American Journal of Physics

PAPERS | JANUARY 01 2025

Quantum information science and technology high school outreach: Conceptual progression for introducing principles and programming skills

Special Collection: Celebrating the International Year of Quantum Science and Technology

Dominik Schneble ; Tzu-Chieh Wei ; Angela M. Kelly

Check for updates

Am. J. Phys. 93, 88–97 (2025)
https://doi.org/10.1119/5.0211535

View Online Export Citation

Articles You May Be Interested In

Reflections of Quantum Educators on Strategies to Diversify the Second Quantum Revolution
Phys. Teach. (January 2025)

Physics Outreach for WYP
Phys. Teach. (November 2004)

Promoting Science via an Equipment Loan Outreach Program
Phys. Teach. (May 2008)

26 October 2026 18:34:56

AAPT PHYSICS EDUCATION®

Quantum information science and technology high school outreach: Conceptual progression for introducing principles and programming skills

Dominik Schneble[a)]
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800

Tzu-Chieh Wei[b)]
Department of Physics and Astronomy and C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794-3800

Angela M. Kelly[c)]
Department of Physics and Astronomy and Institute for STEM Education, Stony Brook University, Stony Brook, New York 11794-5233

(Received 31 March 2024; accepted 16 November 2024)

National data have shown the need to expand and diversify the talent pool of the quantum technologies workforce. This article describes a newly designed 25-h summer quantum information science and technology (QIST) program for high school students in grades 10–12; the goal is to advance physical science literacy and diversify the STEM pipeline through novel quantum science and quantum computing access and learning. This partnership between Stony Brook University and the New York Hall of Science was designed by quantum physicists and physics education researchers. This manuscript describes the rationale and progression of quantum ideas and computing skills introduced in the outreach program. The program design scaffolded physics, mathematics, and computer science concepts to engage high school students in the excitement of quantum information science and technology fields. The disciplinary content included the limitations of classical computing, classical and quantum physics principles (diffraction, polarization, wave-particle duality), the Mach–Zehnder interferometer, superposition, quantum thought experiments (Schrödinger's cat and Wigner's friend), entanglement and Bell's inequality, quantum key distribution, and basic quantum computing skills. Students also spent time visiting laboratories and museum exhibits and learning about academic progressions and career pathways in quantum technologies. This university-based science outreach model may be replicated by other quantum educators and adapted for learning in formal contexts. © *2025 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).*

https://doi.org/10.1119/5.0211535

26 October 2026 18:34:56

I. INTRODUCTION

Quantum information science and technology (QIST) involves a relatively unknown set of disciplines for many students, so teaching quantum science and computing in secondary classrooms may promote interest and career aspirations in the field. Precollege outreach is an important step in developing QIST educational strategies that translate to formal classroom contexts.[1] This paper describes a QIST outreach program for high school students, consisting of a one-week, 25-h camp taught by university physics faculty. To date, 131 students from diverse socioeconomic backgrounds have attended the program, which was offered at both Stony Brook University and the New York Hall of Science. The authors developed a conceptual progression to link new knowledge to prior learning while minimizing cognitive load.[2] This manuscript describes the rationale and progression of classical and quantum principles and computing skills. The goal is to describe a replicable model for introducing early quantum education and inspire students to pursue post-secondary QIST study and careers.

II. BACKGROUND

Quantum education outreach is a means to diversify access among traditionally marginalized students in science, technology, engineering, and mathematics (STEM). Many of these students may not typically enroll in QIST-related high school disciplines such as physics, chemistry, computer science, and advanced mathematics.[3] The *Frameworks for QIS Education*[4] were published by the National Q-12 Education Partnership to identify foundational concepts for QIS engagement and *Next Generation Science Standards*[5] alignment. These frameworks illustrate how core QIS concepts align with traditionally taught principles and skills in secondary mathematics, chemistry, physics, computer science, and middle school STEM.[4] Age-appropriate QIS teaching should involve collaborative discovery through scaffolded instruction where students develop quantum models, analyze data, and engage in scientific discourse.[4] The present project expanded beyond typical secondary curricula through a scaffolded approach that included classical physics, quantum physics, and quantum computing. The compare and contrast approach suggested by Singh *et al.*[6] was consistent with our presentation of classical and quantum physics, and we built upon these concepts to introduce quantum gates and quantum computing with games, simulations, and IBM Quantum Composer.[7] Others have used congruent approaches.[8–10] In addition to the content, we included discussions related to QIST academic and career planning.

 © Author(s) 2025.

III. OUTREACH DESIGN AND CONTEXT

The main goal of the program was to advance physical science and computational literacy and diversify the STEM pipeline through novel quantum science and quantum computing access for students in grades 10–12. The program design was based on a constructivist approach, whereby students could make connections with prior experiences in physics, chemistry, mathematics, and computer science;[11] however, we did not assume that students had broad knowledge of these subjects. A progression of classical and quantum physics and quantum computing concepts was introduced to minimize the cognitive load that often accompanies counterintuitive and abstract ideas.[12]

The program was offered twice at both Stony Brook University and the New York Hall of Science in 2023–2024, for a total of four camps. Over two years, 131 students in grades 10–12 enrolled for a one-week, 25-h experience that included lectures, demonstrations, interactive simulations, games, and collaborative activities. Students came from diverse gender and ethnic groups; the majority had not taken physics and computer science, and most had completed at least Algebra II. Stony Brook University hosted the camp in laboratory space equipped with computers and materials, and students toured a quantum simulation laboratory. The New York Hall of Science also had laboratory space with computers, and students engaged in interactive museum exhibits on light, diffraction, and polarization instead of visiting a research laboratory. Most camps occurred in a single classroom, but the last used two rooms since there were 54 students. The camps were taught by three university faculty in theoretical quantum physics, experimental quantum physics, and physics education research; they were assisted by 3–5 teaching assistants who were graduate students in physics or STEM education, or undergraduate STEM majors. The program was fully funded by the National Science Foundation; in many cases, transportation in the form of busing or subway passes was also provided at no cost to students.

