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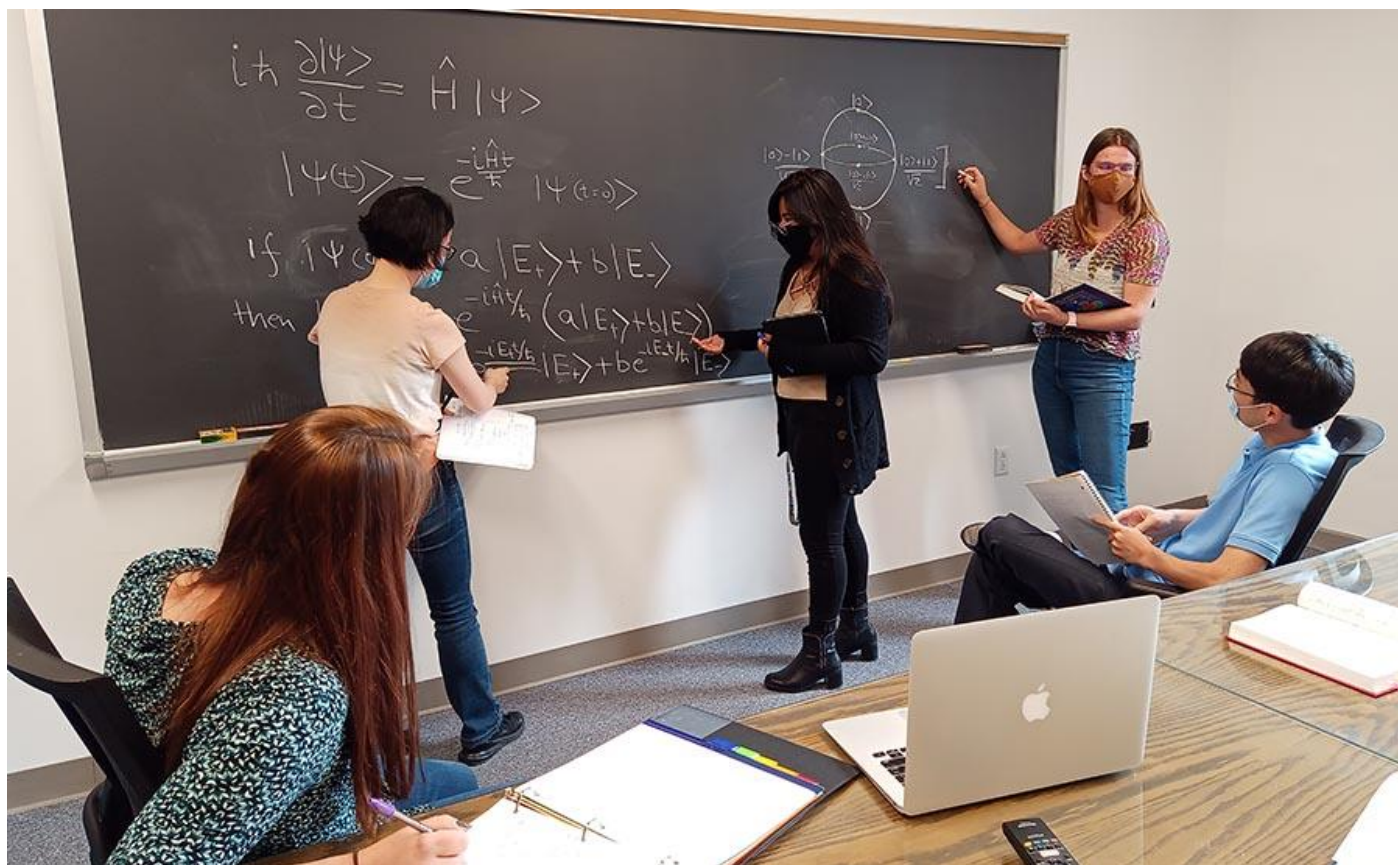
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Preparing students to be leaders of the quantum information revolution

To meet future research and workforce demands, the physics community needs to embrace the challenge of educating students with diverse educational backgrounds.

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University of Pittsburgh students study quantum mechanics. Credit: Jeremy Levy

As the crowning technological inventions of the first quantum revolution—transistors, lasers, and computers—continue to enrich our lives, newfound excitement surrounds the use of quantum phenomena to create a second quantum revolution. Quantum computers will compute faster than existing classical ones and enable computations that were not previously possible. Quantum sensors will detect one-part-in-a-million variations in Earth’s gravitational field or tiny magnetic fields emanating from the human brain. Quantum communication technologies will send information securely over long distances, protected by fundamental laws of nature.

