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From computing to quantum mechanics: accessible and hands-on quantum computing education for high school students

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Abstract

This paper outlines an alternative approach to teaching quantum computing at the high school level, tailored for students with limited prior knowledge in advanced mathematics and physics. This approach diverges from traditional methods by building upon foundational concepts in classical computing before gradually introducing quantum mechanics, thereby simplifying the entry into this complex field. The course was initially implemented in a program for gifted high school students under the Hong Kong Education Bureau and received encouraging feedback, indicating its potential effectiveness for a broader student audience. A key element of this approach is the practical application through portable NMR quantum computers, which provides students with hands-on experience. The paper describes the structure of the course, including the organization of the lectures, the integration of the hardware of the portable nuclear magnetic resonance (NMR) quantum computers, the Gemini/Triangulum series, and detailed lecture notes in Additional file 1. The initial success in the specialized program and ongoing discussions to expand the course to regular high schools in Hong Kong and Shenzhen suggest the viability of this approach for wider educational application. By focusing on accessibility and student engagement, this approach presents a valuable perspective on introducing quantum computing concepts at the high school level, aiming to enhance student understanding and interest in the field.

Keywords: Quantum computing education; High school curriculum; Accessible quantum mechanics; Portable NMR quantum computer

1 Introduction

Quantum computing is an emerging field that explores new computational paradigms based on the principles of quantum mechanics, with the potential to solve certain problems more efficiently than classical computers [1–3]. However, its complexity and reliance on advanced concepts in mathematics and physics have traditionally kept it confined to higher education, specifically at the graduate level. Recent trends, however, indicate a shift towards introducing quantum computing concepts at the high school level, recognizing the importance of early exposure to these future-oriented technologies [4].

Initiatives such as MIT's "Qubit by Qubit" program have been pioneers in bringing quantum computing education to high school students through summer camps and year-long courses [5]. Similarly, hands-on workshops designed for grades 9-12 offer innovative and engaging activities to teach basic quantum computing concepts [6]. These efforts reflect a broader movement in K-12 education to incorporate quantum computing instruction [7]. Collaborative efforts between educational institutions and industry, like the partnership between Stanford Quantum Computing Association and qBraid, further exemplify this trend by developing introductory quantum computing curricula for high school students [8]. Most quantum computing textbooks start from linear algebra and postulates of quantum mechanics [9–11]. According to our experience, linear algebra and postulates will intimidate students and cause them to drop out of the course. There are workshops for high school students on quantum computing which covers some fundamental concepts of quantum computing, without introduction of quantum algorithms [12].

In this context, our paper introduces an innovative approach to teaching quantum computing at the high school level. Designed to cater to students without a strong background in advanced mathematics or physics, this method focuses on making quantum computing accessible and engaging. The course spans eight weeks and is divided into four parts: Introduction to Quantum Computing, Matrices for Quantum Computing, Quantum Circuit Model, and How to Make a Quantum Computer. Each part builds upon the previous, gradually introducing students to more complex concepts in a simplified and comprehensible manner.

The pedagogical approach of this course is strategically designed to bridge the gap between conventional computing and quantum computing. The course commences by laying a solid foundation in the fundamentals of computing, ensuring that students understand the basic principles of binary numbers, Boolean logic [13–15], and computer architecture [16]. This grounding in classical computing concepts is crucial as it sets the stage for a smoother transition into the more abstract and less intuitive quantum computing concepts. Similar approaches are also reported in Refs. [17, 18].

As the course progresses, students are gradually introduced to quantum-specific topics. This gradual introduction is pivotal in avoiding the overwhelming impact that immediate exposure to complex topics like linear algebra and quantum mechanics [19–22] can often have. By contextualizing quantum computing within the broader landscape of general computing and then incrementally introducing quantum concepts, the course maintains student engagement and curiosity. This methodology is crucial for sustaining student interest and ensuring a comprehensive understanding of the subject matter.

A distinctive feature of this course is the incorporation of hands-on experience with quantum computing hardware. This practical aspect is realized through portable NMR quantum computers, the Gemini/Triangulum series. The inclusion of such devices provides students with a tangible connection to the theoretical concepts discussed in the course. It allows them to observe and experiment with real quantum computing processes, thereby reinforcing their learning and enhancing their comprehension of quantum mechanics [21] in a practical setting. The hands-on learning aspect of the course plays a crucial role in clarifying quantum computing concepts [9], making them more accessible and concrete for students.

This paper's organization mirrors the planning and strategy behind the quantum computing course tailored for high school students. Section 2. provides an in-depth introduction to the organization of the lectures, outlining how each component of the course builds upon the previous to offer a gradual and comprehensive understanding of quantum computing. This section details the pedagogical strategies employed to transition from fundamental computing concepts to the more advanced topics of quantum mechanics, ensuring that these complex ideas are presented in an accessible and engaging manner [23, 24].

Following this, in Sect. 3., the paper introduces the hardware of the portable quantum computer, a key element of the course that offers students hands-on experience with real quantum computing. The inclusion of portable NMR quantum computers is a pivotal aspect of the course, allowing students to directly engage with the quantum computing processes they learn about in theory. This practical experience is crucial in solidifying students' understanding of quantum computing principles and bridging the gap between theoretical knowledge and real-world applications.

The paper is complemented by Additional file 1, which include detailed lecture notes. These notes are an essential resource for both educators and students, offering a complete guide to the course content. They are carefully designed to match the course's structured approach, providing clear, step-by-step instructions to navigate the intricate field of quantum computing.

2 Organization of lectures

By adopting a teaching methodology that strategically introduces concepts of quantum mechanics after establishing a strong foundation in quantum computing, this paper describes a course that reverses the traditional approach to instruction [25, 26]. Quantum computing leverages quantum principles, where the postulates of quantum mechanics—state, time evolution, and measurement—play a crucial role. Unlike traditional courses that begin with the abstract postulates of quantum mechanics, our course starts with tangible quantum computing concepts, making it more accessible to students with limited computer science background.