IV. HIGH SCHOOL LEARNING MODULES

The camp modules were designed to transition from classical to quantum concepts, focusing on building intuition and using minimal mathematics. Figure 1 summarizes the conceptual progression (demonstrations and activities are marked in gray boxes, for example, "Bloch sphere model" and "cryptography"). The progression started with basic classical physics notions (top left) and then proceeded rightward, and downward toward advanced topics (bottom right), with conceptual connections shown with dashed arrows. The order of the progression itself was designated with solid arrows. The depiction of Rodin's philosopher denotes epistemological discussions of quantum concepts, most of which are further detailed in Secs. IV C–IV E. The learning modules were organized into five thematic units: (1) the rationale and potential of quantum computing; (2) classical physics: diffraction and

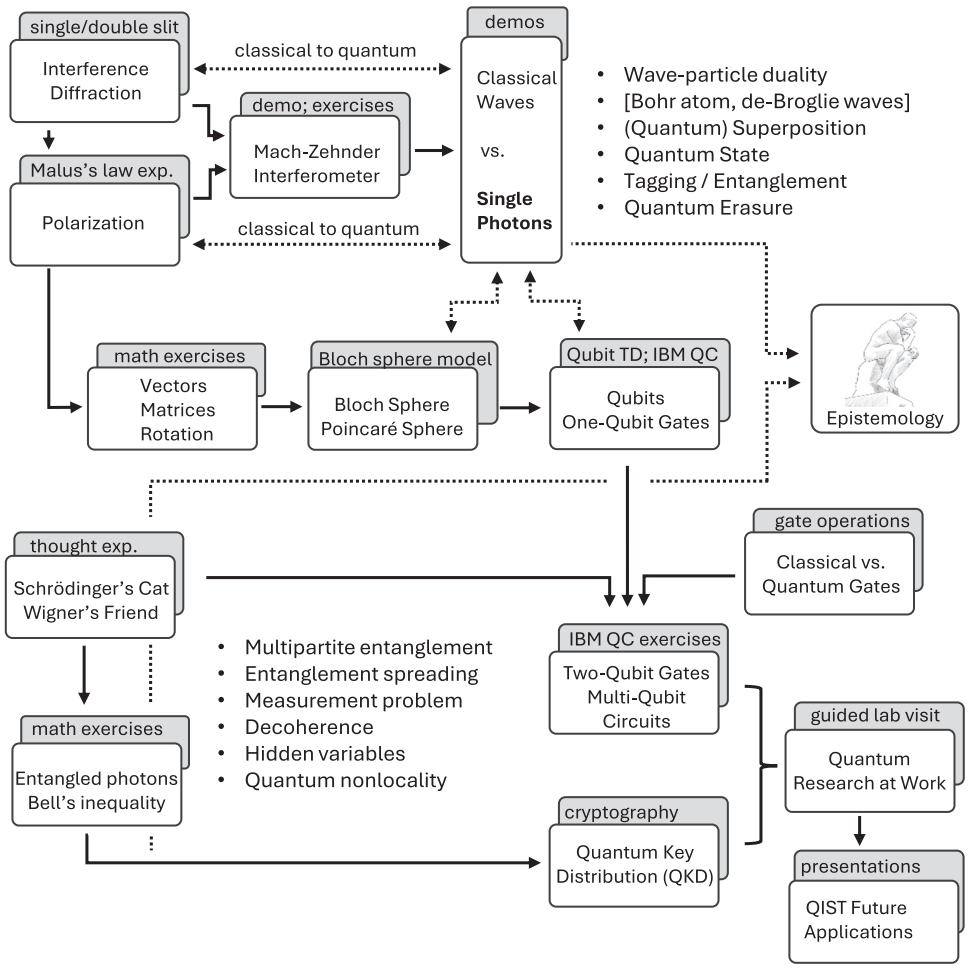


Fig. 1. Conceptual progression of QIST instruction.

26 October 2026 18:34:56

polarization; (3) the building blocks of quantum physics (quantum superpositions, Mach–Zehnder interferometer, Schrödinger's cat and Wigner's friend, entanglement and Bell's inequality, and laboratory visits); (4) quantum computing fundamentals (superposition, qubits, state vectors, the Bloch sphere, gate operations, measurement, quantum circuits, and quantum key distribution); and (5) QIST applications, careers, and student presentations. The conceptual foci and approximate time allocation for each unit are summarized in the supplementary material, although the bulleted lists indicate more specific topics that were addressed in various iterations of the program.

A. Why is quantum computing important?

The program began by introducing quantum computing as a novel and powerful way of information processing using quantum physics. Students learned how modern computing technology is increasingly headed toward the quantum realm by exploring Moore's Law and the reduction of transistor size to the nanometer scale,[13] which was shown graphically to illustrate the limits of classical computing. Quantum computers can solve certain computational problems much more efficiently than any classical computer, as evidenced by Shor's quantum factoring algorithm.[14] Students learned that these capabilities can be used to break RSA encoding, search unstructured databases, and solve large linear equations. However, it was emphasized that existing quantum computers are still very limited—noise and errors are still a critical issue that limits their performance. This lecture with embedded discussion questions led to an introduction of secure communication through quantum key distribution, and the recent 2022 Nobel Prize in Physics, awarded jointly to Alain Aspect, John F. Clauser, and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".[15] Students recognized that modern-day, practicing scientists are contributing to this evolving field with groundbreaking progress—in this case, providing evidence of quantum entanglement. This overview set the stage for a conceptual progression that included classical physics, quantum physics, and quantum computing concepts and skills.

B. Classical physics: Diffraction and polarization

The next module was designed to establish some important classical physics concepts before differentiating these ideas from quantum physics. Students learned about the characteristics of light as an electromagnetic wave, including spectral variations in wavelength and frequency, the speed of light, and polarization. This general introduction was followed by demonstrations of reflection, interference, diffraction, and polarization which included interactive demonstrations with a slinky spring, observations with diffraction grating glasses, and PhET simulations with single and double slits.[16] This allowed students to interact dynamically with simulations and observe the effects of varying slit separation (double), slit width (single), and light frequency (color). They answered clicker questions on pattern predictions to assess their knowledge and correct misunderstandings.

Students performed two hands-on diffraction experiments. First, they determined the wavelength of a weak (<1 mW) laser pointer using a diffraction grating slide. They took simple measurements of diffraction patterns on the wall to determine wavelength (λ) from the condition for constructive interference, where y was the distance between the observed diffraction band (cm) and the central ($m = 0$) band, m was the band order, L was the distance between the diffraction grating and the wall, and d was the distance between the slits,

$$y_{\mathrm{cm}} = \frac{m\lambda L}{d}. \tag{1}$$

The second experiment involved student construction of a slit experiment featuring an apertured human hair. Students constructed a simple apparatus with a paper clip, tape, and a hair (Fig. 2, which was shown to students as part of the instructional materials). They cut two pieces of tape to place across the sides of a paper clip to make an opening. They then placed the hair in the middle of this opening and fixed it into place with a tape. They shined a laser beam through the aperture and observed the single-slit diffraction pattern of the hair on the wall a distance L from the apparatus. They measured the width of the central bright band. If the students positioned the tape to be sufficiently close to the hair, this turned into a double-slit apparatus, and they measured the distance of several bright bands (y). Assuming a laser wavelength (λ), they estimated the width d of the hair in either case. These activities familiarized the students with the concepts of single- and double-slit diffraction and of constructive and destructive interference. The wave must have passed through both slits simultaneously to produce the observed diffraction pattern.