These technologies could dramatically improve society. But the current educational

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science and technology (QIST), the field from which these advances are emerging.

Quantum physicists and physics education researchers have the knowledge and experience to devise a QIST educational program that can help prepare students of all ages to participate in and lead the quantum information revolution.

In 2020, NSF and the White House Office of Science and Technology Policy assembled an interagency working group to develop **Key Concepts for Future Quantum Information Science Learners**—a workshop in which researchers and educators identified core concepts for QIST training, such as qubits, quantum measurement, entanglement, quantum computing, communication, and sensing. Identifying and building educational resources based on those core concepts will help **K–12** and college students become quantum literate and join the growing quantum science and engineering workforce.

In addition to formal education, connecting students with research opportunities, internships, networking, and mentoring is vital for inspiring and nurturing the next generation. To successfully do so, current quantum industry leaders and educators will need to address the lack of representation of women and students from racial and ethnic minority groups and devise approaches to attract demographic groups that are currently underrepresented in the field.

A common QIST curriculum

One challenge in teaching QIST is that there is no common curriculum, in large part because the field is highly interdisciplinary and relatively new. At a **conference** in February funded by NSF, educators across academia and industry reflected on the urgent need for bachelor's degree programs, courses, and

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Interdisciplinary bachelor's and master's programs are being developed at universities across the US and Europe. Those programs are based in physics departments, engineering schools, and interdisciplinary centers. Nearly all the programs have at least one course specifically focused on quantum computing or information. Such courses can rely on traditional textbooks, such as those by Michael Nielsen and Isaac Chuang, N. David Mermin, or Benjamin Schumacher and Michael Westmoreland, or can be designed around resources such as the open-source Qiskit textbook or other interactive textbooks.

Courses on quantum computing and information are invariably surrounded by a host of supporting courses designed to meet the highly interdisciplinary demands of QIST. Those classes cover topics such as programming or computer science foundations, linear algebra, or electrical engineering. Other courses span topics outside core QIST areas or delve into applications related to materials science, chemistry, drug design, machine learning, forecasting, communication, and sensing. The required levels of experience in labs, internships, and hands-on projects can depend on the emphasis of the program.

Improving QIST curricula

Thus far, research on the effectiveness of QIST-related courses, curricula, and pedagogies has been limited in scope (see the article by Chandralekha Singh, Mario Belloni, and Wolfgang Christian, *Physics Today*, August 2006, page 43).

Postsecondary educators have investigated the nature of students' learning difficulties in quantum courses. Educators have also developed modular QIST

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levels.



One such tool, a set of lessons called the **Quantum Interactive Learning Tutorials** (QuILTs), are designed to focus on the **topics** students have been shown to struggle with, such as the time evolution of quantum states, quantum measurements, and quantum key distribution. QuILTs use guided inquiry-based learning sequences that build concepts on one another. Common conceptual difficulties are brought out explicitly by, for example, a written dialogue between two hypothetical students in which one student understands a concept and the other doesn't. Students working through the lesson contemplate which student is correct, and why, with the help of hints along the way.

Each unit starts with measurable learning objectives and then aligns the instruction and assessment with those objectives. The lessons are often supplemented with computer-based visualization tools. QuILT development is iterative: Data from each **implementation** with students are used to improve the tool.

Academia and industry

In addition to providing students with in-house research experiences in individual faculty labs or in capstone courses, postsecondary educators should consider partnering with companies and national laboratories to give students internship and networking opportunities. The Quantum Economic Development Consortium, for example, connects students with full-time QIST jobs in companies and national labs. Those opportunities can get students excited about QIST careers and give them a well-rounded understanding of what it is like to work in the field in a nonacademic setting.

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Developing degree programs, courses, and curricula that balance academic rigor

with the practical needs of the workplace. Since 2016, **IBM Quantum** has made its superconducting quantum computers available to the public, and that access enables an interactive approach to QIST education. Newcomers and experts from around the world can use a free cloud-based interface to run quantum programs on hardware that is located and maintained in a central facility. Other hardware platforms, such as **IonQ**'s ion trap-based quantum computer, offer similar cloud-based interfaces.