The correspondence between the postulates of quantum mechanics and the concepts in quantum computing is illustrated in Table 1, which provides a straightforward mapping to facilitate understanding:

In our course, concepts such as qubits, gates, and measurement are introduced in a simplified manner, enabling students to grasp the fundamental principles of quantum computing without delving into the more complex mathematics typically associated with quantum mechanics. This approach not only makes the field of quantum computing more approachable and comprehensible for younger students but also aims to ignite a passion for quantum science and technology.

After laying the groundwork with quantum computing, we seamlessly transition into the basics of quantum mechanics. This progression allows students to see how the concepts they've learned in quantum computing, such as qubits, gates, and measurement, are underpinned by quantum mechanical principles. By concluding with a module on building a quantum computer, we connect these principles to their practical applications, helping students not only to understand the mechanics behind quantum computing but also to

Table 1 Correspondence between several postulates in quantum mechanics and fundamental concepts in quantum computing

Postulates in quantum mechanics	Concepts in quantum computing formulated appropriate for our course
The state of particle is represented by a vector $\vert\psi(t)\rangle$ in a Hilbert space [27]	The state of a qubit can be described using a two-dimensional complex vector, typically represented as $\vert\psi\rangle = \alpha\vert 0\rangle + \beta\vert 1\rangle$, where $\vert 0\rangle$ and $\vert 1\rangle$ are computational basis states, and α and β are complex probability amplitudes. Thus, the wavefunction postulate corresponds to the qubit concept in quantum computation.
The evolution of a quantum system (not during measurement) is given by a unitary operator or transformation. The unitary operator satisfy $i\hbar\frac{\partial}{\partial t}U(t,t_0) = HU(t,t_0), \quad (1)$ where $U(t,t_0)$ is the transformation operator, and H is the Hamiltonian operator. [28]	In quantum computing, the evolution of qubits is controlled by quantum logic gates, which correspond to unitary transformations in the Hilbert space. Therefore, the evolution postulate corresponds to gates in quantum computing.
If the particle is in a state $\vert\psi\rangle$, measurement of the variable (corresponding to) Ω will yield one of the eigenvalues ω with probability $P(\omega) \propto \vert\langle\omega\vert\psi\rangle\vert^2$,. The state of the system will change from $\vert\psi\rangle$ to $\vert\omega\rangle$, which is an eigenstate of Ω, as a result of the measurement. [27]	In quantum computing, when we measure a qubit in state $\vert\psi\rangle = \alpha\vert 0\rangle + \beta\vert 1\rangle$, we obtain a result of either $\vert 0\rangle$ or $\vert 1\rangle$ with a probability of either $\vert\alpha\vert^2$ or $\vert\beta\vert^2$, respectively. Thus, the measurement postulate corresponds to the readout process in quantum computing.

gain a comprehensive insight into quantum mechanics itself. This full-circle approach, moving from quantum computing to quantum mechanics, provides students with a complete understanding of the subject, linking theoretical concepts with practical uses.

The course is structured to span eight weeks, with each week comprising approximately 3 hours of instruction. Designed for students with a foundational understanding of algebra but without prior knowledge in linear algebra, analytic geometry, or quantum mechanics.

The curriculum is divided into four main sections, each spanning two weeks:

A. Part I: Introduction to Quantum Computing (Week 1 and Week 2)
B. Part II: Matrices for Quantum Computing (Week 3 and Week 4)
C. Part III: Quantum Circuit Model (Week 5 and Week 6)
D. Part IV: How to Build a Quantum Computer (Week 7 and Week 8)

Each section is designed to progressively build upon the previous one, ensuring a smooth transition from basic computing concepts to the advanced theories of quantum mechanics. The paper will detail the rationale behind the structure of these sections, providing a clear and comprehensive pathway for student learning. Detailed course notes for each section are included in the Additional file 1 to support this educational journey.

2.1 Part I: introduction to quantum computing

The first week of this section starts with an exploration of the history of computers and computing. Students are introduced to the fundamentals of binary numbers, Boolean logic, computer architecture, and circuits [29]. This foundation lays the groundwork for understanding classical computing, explaining how computation is executed using basic logical gates and the construction of computers from these gates. Additionally, the concept of Landauer's principle is introduced [30], illustrating the energy costs associated with irreversible computing and leading to a discussion on the potential of reversible computing, exemplified by quantum gates like CNOT and Toffoli gates [9]. This initial week is structured to be accessible, requiring no prior knowledge of linear algebra or quantum mechanics.

In the second week, the focus shifts to providing an overview of fundamental concepts in quantum computing. This includes discussing the historical development of quantum computing, featuring insights from renowned physicists such as Richard Feynman and David Deutsch [31, 32]. Their perspectives highlight the significance and complexity of quantum mechanics in the context of computing, helping to motivate the study of this field. The core content of this week revolves around the "Quantum Circuit Model," which delves into quantum circuits, their key components like the Quantum Processing Unit (QPU), and quantum reversible circuits. The introduction to quantum gates encompasses single qubit gates (NOT, Hadamard, and Z gates), two-qubit gates (Controlled-NOT, Controlled-Z, Controlled-U), and three-qubit gates (Toffoli and Fredkin gates) [9]. Up to now, given the students' lack of prior knowledge in complex numbers, all gates introduced operate in real space. Moreover, complex concepts such as qubits, quantum gates, and quantum algorithms are simplified for better comprehension. A qubit is presented as a quantum analogue of a classical bit capable of existing in states 0, 1, or both simultaneously (superposition), with coefficients assumed to be ± 1. The section avoids delving into the normalization of state vector coefficients and entanglement at this stage. One of the key concepts introduced is quantum measurement, simplified to focus on the probability of obtaining certain states rather than the measured physical operators. With this approach, students can calculate the output of simple quantum circuits and predict probabilities during quantum measurements by counting binary numbers. This foundational knowledge enables students to understand concepts like the DiVincenzo Criteria and Deutsch's Algorithm, making basic quantum algorithms accessible and comprehensible without the need for complex quantum mechanics and linear algebra, thus maintaining and potentially increasing student interest.

