math Level 3 ($n = 23$)	8.39	2.84	13.48	2.87		

matics enrollment was defined by three levels: Level 1 represented completion of Algebra 1 and/or Geometry, Level 2 represented Algebra 2/Trigonometry completion, and Level 3 represented Precalculus and/or Calculus completion. There were no significant differences in performance in terms of prior mathematics course completion ($F(2,197) = 2.294$, $p = .056$). Descriptive and inferential statistics are summarised in Table 7.

9 Discussion

This study explored the effectiveness of a novel QIST outreach program for U.S. high school students of diverse socioeconomic, demographic, and academic backgrounds. The newly developed *QIST Integration Framework* provided an analytical lens for the program design and student outcomes. This conceptual framework integrated elements of prior STEM integration frameworks [49, 50, 60] as well as conceptual change theories [57–59]. QIST is an inherent combination of several disciplines, including physics, mathematics, and computer science [46], and the outreach program was designed to present these ideas within authentic contexts to illustrate the connections among them. The knowledge survey, which aligned with the program structure, incorporated aspects of classical physics, quantum physics, and quantum computing, with applications such as entanglement and quantum key distribution. Conceptual change theories provided the rationale for challenging cognitive conflicts that often arise from conceptual shifts, for example, transitioning from deterministic classical physics to probabilistic quantum physics [19], as well as the often nonintuitive application of linear algebra in understanding quantum circuit representations and measurement [68]. By designing instructional sequences that provided scaffolded conceptual complexity, students contrasted the classical wave behavior of light with quantum ideas, subsequently applying this knowledge to quantum computing.

This research is one of the first to conduct a larger-scale inferential examination of student outcomes in a precollege QIST outreach program; most prior work has focused

on descriptive outcomes or a smaller number of participants [10, 30–32, 37, 40], given the limited QIST teaching and learning in many secondary schools, especially in the United States [56]. The students who participated in the treatment demonstrated significant learning gains in QIST overall and the subdomains of classical physics, quantum physics, and quantum computing, all with large effect sizes. Students performed equitably when considering their academic background in physics, chemistry, computer science, and mathematics. This counters the perception that only the academically elite can participate and succeed in QIST study [45]. That being said, students who had taken a science research course outperformed their peers with a small effect size. Science research courses often require that students engage in self-directed study and work closely with a mentor, often a college professor. This familiarity with research-based competencies both in terms of rigor and expectations, as well as tolerance of ambiguity in engaging in the scientific enterprise, can be a potential factor in improved cognitive outcomes [69], however, the small effect size indicates this result should be interpreted with caution. These overall results support the goal of equitable QIST learning experiences, with the ultimate objective of increased interest in QIST careers and quantum literacy.

QIST learning gains were also consistent for all students regardless of gender, grade level, and ethnicity. This result is promising given the persistent lack of participation of women and underrepresented ethnic minorities in the STEM workforce, particularly in QIST-adjacent fields. The National Center for Science and Engineering Statistics reported that ethnic minorities made up 24% of the total U.S. STEM workforce in 2023 [70]. Although this figure was relatively close to the 32% of individuals who identified as ethnic minorities, their representation in the STEM workforce was highest in the least degree-intensive and lower-paid positions. Regarding the participation of women in STEM, the report highlighted that while women constituted 51% of the U.S. workforce, they only constituted 35% of those employed in STEM jobs [70]. These results are important considerations as precollege QIST education is expanded to foster quantum literacy and meet global workforce demands [8, 52, 71, 72]. Since QIST teaching and learning often have an elitist connotation (similar to other mathematically intensive physical science and engineering disciplines, see for example, Leslie et al. [73]), it is important to examine how prior science and mathematics knowledge and skills relate to QIST outcomes. This is a consideration in secondary QIST program design, particularly when working with students who do not self-select participation. QIST teaching and learning may be accessible to students of all academic and demographic backgrounds, which is promising when considering workforce development and quantum literacy. However, more research is needed to understand how teaching QIST to students in formal educational settings can be done effectively.

10 Implications

Introducing quantum physics at the high school level can spark early interest and encourage students to consider QIST as a viable career path [10, 16, 45], also providing an opportunity to broaden participation [17]. A study of 13 European countries, Australia, and Canada indicated that quantum physics topics constitute a common core of knowledge already in place in upper secondary schools, although with some degree of variability in scope and philosophical approach [52]; however, QIST education is relatively rare in U.S. high school curricula [40, 45]. This study suggests that successful informal outreach programs may serve as starting points for formalising QIST instruction in U.S. secondary

schools, particularly with regard to appropriate conceptual progressions that introduce, review, and build upon intuitive classical wave phenomena to introduce quantum physics concepts [51]. However, it should be noted that the teaching of QIST concepts and skills in formal classrooms will come with challenges. The students in the present study were self-selected and likely highly motivated to learn about quantum science; teaching these concepts in traditional classrooms will likely require additional strategies to engage mainstream students, as well as more instructional support to maximise learning.

The novel *QIST Integration Framework* described in this research provides a logical foundation for facilitating connections among classical physics, quantum physics, and quantum computing concepts. This occurred in the present study through an integrated disciplinary approach [51] that intentionally mitigated the challenges associated with conceptual change [57–59]. This approach incorporated multiple representations, hands-on experiments, and an emphasis on relevant applications and societal impacts [51]. The quantitative results suggest that students made significant gains in content knowledge in all domains. Teachers introducing QIST concepts may follow this conceptual progression with concepts such as diffraction, interference and superposition, wave-particle duality, measurement, and entanglement, which collectively support learning from qubits and quantum gates to quantum programming.