IBM has also released an open-source software development suite called **Qiskit**, which is based on the Python programming language, and an open-source **interactive textbook** that demonstrates how to use Qiskit to implement quantum algorithms on real quantum systems. By directly designing and running quantum algorithms, students gain a better understanding of the benefits quantum systems will bring to computation, sensing, and communication. The textbook covers both elementary concepts and the state of the art, and with additional resources it can be adapted to a wide range of learners.

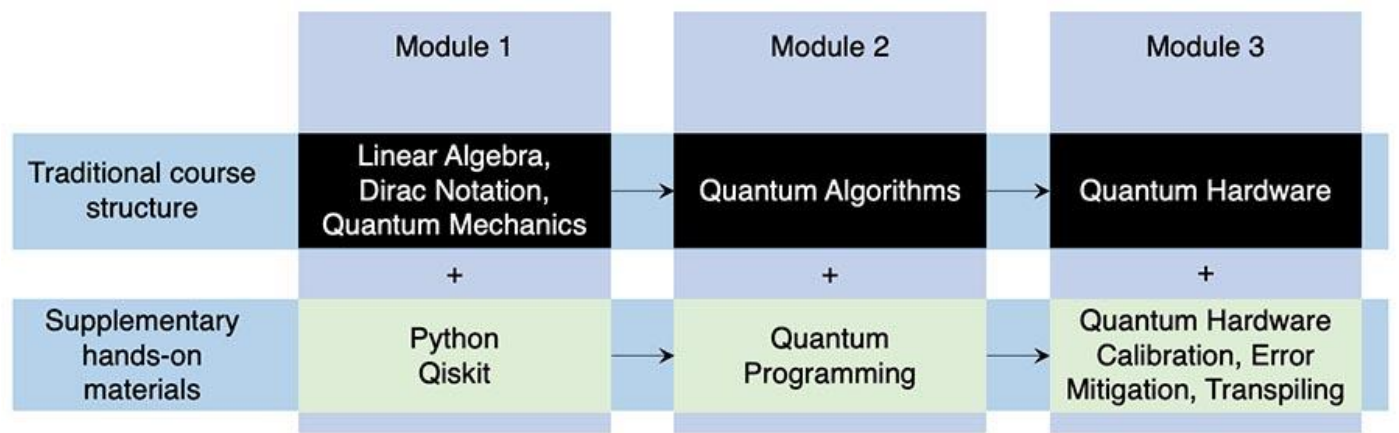


Figure 1. IBM recommends supplementing traditional quantum computation course topics with hands-on supplementary materials that incorporate real quantum systems. Credit: Adapted from **Qiskit Global Summer School**



that introduce quantum information science concepts through the use of **hands-on exercises**. A typical introductory course on quantum computation can easily integrate those resources by pairing lecture topics with activities, as shown in figure 1.

As students learn introductory quantum concepts, they can check their understanding with Qiskit lessons. For example, when they learn about quantum logic gates, they can apply those gates to create a circuit that implements a simple quantum algorithm. Similarly, students learning about quantum algorithms can implement them on simulated or real quantum computers and see how those algorithms solve real problems. Advanced students can opt to learn about the physics behind quantum computer hardware, including ways to control the hardware to manipulate quantum states, the physical layout of superconducting circuits, methods to encode quantum information in physical states, and the limitations of existing hardware.

QIST pedagogy

Hands-on QIST approaches result in deeper understanding and more rapid uptake of quantum concepts, according to a survey conducted after a 2020 remote global summer school hosted by IBM. With more than 4000 students, it was the largest quantum summer school of its kind. The syllabus was based on IBM's educational activities and interactive online textbook.

Eight percent of the attendees were high school students, 40% were undergraduates, 30% were master's students, and 22% were working toward a PhD.

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Surveyed 745 of the attendees about their self-reported skill level (see figure 2), on

a scale of 0 (no experience with QIST) to 10 (able to conduct novel research in QIST). Before the summer school (panel a), the most frequent answer was no prior experience with QIST, and the distribution was heavily weighted toward a skill level of zero. After the summer school (panel b), the distribution of skill levels shifted to the right by 5 points.