2.2 Part II: matrices for quantum computing

The first week of this section introduces the concept of matrix representation of quantum gates [9]. An essential aspect of understanding quantum computing involves grasping the concepts of matrices and vectors. To make this introduction suitable for high school students, the course begins with a simple explanation of how bits and qubits can be represented as vectors. Here, 0 and 1 are represented as vertical two-dimensional vectors, with the quantum states $|0\rangle$ and $|1\rangle$ depicted in a similar manner, but also incorporating the concept of superposition. The introduction to gates starts with the classical NOT gate as an example, leading to a detailed explanation of matrix arithmetic. This foundation enables the exploration of vector representations for two classical bits and matrix representations for two-bit classical gates, with a focus on the NAND gate. The reversible nature of the NAND gate naturally leads to the introduction of the quantum CNOT gate, followed by a generalization to the Controlled-Z gate. By introducing single-qubit and two-qubit classical gates, and their corresponding matrix representations, students are guided towards understanding the tensor product [33]. The rules for computing the tensor product are explained, enabling the extension of these concepts to multiple quantum bits. Through this approach, students gain a fundamental understanding of how gates and states are represented using matrices and vectors in the realm of real numbers, laying the groundwork for more advanced quantum computing topics.

In the second week, the course builds upon the foundational knowledge from previous weeks to introduce matrix representation for general quantum circuits. This week's lecture is dedicated to Grover's algorithm, a pivotal quantum search algorithm known for its ability to find a marked item in an unsorted database more efficiently than any classical algorithm [34]. The lecture breaks down the algorithm into understandable segments, starting with phase separation and progressing to inversion about the average. These steps are crucial for comprehending how quantum states can be manipulated to solve problems more efficiently compared to classical computing methods. The introduction of Grover's algorithm at this stage is strategic, as it consolidates the students' understanding of matrix operations in quantum computing, while simultaneously demonstrating the practical applications of these concepts in solving complex problems.

2.3 Part III: quantum circuit model

This part of the course delves into more advanced topics: the quantum circuit model and the universal quantum gates, using the quantum Fourier transform as an illustrative example.

The first week's lecture introduces the concept of universal quantum gates. Up until this point, the course has primarily dealt with gates in the realm of real numbers. To expand upon this, the lecture begins with an introduction to complex numbers, which is essential for understanding more sophisticated quantum computing concepts [35]. This includes covering the fundamentals of complex numbers, operational rules, and Euler's formula. Building on this foundation, the discussion then progresses to the Bloch Sphere, a critical tool for visualizing the state of a single qubit. This comprehensive introduction sets the stage for understanding single qubit universal quantum gates, a cornerstone concept in quantum computing.

In the second week, the focus shifts to unitary matrices and the introduction of two-qubit quantum gates. This lecture aims to consolidate the students' understanding of unitary transformations, a key concept in quantum mechanics, and how they apply to quantum computing. With a solid grasp of single qubit gates, students are now ready to explore how these gates can be combined with multi-qubit gates to construct more complex quantum circuits. This week culminates with an introduction to the quantum Fourier transform, a transformation widely used in various quantum algorithms [36]. To demonstrate its application, the lecture covers the period finding algorithm and the Shor's algorithm as optional reading materials, both of which highlight the power and potential of quantum computing in solving problems that are intractable for classical computers [37]. The inclusion of these algorithms not only deepens the students' understanding of quantum computing principles but also provides a glimpse into the practical applications and future possibilities of the field.

2.4 Part IV: how to build a quantum computer

This final part of the course introduces students to quantum physics, particularly focusing on the underlying mechanisms of a quantum computer. This section builds on the previously introduced concepts, offering a unique perspective on quantum computing.

The first week's lecture departs from the traditional approach of starting with wave dynamics, often used in undergraduate textbooks. Such an approach can sometimes lead students to become overly focused on solving complex differential equations, losing sight of the fundamental principles of quantum mechanics. With a foundation already established in basic gates, quantum states, and measurements, we introduce the fundamental postulates of quantum mechanics. Given the students' familiarity with multi-qubit quantum systems, extending to the mathematical description of many-body systems and quantum entanglement is a logical next step. This discussion naturally leads to an understanding of the quantum no-cloning theorem, a key theorem in quantum information science, which forms the core of the first week's lecture [38].

In the second week, the focus shifts to the practical aspects of quantum computing, specifically the construction of a basic NMR quantum computer [39]. Recognizing that concepts such as Hamiltonians and Hamiltonian mechanics might be beyond the scope of high school students, the lecture utilizes unitary transformations as a fundamental postulate to derive the Schrödinger equation. This approach simplifies the introduction of the Hamiltonian as a Hermitian operator, representing the system's energy. This level of explanation is tailored to be comprehensible for high school students, while more ambitious learners can explore further into matrix and operator functions. This theoretical groundwork provides a complete framework for understanding the energy levels in NMR quantum computing [39].

Building upon this theoretical foundation, the course seamlessly transitions into a practical exploration of quantum computing hardware, using a portable quantum computer as a prime example. This portable quantum computer serves not just as a tool for demonstration but as a real-world application of the concepts covered in the lectures. By examining the portable quantum computer, students gain insights into the actual construction and functioning of quantum computers [39]. This part of the course is designed to bridge the theoretical principles with their tangible implementation, allowing students to see firsthand how the abstract concepts they have learned materialize in a functioning quantum computing device. The hands-on experience with the portable quantum computer enhances the learning process, enabling students to interact with and better understand the intricacies of quantum computing technology, turning theoretical knowledge into practical understanding.

3 The portable quantum computer

As we transition from the theoretical aspects of quantum computing to its practical applications, the Gemini/Triangulum series, the two/three-qubit portable quantum computers, play a pivotal role in our course. They are not merely a tool for demonstration but an integral part of the curriculum, used extensively to showcase quantum algorithms and hardware usage [40]. In this section, we delve into the specifics of the portable quantum computers, providing a detailed overview of their capabilities and how they are employed in the course to bring abstract quantum concepts to life.