Another experiment was designed to illustrate polarization and Malus's law. The canonical polarization states (linear, circular) were first illustrated in a demonstration where students sent polarized pulses down a long slinky spring and had to identify the polarization state in each case. To test Malus's law, they first assembled simple polarization filters cut from a polaroid film with attached paper circular protractors (Fig. 3) and experimented with an overhead light source and a sensor, and a sensor (e.g., cell phone with a free app (*Light Meter LM-3000 (iPhone), Light Meter-Lux Meter (Android)*). Students taped square pieces of the polarizing film to the back of the circular protractors after cutting them on the outside and in the center, leaving a hole for light to reach the cell phone sensor. This allowed them to orient the polarization filters at different angles and observe illumination through observation and the sensor readings.

They recorded the sensor value when the light source was blocked and unblocked to gauge the range of possible readings. They then placed two polarizers between the source and the sensor, varying the angle of the second polarizer. They plotted the ratio of the sensor reading and the maximum value as a function of the angle θ. The resulting cosine

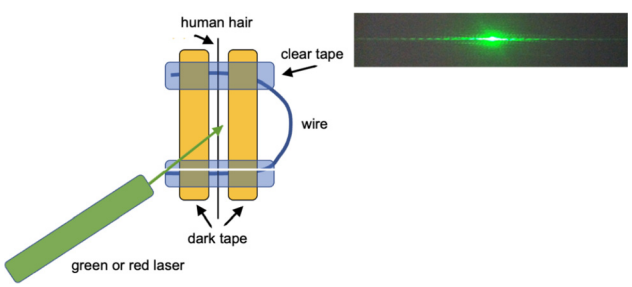


Fig. 2. Diffraction grating and observed pattern.

26 October 2026 18:34:56



Fig. 3. Circular protractor for polarization filters.

function illustrated the mathematical nature of Malus's law, which students were guided toward understanding and applying to their data as they worked in small groups,

$$(I_{transmitted})/(I_{incident}) = \cos^2\theta. \tag{2}$$

Students considered the vectorial character of polarization while learning the basic concepts of vector components and projections. Circular polarization is more conceptually difficult than linear polarization for high school students; we explained that the former is understood as two orthogonally linear-polarized components that are 90° out of phase.

C. Building blocks of quantum physics

1. Diffraction, polarization, and single-particle quantum superpositions

Having discussed classical electromagnetic waves and their interference in diffraction experiments, we introduced wave-particle duality as seen in the diffraction of light at low intensity. We first explained the photoelectric effect to suggest that light is not just a wave but consists of photons as particles of light. Students were guided through lecture and simulations to connect the production of photons to quantum jumps of electrons between the discrete orbits in the Bohr atom. We demonstrated this through a video of an actual experiment[17] in which a thermal source was dimmed with neutral density filters to the single photon level. In these experiments, the diffraction patterns formed click by click, photon by photon. The students answered questions and discussed the notion that each photon seemed to have the ability to go through both slits at once—it is a *wave-particle*. Its actual (quantum) state behind the double slit, before it hits the screen, is a *superposition,*[*]

$$|slit\,1\rangle + |slit\,2\rangle. \tag{3}$$

The photon can appear anywhere on the screen according to the diffraction pattern, but when the detector registers its location on the screen, the state of the photon *collapses* at that specific point. This was the first use of bra-ket notation for the students. We first explained that it represents a photon in a quantum state and then introduced the superposition principle of waves to explain that we can add them. In the case of Eq. (3), this is a representation of a photon that simultaneously goes through both slit 1 and slit 2. This notation was used in lecture slides to represent subsequent discussion of quantum states.

Going back to the Bohr atom, we visually introduced electron de Broglie waves to explain why there are stable orbits and then confronted the students with the stated fact that every material particle, bound or not, can have wave properties. Students observed the results of a double slit experiment performed with free helium atoms in the 1990s[18]—the same double-slit diffraction pattern formed, now due to the diffraction of atoms. Questions for group discussion were: Will the wave-particle duality work for larger objects? Where is the limit? What separates the quantum from the classical? Students were highly engaged in these discussions.

Crucially, the concept of quantum superposition carries over from the propagation of photons to their polarization. Students considered a polarizing beam splitter, in which an incident laser beam is transmitted if horizontally polarized (H) but reflected if vertically polarized (V). When the beam is diagonally polarized, half of the beam is thus transmitted, and the other half is reflected. Students were asked what happens if the beam is so weak that it contains a single photon only—does this photon go straight, or around the corner, or both? What is its quantum state after passing the cube? Students readily proposed the correct answer qualitatively,

$$|\mathrm{H}\rangle + |\mathrm{V}\rangle. \tag{4}$$

2. Mach–Zehnder interferometer

Students advanced their understanding of interference and polarization through *Mach–Zehnder interferometer* demonstrations and discussions. First, we led the students through a lecture with a set of conceptual lecture slides in which we slowly progressed from the single- and double-slit phenomena to more complicated combinations. For example, we showed one slide depicting a plane wave impinging on a double slit at normal incidence, and students observed a specific position at the screen. We showed a theoretical small hole in the screen and the lines of sight (rays) from the slits to the little hole. Students were asked to consider the path length difference. From the previous diffraction and interference simulations and activities, students had learned that an integer number of wavelengths would represent constructive interference (large signal), and a half-integer number, destructive interference (no signal). Rather than using a plane wave for illumination, we illuminated the slit on the lecture slide with light escaping from another small hole (single-slit point source) on a screen symmetrically placed on the other side. The lines of sight (light rays) connecting the emitting hole to each of the slits and then to the detection hole (path 1 and path 2) were then considered. These rays formed a parallelogram, and a Mach–Zehnder interferometer was formed.

Repeating the approach from before, we proposed a hypothetical situation where the light source was so weak that only a single photon entered the Mach–Zehnder interferometer at a time. Which path will the photon take? By now the students understood that the photon as a wave-particle "does not have to make up its mind," and therefore there will be interference at the detection hole,

$$|path\,1\rangle + |path\,2\rangle. \tag{5}$$

Alternatively, we cannot possibly tell which path the photon took; it is this superposition state that guarantees the interference. However, now suppose that we put a polarizer in each of the two paths, and that they are perpendicular (transmitting horizontal (H) polarization in path 1 and vertical (V) in

[*]For the remainder of this unit, we left out normalization factors for pedagogical purposes.

26 October 2026 18:34:56

path 2). By placing the filters in the paths, we have labelled or (tagged) the photon,

$$|H,\, path\, 1\rangle + |V,\, path\, 2\rangle. \tag{6}$$

The tagging provides us with the *which-way information* about the path taken by a single photon—one can also say that the path is entangled with the polarization—and there is no interference (after all, perpendicularly polarized laser beams cannot interfere in intensity). However, if we measure behind a third polarizer oriented diagonally, the interference is back—what is transmitted coming from each path now has the same polarization. At the level of a single photon, we are deprived of the which-way information (*quantum erasure*), and the ability to interfere returns.