Exploring the foundations of QIST can contribute to students' broader intellectual development and deepen their awareness of the technological dimensions of the modern world. That said, part of the challenge of developing QIST curriculum and instruction is achieving consensus on what should be (or needs to be) taught beyond a set of core quantum concepts, as global industries are rapidly developing new technologies and applications [74]. As is the case for Kuhnian scientific revolutions [75] that translate to subsequent educational reforms and workforce development, emerging QIST educational paradigms will take time to coalesce around the essential concepts, skills, and applications that are most beneficial for students in precollege settings. Beyond humanistic goals, this requires consistent coordination among key stakeholders to inform global K-12 educational reforms to align with QIST workforce readiness demands. A recent Delphi study of quantum experts suggested a core set of concepts for secondary learners, including primarily conceptual treatment of quantum topics such as "wave interference, superposition, quantum states, probability amplitudes, quantum measurement, and atomic models" [74, p. 9], which are typically already represented in the upper secondary curricula of many European countries, Australia, and Canada [52]. The National Q-12 Partnership Frameworks incorporate similar ideas among their nine QIS key concepts, which also include coherence, quantum computing, and quantum communication [55]. These publications provide emerging agreement on guidance for teaching QIST in secondary schools around the globe.

However, the adoption of QIST standards has its challenges. For example, it is likely that many U.S. STEM teachers lack the tools to meaningfully expose students to QIST in existing coursework, which will require professional development at a large scale. Increased adoption of research-based QIST standards and guidelines will allow teachers to plan effectively and provide students with learning opportunities in the field. This is supported by research that suggested that standards-based instructional design leads to improved student learning that aligns with established objectives [76]. For example, the QTEdu CSA project in Europe developed an organizational approach that incorporates lifelong learn-

ing and retraining [77]. This serves a critical function since teachers often need sustained support to teach QIST concepts after preliminary professional development [78, 79]. Professional societies such as the National Q-12 Partnership and Physics Teacher Education Coalition (PhysTEC) in the United States, as well as the QTEdu CSA project in Europe, can serve as networking resources to develop standards for teaching QIST effectively.

11 Limitations and future research

This study has several limitations. The study participants self-selected into the outreach program and may not be representative of the general population of U.S. high school students. The intervention was somewhat limited in duration (25 hours), so future studies might examine the impacts of more sustained programs. 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.

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 student knowledge of classical physics, quantum physics, and quantum computing. Although this research utilised one such validated and reliable instrument, the individualised, unstandardised nature of QIST outreach programs and formalised QIST instruction may necessitate a variety of research instruments for this purpose. Furthermore, this research analysed overall test scores but did not explore the depth of students' conceptual understanding, which may have been elicited through performance tasks or open-ended survey questions. Qualitative research that evaluates data from several sources (e.g., observations, student artifacts, interviews, and focus groups) with rigorous inductive techniques will provide explanatory frameworks for analysing student experiences. Longitudinal research will provide insights on long-term programmatic impacts in terms of STEM performance, QIST career aspiration formation, and persistence to QIST careers. In the current landscape of rapidly advancing QIST knowledge acquisition to meet workforce needs, it is essential to collect evidence for promising, scalable interventions that promote quantum literacy, interest, and post-secondary study.

12 Conclusions

The present study proposes a mechanism for measuring a conceptual progression for introducing pre-quantum ideas (classical physics), quantum physics and quantum computing in secondary education. High school students improved their knowledge and skills in all three domains with large effect sizes, regardless of prior coursework in physics, chemistry, mathematics, and computer science. Students who had taken science research had higher learning gains with a small effect size. Learning gains were unrelated to grade level, gender, and ethnicity. Given limited research in this emergent field for precollege students, the instrument used in this study can be a model for future research, with the understanding that the conceptual focus of QIST outreach and formal education will vary depending upon numerous contextual factors. Ultimately, the results suggest this QIST informal outreach program was a promising intervention for improving QIST literacy and potentially broadening participation in the field among diverse groups of precollege students.

Abbreviations

AMO, atomic, molecular, optical; ANCOVA, analysis of covariance; ANOVA, analysis of variance; AP, Advanced Placement; DRL, Division of Research and Learning; QIS, quantum information science; QIST, quantum information science and technology; SD, standard deviation; SE, standard error; STEM, science, technology, engineering, and mathematics.

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Author contributions
RD: conceptualisation (supporting); writing – review and editing (co-lead); data collection and analysis (lead). AMK: conceptualisation (co-lead and corresponding); writing – review and editing (co-lead); data collection and analysis (supporting). TCW: conceptualisation (co-lead); writing – review and editing (supporting); data collection and analysis (supporting). DS: conceptualisation (co-lead); writing – review and editing (supporting); data collection and analysis (supporting). All authors reviewed the final manuscript.

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Data availability
The datasets generated and analysed during the current study are not publicly available due to agreed upon privacy restrictions outlined in Institutional Review Board approval.

Declarations

Competing interests
The authors declare no competing interests.

Author details
[1]Institute for STEM Education, Stony Brook University, Stony Brook, NY 11794-5233, USA. [2]Department of Physics & Astronomy and Institute for STEM Education, Stony Brook University, Stony Brook, NY 11794-5233, USA. [3]Department of Physics & Astronomy and C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794-3800, USA. [4]Department of Physics & Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA.

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