The following subsections will provide a comprehensive overview of the Gemini/Triangulum series, covering their overall system and user interface:

System: This subsection will explore the physical components and architecture of the Gemini/Triangulum series, explaining how they contribute to their functionality as

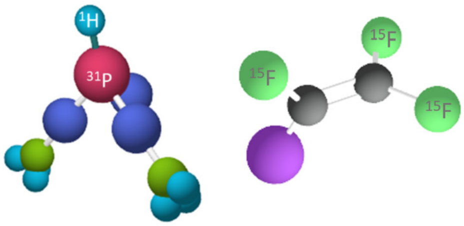


Figure 1 The molecule structures of samples used in Gemini/Triangulum series. In Gemini Mini/Mini Pro and Gemini, the ^{31}P and ^{1}H nuclear spins in Dimethylphosphite ($(CH_3O)_2PH$) labeled in the figure are used as the two qubits. In Triangulum Mini and Triangulum, the three ^{15}F nuclear spins in Iodotrifluoroethylene (C_2F_3I) are used as the three qubits

a quantum computer. It will cover the essential hardware elements that enable quantum computing, providing students with a clear understanding of the machine's operation at a physical level.

User Interface: This subsection will focus on the user interface of the Gemini/Triangulum series, explaining how users can interact with the quantum computer to run experiments and observe results.

Through exploring the Gemini/Triangulum series, students will acquire a comprehensive understanding of the nature and operation of quantum computers, and how theoretical concepts in quantum computing are implemented in actual hardware and software solutions.

3.1 System

Gemini/Trangulum series are based on Nuclear magnetic resonance (NMR). A nuclear spin which has a spin number 1/2 has two energy levels in a static magnetic field, and thus can be used as a qubit [41, 42]. The ^{31}P and ^{1}H nuclear spins in Dimethylphosphite ($(CH_3O)_2PH$) which are connected directly (see Fig. 1) are used as the two qubits in Gemini series [39]. The three ^{19}F nuclear spins in the Iodotrifluoroethylene (C_2F_3I) molecule (see Fig. 1) are used as the three qubits in Triangulum series [40]. The Dimethylphosphite or Iodotrifluoroethylene molecules are in the liquid form and contained in a sample tube. The sample tube is placed in a pair of parallel plate NdFeB magnets (see Fig. 2). The nuclear spins in the magnetic field have their own frequencies (see Table 2). Therefore, nuclear spin qubits can be controlled using microwave pulses on resonance with them. Quantum gates are realized by microwave pulses together with the help of the natural couplings mediated by bonds between different nuclear spins. The measurement of a quantum state is realized by detecting the microwave signals irradiated by the nuclear spin qubits [39].

The Gemini/Triangulum series include Gemini Mini/Mini Pro, Gemini, Triangulum Mini and Triangulum. Gemini and Triangulum, launched earlier, were introduced in details in [39, 40]. Hence here we only show the structure of the Mini ones in Fig. 2. As show in Fig. 2, apart from the sample tube and the magnets, the overall structure of the device includes a tablet, a master board, a radio frequency (RF) transmission system, and the shimming and locking systems. As mentioned above, the sample tube and the magnets provide the qubit system. The master board incorporates an FPGA, a digital-analog converter (DAC) and an analog-digital converter (ADC). The master board realizes the function of control pulse generation, i.e., the generation of quantum control pulses. The

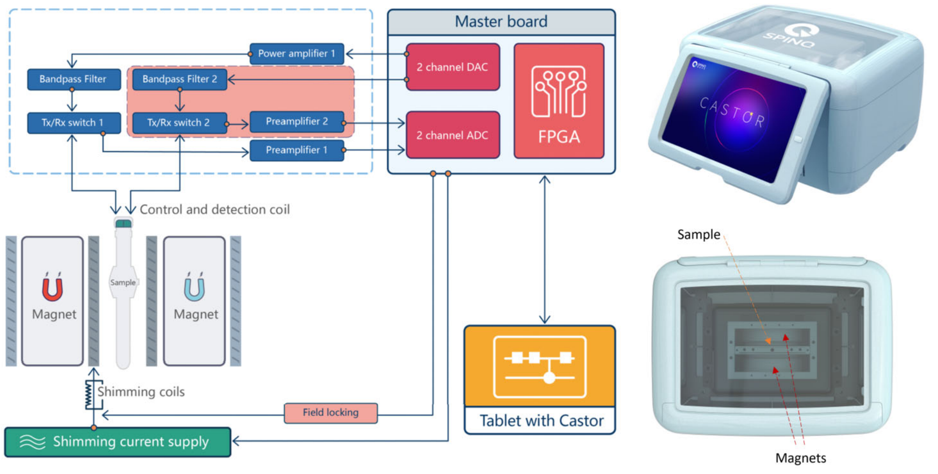
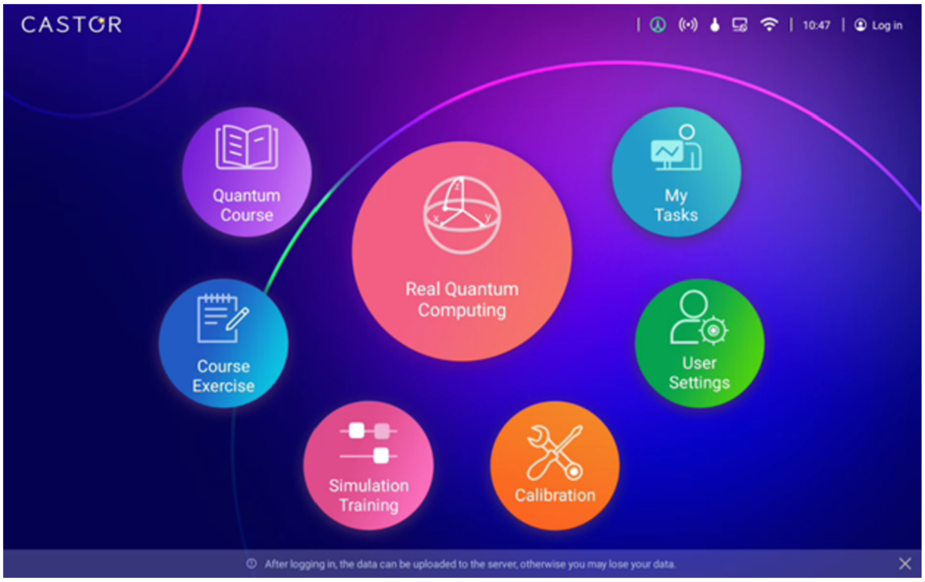