To reinforce these concepts, the students then observed an actual lab-grade Mach–Zehnder interferometer on an optical breadboard (built from commercial optics components), which featured two 50:50 beamsplitters and two mirrors. An incident laser beam was split into two paths and then recombined. Students predicted, tested, and discussed the behavior of light in a Mach–Zehnder interferometer with polarizers in various orientations (Fig. 4), conceptualizing the transition from a laser beam to the behavior of a single photon. They completed an activity where they drew the predicted paths of light through a series of filters and explained how and why the pattern changed with the addition of polarizer films in different configurations (H, V, diagonal). Students in small groups compared their predictions with actual observations of the setup.

3. Schrödinger's cat and Wigner's friend

Going beyond single-particle quantum superpositions, we conducted thought experiments on Schrödinger's cat and Wigner's friend[19] to introduce and illustrate the concept of entanglement between objects. This was done through Socratic questioning with the students viewing lecture slides and answering questions as the instructor led them through successive hypothetical situations. Students again considered the scenario in which a laser beam polarized at 45 degrees hit a beam splitter, assuming that the beam was attenuated to one photon at a time. One of the output ports was connected to a device that, upon nondestructive detection of the photon, released some poison. Another device was connected to the other output port but had no effect; we assumed that the two devices did not destroy photons when detecting them. At this point, a cat was introduced to the scene, and a box was put around everything—the cat, the polarizing beam splitter, and the two devices—with just a small hole in the wall of the box

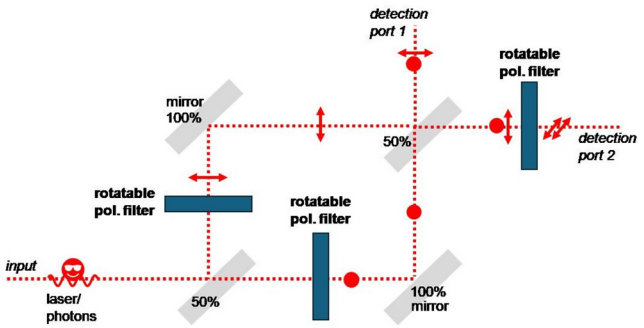


Fig. 4. Example of Mach–Zehnder interferometer activity.

to allow a photon to enter the beamsplitter from the outside. We asked the students: What is the state of the system after the photon enters the box, but before the box is opened? Most students made the correct prediction that the polarization state ($|H\rangle + |V\rangle$) of the photon was *entangled* with the vital state of the cat, and everything was in a superposition state,**

$$|H; alive\rangle + |V; dead\rangle. \tag{7}$$

We followed up with possible measurement outcomes, showing how the state collapsed into one possibility when the box was opened, making the observer happy or sad. The students were then introduced to the scenario that they, the laser, and the box with the cat were actually in a closed room, and that a friend was waiting outside. The students just opened the box (the cat is alive and well) but agreed to not leave the room until an hour later. From the friend's perspective, what was the state of the system after the students opened the box? The system now included the photon, the cat, and the student observers. We discussed with the students how their friend correctly stated that everything and everyone in the room was in a superposition state,

$$|H; alive; happy\rangle + |V; dead; sad\rangle. \tag{8}$$

However, we have opened the box, we saw that the cat is alive $|H; alive\rangle$ and were happy, never in a superposition state … Who is right? What if we were to involve and ask yet another friend, located outside the thick walls of the windowless building? The previous questions are examples of how we questioned the students as they developed a rudimentary understanding of entanglement.

Discussions of these concepts relating to the *measurement problem* illustrated the weirdness of quantum mechanics and its philosophical implications. We discussed the fundamental role of *decoherence* (information about the cat invariably leaked out of the box and the room) in establishing the concept of a shared classical reality without such quantum superposition states.

We introduced the "room" as a paradigm for a quantum computer. Before observation and decoherence, entangled states of many qubits can be created and manipulated inside—for example, Schrödinger-cat (Bell) and Wigner's-friend (GHZ) states are produced by sequentially applying two-qubit quantum gates (CNOT) to a growing number of qubits involved, leading to a spreading of entanglement inside. When students later ran such algorithms in IBM Quantum Composer,[7] they were reminded of these thought experiments to make conceptual sense of the gate operations.

4. Long-distance entanglement and Bell's inequality

Through the discussions of Schrödinger's cat and Wigner's friend, the students were familiarized with the concept of multi-partite entanglement. They then considered a situation in which the pair was separated by an astronomical distance. We swapped the photon and the cat for an entangled *photon pair*. We explained how such a photon pair is produced by *spontaneous parametric down conversion*, and that the entanglement of the two photons is in their polarization state: $|H; H\rangle + |V; V\rangle$. What happens to the state

**Here, the "vital state of the cat" includes all other macroscopic features inside the box, such as those of the poison, broken glass vials, etc.

26 October 2026 18:34:56

of one photon upon measurement of the other—does it change instantaneously, over arbitrary distances?

Students learned about the notion of *hidden variables* introduced by Einstein *et al.*[20] and methods inspired by John Bell[21] to test for their existence by looking for correlations between projective random measurements of the two polarizations. Bell's inequality and the results of experimental tests showed a violation, which led to the 2022 Physics Nobel prize. These experiments ruled out the existence of hidden variables and proved that the structure of quantum reality is indeed *non-local*.

Students explored these ideas by verifying a simple equality. Students were instructed to consider four variables: a, a', b, b', all of which can only take two values ± 1; we had them choose an arbitrary combination and demonstrate that the expression

$$B = ab + a'b + ab' - a'b' = a(b + b') + a'(b - b') \tag{9}$$

can only be ± 2. We interpreted the expression B in an experimental context: the variables represented results from a measurement that gave a value of either $+1$ or -1 and two observers (Alice and Bob) separated by a distance each measured the polarization (or spin) of particles that were supplied to them one by one. Alice used two different measurement settings and the respective results were recorded in variables a and a', respectively; and similarly Bob used another set of two different measurement settings with results recorded in variables b and b'. This equality showed that for each round of the experiment, they collectively produced one of the four combinations in the expression B, and if they randomly switched between their two respective settings and repeated the measurements, they could estimate the statistical expectation value of B, which we labeled $\langle B \rangle$. This led to the inequality that $-2 \leq \langle B \rangle \leq 2$, or equivalently $\lceil \langle B \rangle \rceil \leq 2$.