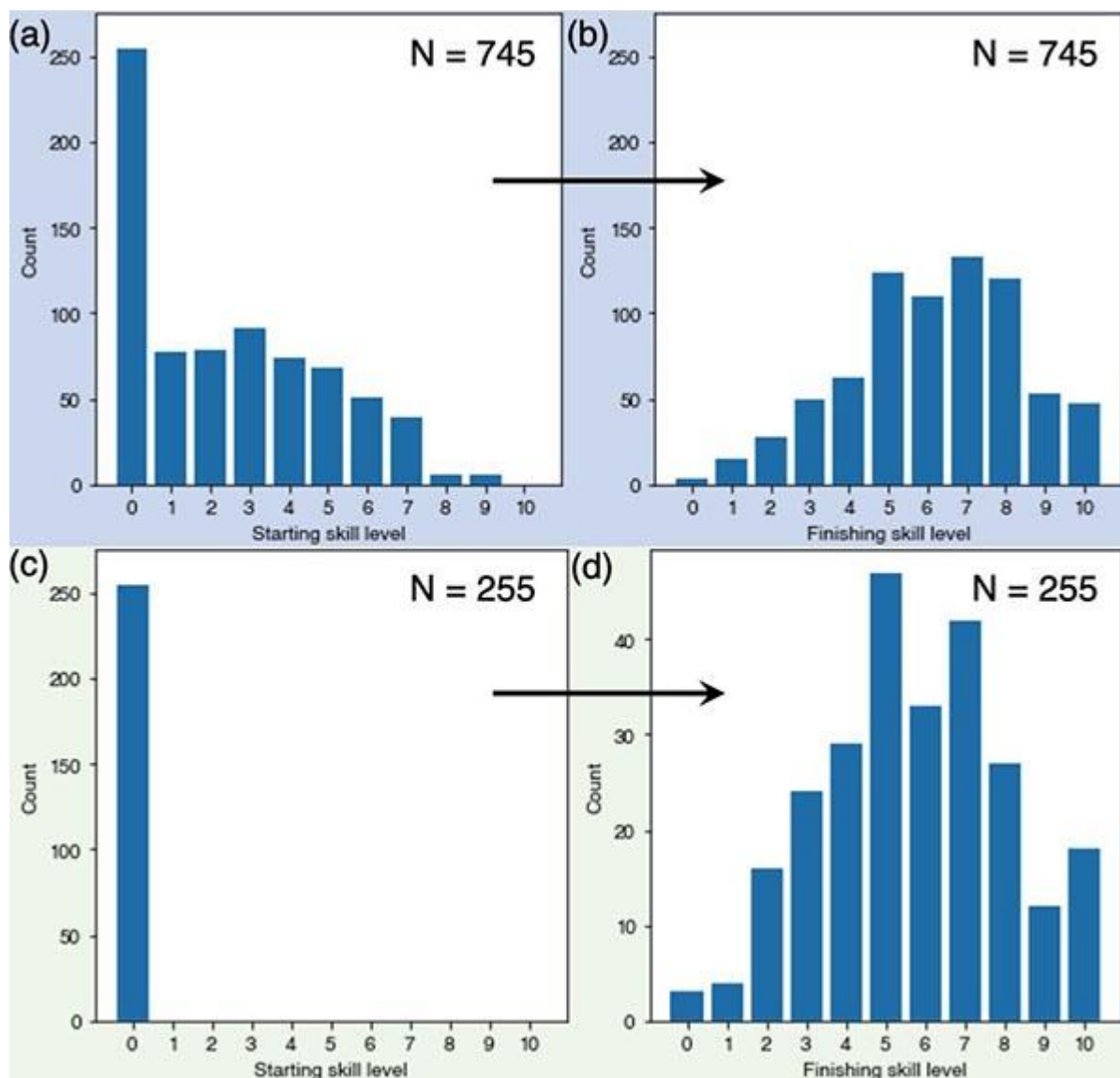


Figure 2. In 2020, IBM's Qiskit Global Summer School incorporated traditional and hands-on QIST educational materials. The self-reported skill levels of all the attendees who responded to the survey before (a) and after (b) attending the summer school showed about a 5-point increase on average. The distribution for just those

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Attendees who entered the summer school with no prior programming experience also self-reported on average a 5-point increase in their skill level. Although self-reported skill levels are not a direct measurement of learning outcomes, they do indicate success in lowering the intimidation that students of diverse educational backgrounds feel about learning quantum concepts.