Figure 2 Left: The schematics of Gemini Mini/Mini Pro and Triangulum Mini. Right: The side view and top view of the device. The device include a tablet which provides the user interface Castor, a master board, an RF transmission system (enclosed by the dashed box), a pair of parallel plate magnets, a sample tube, probe coils and shimming coils, etc. The RF transmission system provides RF pulse and signal paths for both qubit control and field locking. Depending on different frequencies in different models, the number of RF channels might be different. There is a removable cover on top of the device. Students can observe the inner structure after removing the cover

Table 2 Specifications of Gemini and Triangulum portable products, including Gemini, Triangulum, Gemini Mini/Mini Pro and Triangulum Mini. The Gemini and Triangulum specifications displayed here represent the latest updates, which may vary slightly from the initially launched version as in Refs. [39, 40]. The magnetic fields of Gemini and Triangulum are higher than those of their mini versions. Additionally, they require a PC equipped with SpinQuarsar for operation. These features allow for more precise quantum control, manifested as larger circuit depths, and low-level control such as quantum gate design

	Gemini	Triangulum	Gemini Mini/Mini pro	Triangulum Mini
QPU	2 qubits	3 qubits	2 qubits	3 qubits
PC/Tablet	PC	PC	Tablet	Tablet
Software	SpinQuarsar	SpinQuarsar	Castor	Castor
SpinQit	Yes	Yes	No/Yes	Yes
Weight	44 kg	44 kg	14 kg	16 kg
Size	600 ∗ 280 ∗ 530 mm	610 ∗ 330 ∗ 560 mm	200 ∗ 350 ∗ 260 mm	200 ∗ 350 ∗ 260 mm
Magnets	0.85 T	0.85 T	0.65 T	0.65 T
Frequencies	H 36.0 MHz P 15.9 MHz	F 33.9 MHz	H 27.0 MHz P 11.0 MHz	F 25.5 MHz
Circuit depth	1-qubit gates 100 2-qubit gates 50	1-qubit gates 40 2-qubit gates 10	1-qubit gates 40/80 2-qubit gates 10/40	1-qubit gates 20 2-qubit gates 6
Circuit design	Yes	Yes	Yes	Yes
Gate design	Yes	Yes	No	No
Measurement speed	100 s	50 s	30 s	50 s

generated pulses go through the RF transmission path which include filters and amplifiers, and finally reach the probe coil near the qubit system to realize quantum control gates. The signal irradiated by the qubit system can be collected by the probe coil and goes through the RF transmission path and also gets filtered and amplified. Then the detected signal reaches the master board. It get digitized and processed by the master board and returned



After logging in, the data can be uploaded to the server, otherwise you may lose your data.

Figure 3 Castor Homepage

to users in the form of entries of quantum state density matrices. The master board also realizes the functions of magnetic field shimming and field locking with the help of the shimming coils [43], which ensures a homogeneous and stable magnetic field and thus stable and homogeneous qubit frequencies for better quantum control [44].

Table 2 lists specifications of Gemini and Triangulum series. Compared with Gemini and Triangulum, the most significant difference the Mini ones have is the small size and weight. They are also more cost-effective. They are more suitable to be used in high schools for K12 education because of their more portable and cost-effective features. There are also compromises. The magnetic field is weaker and thus the qubit frequencies are smaller in Mini ones [45–47]. Because of multiple factors related to a lower magnetic field, the Mini ones have slightly worse control performance and a shallower circuit depth [48, 49]. In spite of this, they are still very good tools for demonstrating the basic ideas of quantum gates and quantum algorithms. Most of the experiments in this course are realized on Gemini Mini and Triangulum Mini. However, for experiments related to low-level control, Gemini and Triangulum are needed. For example, in the experiment of Week 8, Gemini is applied to demonstrate how a CNOT gate is composed by hardware-level pulse sequences. In view of this, compared to their mini counterparts, Gemini and Triangulum are more suitable to scientific research where quantum gate design is usually important.

3.2 User interface

As introduced in Refs. [39, 40], Gemini and Triangulum integrate a PC with a user-friendly software SpinQuasar. Here we introduce the user interface of Gemini Mini/Mini Pro and Triangulum Mini. They integrate a pad that runs a new operating system named Castor. This provides a more compact and convenient user interface for managing quantum computing tasks. Figure 3 shows the Homepage of Castor. The two/three-qubit QPU can be accessed through the module "Real Quantum Computing" and an eight-qubit simulator can be accessed through "Simulating Training". In both the two modules, users edit and

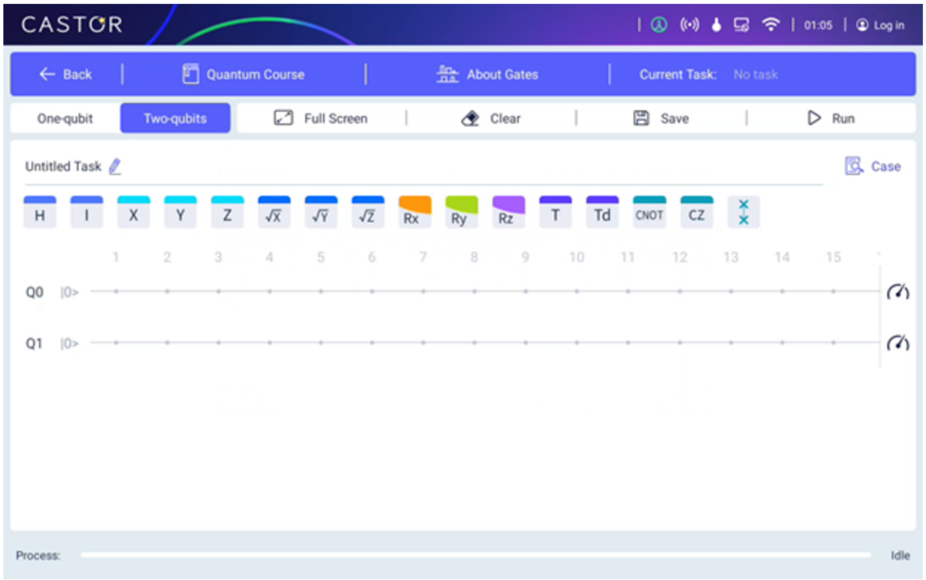


Figure 4 The circuit construction interface in "Real Quantum Computing" of Castor