After students completed the Bell's inequality activity, we explained the historical significance of this discovery along with some examples of how it can be applied to experimental data. While the thought of deriving such an inequality that can be tested experimentally originated from John Bell,[21] the version that we used was based upon the work of John Clauser, Michael Horne, Abner Shimony, and Richard Holt (CHSH).[22] Bell showed a violation of his inequality if one uses a source of entangled pairs. CHSH showed that their version of the inequality can be violated and the value of $\langle B \rangle$ can be as high as $2\sqrt{2}$. This emphasis on the historical development of quantum ideas has been shown to promote student interest.[23]

5. Laboratory visits with students

In addition to the disciplinary principles and applications, students visited a research laboratory and observed "quantum" at work in an AMO (atomic, molecular, optical) setting. This involved some discussions with scientists and graduate students about ways to control light and matter at the quantum level, methods to achieve Bose–Einstein condensation, its properties related to motion and temperature, macroscopic coherence, the manipulation of hyperfine spins on the Bloch sphere, and the engineering of optical-lattice systems with targeted properties. These ideas were explicitly related to students' learning of classical and quantum principles, as well as their understanding of the limitations of quantum computing that researchers are attempting to overcome. Quantum simulations and quantum computation were discussed and differentiated, and students were shown the basic operational principles of a programmable analog quantum simulator for studies of questions in fundamental physics.

These visits gave students the opportunity to discuss quantum careers and academic pathways informally with quantum scientists, physics faculty, graduate students, and undergraduate students. Alternatively, students at the New York Hall of Science attended a panel discussion with scientists working in artificial intelligence and quantum computing industries. These experiences allowed students to develop expectations of the roles and responsibilities in both QIST theoretical and experimental domains, and how these expectancies may have aligned with their personal values; these are important considerations in career aspiration development.[24]

D. Quantum computing fundamentals

Once students were familiar with the building blocks of quantum physics, we transitioned to quantum computing. We began by reviewing the concept of a classical bit, which is a binary digit that can be 0 or 1, false or true, off or on, head or tail, etc. Students learned classical gate functions and practiced predicting outcomes with a worksheet activity before proceeding to learn quantum gates. This guided practice was done in small groups with the instructors answering questions as students developed an understanding of the gate functions. Sample gate exercises (NOT, AND, CNOT) are shown in Fig. 5, yet they also worked with other gates such as OR and XOR. The instruction and activity took approximately 30 min to complete.

Like classical waves, a quantum object can be a superposition of several different possible states. A quantum bit can thus be in a superposition of 0 and 1. We usually place 0 or 1 inside a bracket, such as $|0\rangle$ or $|1\rangle$. However, if one tries to observe or measure the quantum bit, one sees either 0 or 1 probabilistically. A classical bit can be flipped between 0 and 1 by changing voltages, the action of which is usually referred to as a NOT gate. Correspondingly, a quantum bit can be flipped from 0 to 1 or vice versa by a *quantum NOT* (or X) *gate*. Students became familiar with the basic notion of gate functions through these exercises.

1. Superposition, state vectors, and the Bloch sphere

Students had learned that classical waves produce interference patterns, such as ripples on the water surface. This can be visualized by waves superimposed on one another. We then built upon this conceptualization by adding the mathematical description of waves. We reminded students of the bra-ket notation of a quantum state (which is like a vector), and they could add two kets together formally just like adding two vectors. For a quantum bit, we can add $|0\rangle$ and $|1\rangle$ together with different weights, such as

$$|\psi\rangle = a|0\rangle + b|1\rangle, \tag{10}$$

where a and b are complex numbers, and we usually normalize them to satisfy $|a|^2 + |b|^2 = 1$. This is related to measurement and the probability of outcomes adding up to unity. We made connections to polarization states and complex

26 October 2026 18:34:56

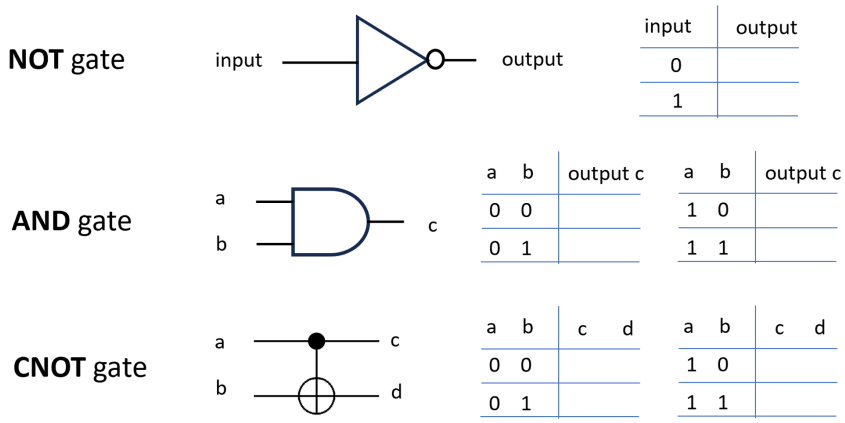


Fig. 5. Classical gate function exercises.

numbers we introduced previously and stated that we "normalize" them this way in order to make sure the vector (representing a quantum state) has a unit length. The formula applies regardless of whether a and b are real or complex (in general).

Students visualized a qubit's state using the Bloch sphere, building a physical model by using a tennis ball and three rubber bands, and labeling six special states that were pinned on the sphere (with the abstract qubit notation and photon polarization symbols, Fig. 6). Students engaged with interactive simulations (Fig. 7), changing the two angles and observing the resultant arrow's position on the sphere's surface. We shared with them that points inside the sphere represent the mixed states that require matrices to express them mathematically, as opposed to pure states that can be expressed by a unit vector (Fig. 7). We highlighted that light from the Sun or the light bulb is not described by points on the Poincare sphere, but by a point inside the sphere. They represent incoherent mixture, and to understand that you have a weighted sum of these vectors on the sphere. For example, the two arrows with one pointing to the north pole and the other pointing to the south pole average to a point at the origin of the sphere. The arrows were constructed by adding arrows on the surface with appropriate weights; this skill was reinforced as they worked with IBM Quantum Composer.[7]

To reinforce the notion of superposition in a single qubit, students visualized a coin as a quantum object, where it can exist in a superposition of heads and tails simultaneously, illustrating the abstract notion of a state, for example, $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$. Its Bloch sphere representation is an arrow pointing at the positive x axis. Other superposition states were shown along the equator of the sphere, including $|-\rangle$, $|+i\rangle$, and $|-i\rangle$. The majority of the students were not familiar with complex numbers, which was a limitation that was overcome by using multiple representations. We explained that the notation $|+\rangle$ represents $(|0\rangle + |1\rangle)/\sqrt{2}$ and $|i\rangle$ represents $(|0\rangle + i|1\rangle)/\sqrt{2}$, and the symbol $+$ or i inside the ket simply reminds us of the factor in front of $|1\rangle$. We showed the vector form as well. We felt that most students were receptive and became comfortable with these notations.

Extending the vector picture beyond one qubit is straightforward, but the consequence is profound. Two quantum coins can, for example, be in a superposition of being both heads and tails, such as the state $(|00\rangle + |11\rangle)/\sqrt{2}$. This is a manifestation of quantum entanglement, which the students had learned with Schrödinger's cat and Bell's inequality violation, and they would explore this further with quantum circuits.