Upskilling quantum-adjacent roles

Decades ago, only a select group of specialists had access to and could operate computers. Thanks to advanced software and layers of abstraction from the underlying semiconductor technology, today everyone can use a computer. At the current stage of the second quantum revolution, working in the industry and developing quantum computers still generally require a PhD. But a growing set of “quantum-adjacent” industry jobs also require quantum literacy. Those jobs include ones in programming, software development, electronics, cryogenics, vacuum technology, and algorithms.

For those with expertise in quantum-adjacent areas to become familiar with and interested in QIST, courses are needed to help them develop basic understanding of QIST concepts such as quantum bits, superposition, and entanglement. Michael Raymer of the University of Oregon has developed one such quantum literacy course and textbook, *Quantum Physics: What Everyone Needs to Know* (2017), which is appropriate for those interested in quantum-adjacent jobs or undergraduate students with no previous understanding of QIST concepts.

Sophia Economou and Edwin Barnes of Virginia Tech and Terry Rudolph of Imperial College London have developed a **teaching method** for college and high school students that uses Rudolph’s pictorial representations to minimize the need for linear algebra to explain QIST concepts—such as quantum gates—that are essential for quantum literacy and quantum-adjacent jobs. In addition, Diana Franklin and Kaitlin Smith from the University of Chicago are offering a sequence of edX courses that started in January 2021. Requiring only basic algebra skills, their **Introduction to Quantum Computing for**

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as superposition, measurement, and entanglement—that focus on the implications of the quantum operations rather than the details.



QIST equity

Introducing students to QIST concepts early is critical to getting them excited about the topic and careers in the field. That is especially true for students who are part of historically underrepresented groups, come from low-income families, or have parents who did not attend college. Without exposure at the K–12 level, those students will likely not pursue courses related to QIST technologies at the college level.

The Institute for Quantum Computing at the University of Waterloo in Ontario, Canada, has been conducting **professional development activities** and disseminating materials to K–12 educators to help them introduce their students to QIST in a conceptual manner. In those lesson plans, students learn, for example, about quantum key distribution and the effect of an eavesdropper by analyzing the polarization states of light with inexpensive polarizers.

Postsecondary educators should also consider working with K–12 educators—as part of the new **Quantum for All** program or similar efforts—to incorporate QIST concepts in national K–12 standards and in existing courses in physics, chemistry, computer science, or mathematics. They should also think about developing short courses focused exclusively on QIST concepts.

Recently, the American Association of Physics Teachers partnered with IBM to organize professional development workshops in which K–12 teachers learned how to use a cloud-based quantum computer so that they could incorporate it in their

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Rudolph of Imperial College London, which presents diagrammatic explanations of

QIST concepts that are accessible to anyone with basic arithmetic skills. The website [the Quantum Atlas](#) also hosts a collection of images, animations, and audio and written explanations on quantum topics for the public and educators alike.

Students from historically underrepresented groups need opportunities to access resources if they are to become leaders in QIST. Fortunately, quantum computers are accessible to any school through the cloud. And the recently formed [IBM-HBCU Quantum Center](#) is collaborating with historically Black colleges and universities to develop a more diverse future QIST workforce and advance quantum information science. At a recent conference, a team of researchers and educators from academia and industry presented a [road map](#) for building quantum engineering education programs with diversity, equity, and inclusion at the forefront.

Inclusive and equitable approaches to teaching, mentoring, and student support are also critical to ensure [equitable outcomes](#) (see the article by Lauren Aguilar, Greg Walton, and Carl Wieman, *Physics Today*, May 2014, page 43). For example, at the beginning of a quantum course, a short [ecological-belonging intervention](#), in which the class discusses how social and academic adversity is normal and surmountable, can help underrepresented students develop a better sense of belonging and thus improve their learning outcomes. Educators, internship or research mentors, course or workshop instructors, and outreach leaders or coordinators should receive [inclusive-mentoring training](#) to learn how to increase each of their mentees' sense of belonging, [self-efficacy](#), and

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AndyPlimaier • a year ago • edited

The article doesn't even hint at the ethical concerns that should surround QIST. The authors claim "These technologies could dramatically improve society," but every new technology opens a Pandora's box of blessings and curses, and judging by the challenges we currently face as the result of the enthusiastic embrace of past technologies, I worry that the balance is usually tipped towards that latter. Any curriculum that we develop for QIST must include lessons developed by well versed and highly enthusiastic skeptics of the benefits of technological advancement to awaken young technophiles to the perils of a technology that has the potential for unleashing forces that could render all life on earth obsolete.

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