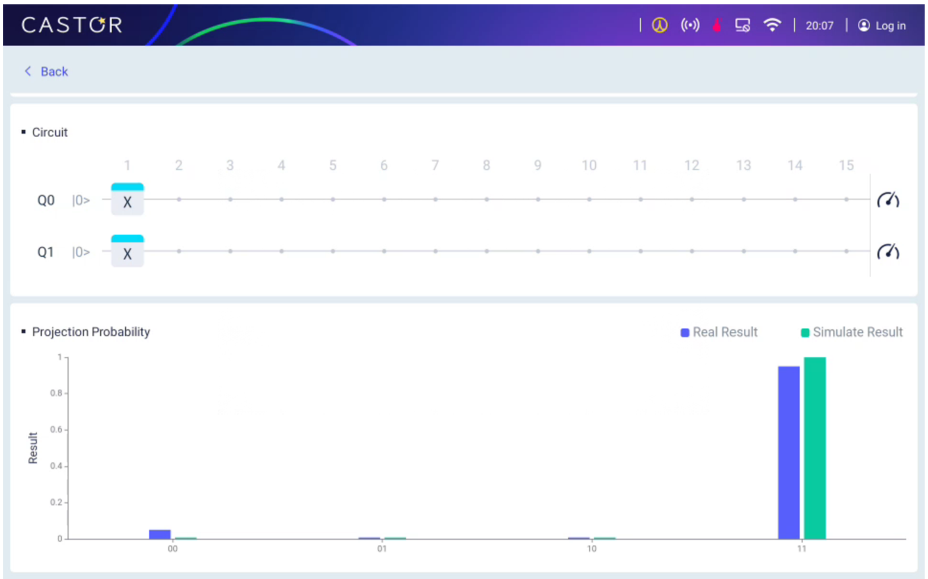


Figure 5 The results of a task is in the form of projection probabilities of each basis states

construct a quantum circuit using a drag-and-drop manner (see Fig. 4). There are multiple built-in quantum algorithms as well that users can select from the "Case" button (see Fig. 4) and run directly, such as the Grover's algorithm and the Deutsch's algorithm. All experimental or simulation task information can be managed in "My Tasks" module. For example, the quantum circuit and results for each task that users have run can be revisited in "My Tasks". The results for each task contain the diagonal elements of the final quantum state density matrices of the task, i.e. the probabilities for each basis states (Fig. 5). In "Calibration" module, users can calibrate the NMR signals and quantum control parameters by themselves, or they can also run a standard automatic calibration instead.

In Castor users can also access a quantum course that was developed based on the curriculum introduced in this paper, in the module "Quantum Course". There is a course exercise module as well, "Course Exercise". The "User Setting" enables the configuration of various parameters for the user account, such as WIFI setting and remote control setting.

In addition to the graphic user interface Castor, Gemini Mini Pro and Triangulum Mini provide access via SpinQit (https://spinquanta.com/products-solutions/spinqKit). SpinQit is a quantum software development kit (SDK) created by SpinQ (https://spinquanta.com/products-solutions/spinqKit). SpinQit supports three types of programming syntaxes, native SpinQit Python syntax, OpenQASM 2.0 syntax, and IBM Qiskit Python syntax. It also offers a rich interface for quantum algorithms, and facilitates terminal connections with different types of back-ends, such as quantum computers, quantum simulators, and quantum computing cloud platforms.

The Gemini and Triangulum series serve as a tangible example for students, bridging the gap between theory and practice. Their use throughout the course allows students to directly observe and understand the application of quantum algorithms and the intricacies of quantum computing hardware. This hands-on experience is invaluable in enhancing students' comprehension and appreciation of the field.

As a real quantum computer is used in experiments, students could easily observe that the results of the experiments differ from the theoretical predictions, as shown in Fig. 5. It can be explained to the students that errors can occur in quantum computing, and to correct these errors, quantum error correction was invented. Quantum error correction [50, 51] can rectify errors that occur during computations, making the construction of quantum computers possible. While the knowledge of quantum error correction is beyond the scope of this course, informing students about errors and correction can help them develop a better understanding of the subject matter.

4 Discussion

4.1 Course evolution

The evolution of the quantum computing course and its lecture notes is rooted in years of teaching, hands-on experience, and collaboration. This section provides a detailed account of the project's development and the rationale behind the decisions made in preparing the course material.

Between 2010 and 2018, while teaching the course "NANO3700/4700: Quantum Computer Science" every fall semester at the University of Guelph, Bei Zeng observed the significant challenges students faced with the abstract mathematical concepts integral to quantum computing. This course was a required component for the nano-science program and an elective for mathematics majors. Bei's experience highlighted the necessity of integrating hands-on experience to demystify these complex topics and enhance student understanding. She realized that students struggled with abstract mathematical concepts without practical context. To address this, she emphasized the importance of foundational understanding and hands-on experience, integrating classical computing concepts as a precursor to quantum topics. In Fall 2018, leveraging insights from teaching, Bei co-founded SpinQ with the aim of creating portable quantum computers tailored for educational purposes. As of Spring 2024, SpinQ has successfully sold over 200 portable quantum computers to more than 30 countries and territories, marking a significant milestone in making quantum computing accessible to students worldwide. The development of portable quantum computers was driven by the need to provide students with tangible experience. This hands-on approach is essential for bridging the gap between theoretical understanding and practical application, reinforcing complex concepts through realworld experimentation.

Upon moving to the Hong Kong University of Science and Technology (HKUST) in Fall 2019, Bei was encouraged by the physics department to offer a new common core course, "PHYS1007: Quantum Information for Everyone." This course was designed for first-year undergraduate students from various majors, requiring only a high school level mathematics background. Drawing from prior teaching experiences, Bei focused on simplifying the complex and abstract parts of the curriculum. Additionally, the course aimed to incorporate hands-on experience using SpinQ's first-generation product, introduced in January 2020. The course was first offered in Spring 2021 amidst the COVID-19 pandemic, necessitating online delivery via Zoom, which limited hands-on experiments to virtual demonstrations. Despite these constraints, the course received positive feedback, alongside constructive comments for further enhancement. The course was structured to gradually introduce students to quantum computing, beginning with classical computing concepts. This step-by-step approach ensured students built a strong foundation before tackling more advanced topics. The inclusion of hands-on experiments, although limited during the pandemic, was intended to reinforce theoretical concepts and maintain student engagement.