2. *Gate operations*

Students learned about quantum gate operations through computer simulations with Mathematica, matrices, and Thomas Wong's Qubit Touchdown game[25]—we found that multiple representations of complex ideas helped their understanding and their ability to construct quantum circuits. Several (single-qubit) quantum gates and matrices are shown

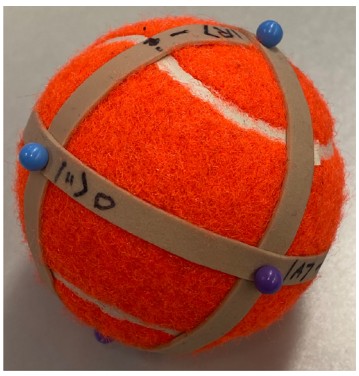


Fig. 6. Student's model of the Bloch sphere (in terms of spin) or Poincaré sphere (in terms of light polarization).

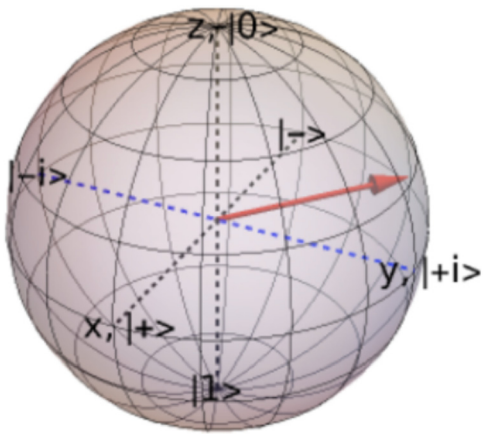


Fig. 7. Bloch sphere representation of a pure quantum bit with a vector pointing from the center to a point on the surface. The direction can be varied by the two angles θ and φ.

26 October 2026 18:34:56

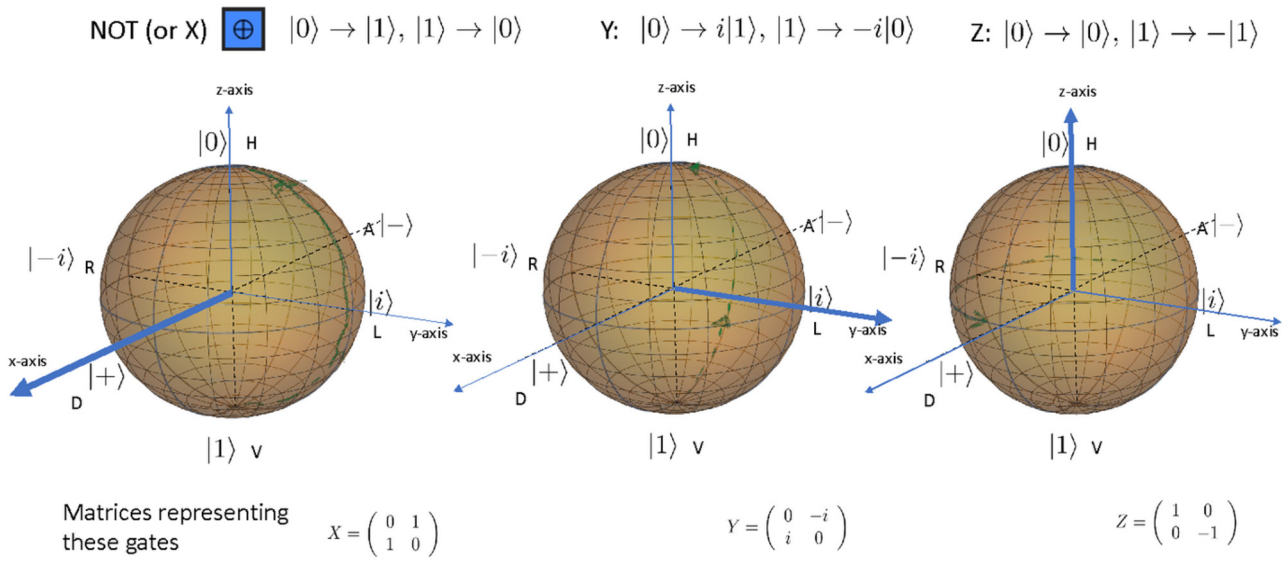


Fig. 8. Basic quantum gates and matrices.

in Fig. 8, and their actions were explained as students held their Bloch sphere models and envisioned rotating points on the sphere. These visual representations served as examples before students constructed their own simulations using Mathematica to confirm the probabilities that were observed in IBM Composer.

Students also learned about wave plates in quantum gates. We discussed quantum gates in two representations. First, one-qubit quantum gates were explained as those that rotate a vector on the Bloch sphere to another direction. Second, we identified states on the Bloch/Poincare sphere as photon polarization states, and we informed students that wave plates were those that could rotate polarization states.

3. Measurement and quantum circuits

In the quantum world, the act of observing or measuring changes the state of the system. Moreover, we need to specify the "observable" or basis that we measure in. It is natural for us to measure in the $|0\rangle$ and $|1\rangle$ basis, to which the corresponding observable is the Pauli Z. This means that when we perform the measurement on the system in a state, we will either see $|0\rangle$ or $|1\rangle$, and that they occur with a probability $|a|^2$ and $|b|^2$, respectively. In terms of the Bloch sphere, students observed this measurement by examining the projection of the qubit's arrow along the z axis. If that projection is r_z, then the two probabilities are, respectively $(1+r_z)/2$ and $(1-r_z)/2$.

Students were introduced to quantum circuits. We used a single photon polarization as a physical qubit, wave plates as one-qubit gates (which were shown on a lecture slide as a visualization), and a beam splitter or polarizers (and detectors) as measurement. Students had a physical picture of a one-qubit quantum circuit, and they used IBM Quantum Composer[7] to illustrate the six special single-qubit states (for example, $|+i\rangle = (|0\rangle + i|1\rangle)/\sqrt{2}$) and $|-i\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}$) on the Bloch sphere, and four different so-called two-qubit Bell states, which are $|\Phi^{\pm}\rangle = (|00\rangle \pm |11\rangle)/\sqrt{2}$ and $|\Psi^{\pm}\rangle = (|01\rangle \pm |10\rangle)/\sqrt{2}$).

However, as we explained to students, there are generally multiple qubits in a circuit. Students then constructed multiple qubit circuits as illustrated in the following example. In a quantum-circuit diagram (Fig. 9), each line represents a quantum bit. The diagram is read from left to right, as quantum gates are applied in that order. A one-qubit gate appears on one line; two-qubit gates, such as CNOT, extend across two qubits; and there are multiple qubit gates. Measurements are represented by meter symbols with dashed lines connecting to classical registers.

Students also used IBM Quantum Composer to illustrate the stochastic nature measurement in a single-qubit superposition state and the correlated outcomes in the Bell states (see the supplementary material). We discussed with them that the statistics from measuring a Bell state can violate the CHSH-Bell inequality satisfied by classical physics.

4. Quantum key distribution

With the Bell inequality violation experimental setup, we introduced students to Ekert's 1991 protocol[26] that established a common random bit string shared between two

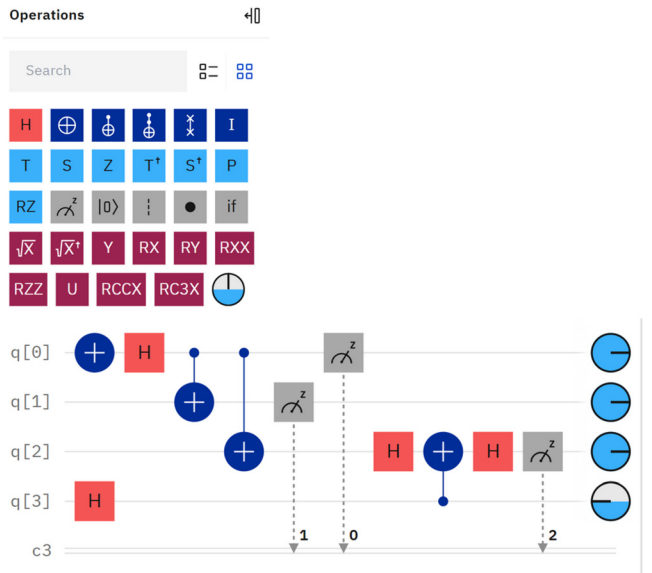


Fig. 9. Example of web-based Qiskit Quantum Circuit Composer.[7] On the left is a set of quantum operations, including gates and measurement. On the right is an example of a quantum circuit.

26 October 2026 18:34:56

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?

a. 11011
b. 11000
c. 01001
d. 01010

Fig. 10. QKD sample assessment question.

distant observers; students were told that scientists could check the security level by performing the Bell inequality test. We also showed the measurement axes for maximal violation of the inequality for one of the Bell states and remarked that this could be done with IBM Quantum Composer by combining results from four different circuits. We also discussed the BB84 (Bennett and Brassard) protocol[27] for quantum key distribution (QKD) by using two nonorthogonal states 0 (horizontal polarization state H) and + (diagonally polarized state D) to represent a logical "0" and the other two states: 1 (vertical polarization state V) and − (anti-diagonally polarized state A) to represent a logical "1."

Students practiced encoding 26 English alphabet letters into five-bit binary digits (e.g., A = 00001 and B = 00010) and used a random one-time pad to encode and decode messages. They created individual messages and wrote them on paper, encrypted them, and deciphered each other's coded message in pairs. An example of a post-camp assessment question measuring this particular skill is shown in Fig. 10; other assessment questions were developed for classical physics, quantum physics, and quantum computing concepts and applications.[28]

After foundational principles and potential applications were introduced, students were prepared and encouraged to explore advanced topics, such as coding and simulations on dense coding and teleportation, simple quantum algorithms, quantum repeaters, and the quantum internet.

E. QIST applications and careers

To connect QIST to students' everyday lives, they worked in groups to explore potential applications of quantum technologies. These applications included cryptography and cybersecurity, climate change and weather forecasting, pharmaceuticals, financial modeling, artificial intelligence, solar capture, traffic control, clean fertilizers, and enhanced batteries. Student groups chose and researched one application with suggested internet sources and participated in a jigsaw activity,[29,30] where student "experts" informed other groups about the potential usefulness of quantum computing in solving complex technological problems.

QIST-related careers and academic pathways were discussed formally and informally with quantum physicists, physics educators, graduate and undergraduate students, and university admissions staff. The was done through separate 30-min panels with graduate students and quantum physicists, and a one-hour session on applying to college to pursue STEM majors. Students also learned about important elective high school STEM coursework for post-secondary QIST study, and survey data indicated their intention to enroll of four years of mathematics and science increased after they participated in the program.

As a final activity on the fifth day of the camp, students worked in teams of 3–5 to create group presentations on a topic of their choice from the lectures, demonstrations, and activities. They worked for three hours in the morning to perform background research and prepare slides (Google/PowerPoint/Canva) that explained the main concept, gave examples of potential applications, and posed interactive clicker questions that students could answer on their cell phones. Their presentations were generally 10–15 min, followed by peer review and feedback from the instructors on the quality, accuracy, and level of engagement of their presentations.

V. CONCLUSIONS

This precollege QIST model advances knowledge in quantum education through the design implementation of an informal outreach program. The partnership between Stony Brook University and the New York Hall of Science allowed for diverse student participation, while leveraging the QIST expertise and resources that are not commonly accessible at the precollege level. The growing need for K-12 QIST education requires collaboration among quantum theorists, quantum experimentalists, STEM educators, and curriculum developers (for example, this is evidenced in the *QIS Key Concepts for Early Learners: K-12 Framework*[4]) We acknowledge that this specialized knowledge base is a limitation to project scaling, and we recommend future hybrid and/or online offerings for precollege students, professional learning for preservice and inservice STEM teachers, interuniversity partnerships to scale to rural contexts, and a national quantum education center to lead precollege educational outreach.

Although students demonstrated improved QIST knowledge and skills with a large effect size, as evidenced by pre-/post-testing, there were formative programmatic adjustments as we reflected on successes and challenges. We sought to simplify the mathematics for students, particularly linear algebra applications, by including multiple representations, interactive simulations, and mathematics-based activities. However, this is an ongoing challenge as we revise our approach in future outreach iterations. We hope to improve student QIST knowledge outcomes, particularly with regard to improving their ability to predict probabilities and apply gate functions.

By exposing secondary students to quantum concepts and computing skills, they may be attracted to careers in developing next-generation technologies, meeting the national priorities of expanding and diversifying the QIST talent pool and workforce. This study illustrated the positive outcomes associated with a rigorous QIST curriculum that included 45% women and 24% ethnic minorities traditionally underrepresented in STEM. Providing informal learning opportunities for precollege students is a first step in promoting interest, engagement, and QIST literacy. Future research might assess the longitudinal outcomes of QIST outreach on students' career aspirations and participation in post-secondary QIST study. Quantum science content knowledge and quantum computing practices that promote critical thinking, reasoning, and communication skills are necessary in secondary education. Curriculum developers may consider our model in developing innovative strategies for teaching fundamental quantum concepts and relating them to traditional physical science concepts, while expanding these ideas to incorporate the basics of quantum computing.

26 October 2026 18:34:56

SUPPLEMENTARY MATERIAL

Please click on this link to access the supplementary material online for more details on the conceptual progression and specific examples of quantum circuits used to test the CHSH-Bell inequality. Additional updated materials may be available by contacting the authors. Print readers can see the supplementary material at https://doi.org/10.60893/figshare.ajp.c.7544586.