In Summer 2021, Prof. Tai Kai Ng from HKUST physics department, former director of the Hong Kong Academy for Gifted Education (HKAGE), approached Bei with the idea of adapting the course for gifted high school students. Embracing this opportunity, Bei quickly developed a condensed outline based on accumulated teaching experiences. Starting the following weekend, a pilot course was organized for 10 HKAGE students, spanning 5 weekends with each session lasting 3 hours. The pilot course received excellent feedback, prompting HKAGE to seek funding to develop a comprehensive training program on quantum computing for gifted students. Adapting the course for high school students involved simplifying content further while ensuring the material remained challenging and engaging. The success of the pilot course demonstrated the effectiveness of this approach, validating the structure and choice of topics.

With the leadership of Prof. Jensen Li and Prof. Bei Zeng, funding from the Hong Kong Education Bureau (EDB) for the project was successfully secured. Dr. Ting Pong Choy and Dr. King Tai Cheung joined the team to deliver the course, while Bei focused on developing detailed course content. The program ran successfully over the years 2022, 2023 and 2024, further refining the curriculum based on continuous feedback and advancements in the field. The iterative development and refinement of the course were based on continuous feedback from students and educators. This process ensured that the material remained relevant and effectively addressed the learning needs of the students. In Fall 2023, Bei decided to compile and formalize the extensive lecture notes, collaborating with her post-doc Dr. Shi-Yao Hou and his students Qihong Sun, Shuangxiang Zhou, and Ronghang Chen from Sichuan Normal University. This collective effort culminated in the detailed and structured course material presented in this paper, encapsulating years of iterative development, teaching innovation, and practical application. The comprehensive lecture notes were developed to provide a structured and detailed resource for both educators and students. The inclusion of hands-on experiments, clear explanations of complex concepts, and a logical progression from classical to quantum topics were key to ensuring the material was accessible and effective.

4.2 Students perception

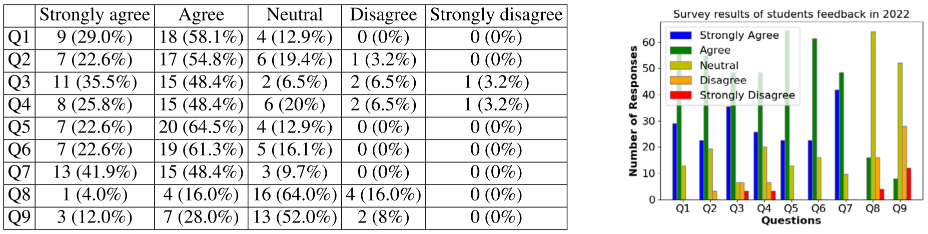
The initial offering of this course under the EDB's program for gifted students in 2022 and 2023 provided significant feedback on its impact and attractiveness. A total of 196 applications from high schools were received, and 80 students were selected over two years. Catering to 40 gifted high school students per year, the program received favourable reviews, demonstrating substantial engagement and enthusiasm for quantum computing. Such feedback underlines the course's potential for wider adoption in high school curricula.

A pivotal element in the course's success is its pedagogical journey from quantum computing to quantum mechanics, requiring no extensive background in mathematics or physics. By initiating with fundamental computing principles and progressively unveiling quantum concepts, the curriculum effectively maintains student interest and enhances comprehension. This gradual progression culminates in the "How to Build a Quantum Computer" module, where theoretical learning transitions into practical application. Here, students not only grasp the underpinnings of quantum mechanics but also engage in constructing and operating a quantum computer. The incorporation of portable quantum computing hardware allows students to directly apply what they have learned, bridging the gap between abstract theory and tangible experience. This hands-on approach not only solidifies their understanding of quantum computing concepts but also empowers them with the skills to assemble and use quantum computers, thereby offering a comprehensive and immerse learning experience that embodies the course's innovative teaching methodology.

The course materials are distributed through Google Classroom, with continuous feedback collected on teaching pace and any problems encountered. At the end of the course implemented in 2022 and 2023, questionnaires were distributed to the students via Google Forms to obtain anonymous feedback. Basically, almost the same teaching materials are adopted for the two consecutive years of 2022 and 2023. However, to improve the quality of teaching based on student feedback, the pace of different lectures is adaptively adjusted, and Additional file 1 are provided to suit students with different backgrounds for year 2023. Questions ranged from overall satisfaction to difficulty, learning materials, and instructors, with ratings from strongly agree to strongly disagree (5 levels), as shown in Table 3. The feedback revealed an overwhelmingly positive perception of the program, as shown in Fig. 6 and Fig. 7. From these figures, we can see that a significant majority of students expressed high satisfaction with the lectures, finding them both fruitful and interesting. Over 85% of students agreed or strongly agreed that the lectures met their expectations, highlighting the program's success in delivering engaging and valuable content. The program's activities were also well-received, with 66.6% of students finding them challenging and stimulating. Additionally, 81.7% of students felt a strong sense of achievement through the showcase of learning outcomes, underscoring the program's effectiveness in fostering a sense of accomplishment. While the clarity and usefulness of handouts received positive feedback from 71.6% of students, the program shows potential for further

Table 3 The questions of the questionnaire. Q8 and Q9 are two additional questions on pace and difficulty of the course. Questions are not mandatory so some students did not answer Q8 and Q9

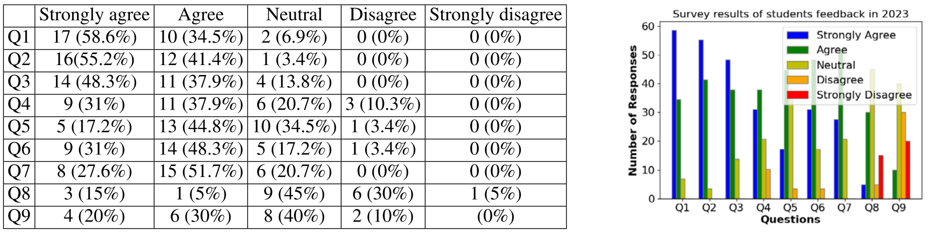
Q1	Overall, I was satisfied with the lectures.
Q2	I found the activities of the programme challenging.
Q3	I found the lectures fruitful and interesting.
Q4	I found the handouts, reference materials provided and the presentation of instructors clear and useful.
Q5	I enjoyed the opportunities to work with my classmates.
Q6	I gained a sense of achievement through the showcase of learning outcomes.
Q7	I was satisfied with the learning environment, facilities and program administration.
Q8	The pace of the lesson is too fast.
Q9	The course materials (or exercise) are too difficult to understand.