ACKNOWLEDGMENTS

The authors would like to acknowledge Xinyue Wang and Kanishka Wijesekara for their help in designing some of the activities. Katie Culp, Laycca Umer, and Sam Tumulo provided support at the New York Hall of Science for all project activities. Stony Brook University graduate student teaching, mentoring, and research support was provided by Michele Darienzo, Robert DeLaCruz, Austin Colon, Yabo Li, Wenhan Guo, Loc Ngo, Muxi Liu, Aswin Mana, Hiroki Sukeno, Hongye Yu, Shuyu Zhang, and Yan Mong Chan. Undergraduate student teaching and research support was provided by Sarah Cocuzza, Grace Ding, and Nisat Nosin. SandboxAQ researchers Amro Imam, Janet Faakye, and Sheenam Khuttan participated in the QIST career panel. Permission for research involving human subjects was granted by Stony Brook University's Institutional Review Board (IRB2022-00244). This work was funded by the National Science Foundation (DRL-2148467).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Note: This paper is part of the special issue celebrating the International Year of Quantum Science and Technology.

[a)]Electronic mail: dominik.schneble@stonybrook.edu, ORCID: 0000-0002-5779-4054

[b)]Electronic mail: tzu-chieh.wei@stonybrook.edu, ORCID: 0000-0003-4897-3410

[c)]Electronic mail: angela.kelly@stonybrook.edu, ORCID: 0000-0003-1393-1296

[1]Subcommittee on Quantum Information Science, *Quantum Information Science and Technology Workforce Development National Strategic Plan* (National Science and Technology Council, Washington, DC, 2022). https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf.

[2]F. J. Scharfenberg and F. X. Bogner, "Instructional efficiency of changing cognitive load in an out-of-school laboratory," Int. J. Sci. Educ. **32**(6), 829–844 (2010).

[3]National Action Council for Minorities in Engineering, Inc., *Pre-College Challenges for URMs in Engineering* (National Action Council for Minorities in Engineering, Inc., 2014).

[4]National Q-12 Education Partnership, *QIS Key Concepts for Early Learners: K-12 Framework* (National Q-12 Education Partnership, 2023). https://q12education.org/learning-materials-framework.

[5]NGSS Lead States. *Next Generation Science Standards: For States, By States* (National Academies Press, Washington, DC, 2013). https://nap.nationalacademies.org/catalog/18290/next-generation-science-standards-for-states-by-states.

[6]C. Singh, A. Levy, and J. Levy, "Preparing pre-college students for the second quantum revolution with core concepts in quantum information science," Phys. Teach. **60**(8), 639–641 (2022).

[7]See https://quantum.ibm.com/composer/ for "IBM Quantum Composer" (2024).

[8]J. A. Walsh, M. Fenech, D. L. Tucker, C. Riegle-Crumb, and B. R. L. Cour, "Piloting a full-year, optics-based high school course on quantum computing," Phys. Educ. **57**(2), 025010 (2022).

[9]S. Satanassi, E. Ercolessi, and O. Levrini, "Designing and implementing materials on quantum computing for secondary school students: The case of teleportation," Phys. Rev. Phys. Educ. Res. **18**(1), 010122 (2022).

[10]Q. Sun, S. Zhou, R. Chen, G. Feng, S.-Y. Hou, and B. Zeng, "From computing to quantum mechanics: Accessible and hands-on quantum computing education for high school students," EPJ Quantum Technol. **11**, 1–18 (2024).

[11]R. Driver, "Constructivist approaches to science education," *Constructivism in Education*, edited by L. P. Steffe and J. Gale (Routledge, 2012), pp. 385–400.

[12]National Research Council, *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research* (National Academies Press, Washington, DC, 2014).

[13]G. E. Moore, "Cramming more components onto integrated circuits," Electronics **38**, 114–117 (1965); available at https://www.cs.utexas.edu/~fussell/courses/cs352h/papers/moore.pdf.

[14]P. W. Shor, "Algorithms for quantum computation: Discrete logarithms and factoring," in *Proceedings 35th Annual Symposium on Foundations of Computer Science* (IEEE, 1994), pp. 124–134.

[15]See https://www.nobelprize.org/prizes/physics/2022/summary/ for "The Nobel Prize in Physics" (2022).

[16]See https://phet.colorado.edu/ for "PhET Interactive Simulations" (2024).

[17]Hamamatsu Photonics, *Young's Interference Experiment with Single Photons* (Hamamatsu Photonics, 1982). https://www.youtube.com/watch?v=I9Ab8BLW3kA.

[18]Ch. Kurtsiefer, T. Pfau, and J. Mlynek, "Measurement of the Wigner function of an ensemble of helium atoms," Nature **386**(6621), 150–153 (1997).

[19]M. Violaris, "A physics lab inside your head: Quantum thought experiments as an educational tool," in IEEE International Conference on Quantum Computing and Engineering (QCE), 2023.

[20]A. Einstein, B. Podolsky, and N. Rosen, "Can quantum-mechanical description of physical reality be considered complete?," Phys. Rev. **47**(10), 777–780 (1935).

[21]J. S. Bell, "On the Einstein-Podolsky-Rosen Paradox," Phys. Phys. Fiz. **1**(3), 195–200 (1964).

[22]J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, "Proposed experiment to test local hidden-variable theories," Phys. Rev. Lett. **23**(15), 880–884 (1969).

[23]T. Bouchée, L. de Putter-Smits, M. Thurlings, and B. Pepin, "Towards a better understanding of conceptual difficulties in introductory quantum physics courses," Stud. Sci. Educ. **58**(2), 183–202 (2022).

[24]I. Ajzen, "Perceived behavioral control, self-efficacy, locus of control, and the theory of planned behavior," J. Appl. Soc. Pyschol. **32**(4), 665–683 (2002).

[25]T. Wong, see https://www.thomaswong.net/ for "Qubit Touchdown" (2022).

[26]A. K. Ekert, "Quantum cryptography based on Bell's theorem," Phys. Rev. Lett. **67**(6), 661–663 (1991).

[27]C. H. Bennett and B. Brassard, "Quantum cryptography: Public key distribution and coin tossing," IEEE Int. Conf. Computers, Syst., Signal Process. **175**, 175–179 (1984).

[28]A. M. Kelly, D. Schneble, T. C. Wei, and M. Darienzo, *Conceptual and Mathematical Challenges in Precollege Quantum Information Science & Technology Outreach* (American Physical Society March Meeting, Minneapolis, MN, 2024). https://meetings.aps.org/Meeting/MAR24/Session/Q61.6.

[29]L. M. T. Márquez, J. G. Llinás, and F. S. Macías, "Collaborative learning: use of the jigsaw technique in mapping concepts of physics," Probl. Educ. 21st Century **75**(1), 92–101 (2017).

[30]G. Pelobillo, "Jigsaw technique in learning physics and problem-solving dimensions of senior high school students," JPAIR Multidiscip. Res. **32**(1), 90–109 (2018).

26 October 2026 18:34:56