	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Q1	9 (29.0%)	18 (58.1%)	4 (12.9%)	0 (0%)	0 (0%)
Q2	7 (22.6%)	17 (54.8%)	6 (19.4%)	1 (3.2%)	0 (0%)
Q3	11 (35.5%)	15 (48.4%)	2 (6.5%)	2 (6.5%)	1 (3.2%)
Q4	8 (25.8%)	15 (48.4%)	6 (20%)	2 (6.5%)	1 (3.2%)
Q5	7 (22.6%)	20 (64.5%)	4 (12.9%)	0 (0%)	0 (0%)
Q6	7 (22.6%)	19 (61.3%)	5 (16.1%)	0 (0%)	0 (0%)
Q7	13 (41.9%)	15 (48.4%)	3 (9.7%)	0 (0%)	0 (0%)
Q8	1 (4.0%)	4 (16.0%)	16 (64.0%)	4 (16.0%)	0 (0%)
Q9	3 (12.0%)	7 (28.0%)	13 (52.0%)	2 (8%)	0 (0%)

(a) (b)

Figure 6 Survey results of students' feedback on the satisfaction level of course quality in 2022, evaluated based on the 9 questions in Table 3. The number of the students is 31. The questions are not mandatory. 25 students answered Q8 and Q9



	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Q1	17 (58.6%)	10 (34.5%)	2 (6.9%)	0 (0%)	0 (0%)
Q2	16(55.2%)	12 (41.4%)	1 (3.4%)	0 (0%)	0 (0%)
Q3	14 (48.3%)	11 (37.9%)	4 (13.8%)	0 (0%)	0 (0%)
Q4	9 (31%)	11 (37.9%)	6 (20.7%)	3 (10.3%)	0 (0%)
Q5	5 (17.2%)	13 (44.8%)	10 (34.5%)	1 (3.4%)	0 (0%)
Q6	9 (31%)	14 (48.3%)	5 (17.2%)	1 (3.4%)	0 (0%)
Q7	8 (27.6%)	15 (51.7%)	6 (20.7%)	0 (0%)	0 (0%)
Q8	3 (15%)	1 (5%)	9 (45%)	6 (30%)	1 (5%)
Q9	4 (20%)	6 (30%)	8 (40%)	2 (10%)	(0%)

(a) (b)

Figure 7 Survey results of students' feedback on the satisfaction level of course quality in 2023, evaluated based on the 9 questions in Table 3. The number of the total students is 29. The questions are not mandatory. 20 students answered Q8 and Q9

enhancement in this area to achieve even higher satisfaction. Similarly, the collaborative opportunities were enjoyed by 75% of students, indicating a solid foundation for peer interaction that can be further enriched. Overall, the learning environment and program administration were highly praised, with an 85% satisfaction rate, reflecting the program's commitment to providing a supportive and well-organized educational experience. These results underscore the program's strengths and its positive impact on student learning and engagement.

We conducted additional questions on pace and difficulty in evaluating this approach (Q8 and Q9 in Table 3). Not all students answered these two questions. For these two questions, 80% of the students reported that the lesson pace was either acceptable or slow, with only 8.9% indicating that the pace was too fast and 15.6% finding the course too difficult. These findings suggest that the course content and delivery were appropriate for

Table 4 List of abbreviations used in the article

Full name	Abbreviation
Kindergarten to 12	K-12
Quantum Processing Unit	QPU
Massachusetts Institute of Technology	MIT
Nuclear Magnetic Resonance quantum computer	NMR quantum computer
Dimethylphosphite	$(CH_3O)_2PH$
Iodotrifluoroethylene	C_2F_3I
Controlled NOT gate / controlled-X gate	CNOT gate / CX gate
software development kit	SDK
radio frequency	RF
Field Programmable Gate Array	FPGA
digital-analog converter	DAC
analog-digital converter	ADC

the students' level of understanding, supporting our approach in introducing quantum computing without extensive background in mathematics or physics.

Given the encouraging response from the gifted program, there is a significant opportunity to include this curriculum in standard high school programs. Efforts are underway to introduce the course in schools in Hong Kong and Shenzhen, reflecting a growing recognition of the importance of early exposure to advanced scientific concepts in general education. This expansion aligns with global educational trends and aims to prepare students for emerging technological challenges and opportunities. Integrating this course into the standard high school curriculum could significantly widen student exposure to quantum computing. Making these advanced concepts accessible to a broader audience helps create a more diverse and well-prepared cohort of future learners and professionals, especially as quantum computing's relevance grows across various sectors. Moreover, the course's structure and content could serve as a model for other educational institutions aiming to incorporate quantum computing into their syllabi. It shows how complex scientific topics can be tailored to younger learners, aligning the subject's intricacies with the students' educational level.

5 Conclusion

In conclusion, the favourable reception of the quantum computing course in the gifted program establishes a solid foundation for its broader adoption in high schools. Designed to deepen students' understanding of quantum computing, the course's widespread integration could significantly enhance the educational framework in this emerging field. As more schools and regions adopt the course, it presents an excellent opportunity to enrich the quantum computing learning experience for students worldwide.

Abbreviations

The abbreviations in the article are shown in Table 4.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1140/epjqt/s40507-024-00271-9.

Additional file 1. (PDF 12.4 MB)

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Author contributions

Q.S., S.Z., R.C. contributed equally to this paper and they wrote the lecture notes as Additional file 1. G. F. prepared and implemented the experiments. KT.C and J.L contributed to delivering the course and collecting the responses from the students. SY.H. is the corresponding author. B.Z. organized and prepared the initial teaching materials. All authors contributed to write and review the manuscript.

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Data Availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

This paper does not include images that may identify the person so consent is not required.

Competing interests

The authors declare no competing interests.

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