Design of a quantum computing education program for high school students

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***Abstract*— This study aims to design and implement a quantum computing education program suitable for high school students, given the growing significance of quantum computing in diverse scientific and industrial fields. While quantum computing is rapidly gaining attention for its potential to revolutionize computational speed and address complex problems, the gap in early education for pre-university students remains notable, especially in South Korea. This research examined international and domestic trends in quantum computing education, developed an activity-based curriculum integrating simulation tools and collaborative problem solving, and applied it to a group of high school students. Through pre- and post-program surveys, activity sheets, and qualitative feedback, the results show a significant increase in students' understanding and interest in quantum computing concepts such as superposition, entanglement, and quantum gates. The study highlights that an experiential, STEAM-integrated approach using visual and hands-on resources effectively lowers conceptual barriers and enhances engagement. However, challenges such as a lack of prior knowledge and limited educational materials persist. The research suggests policy and curriculum improvements as well as extended teacher training are required to bridge the global educational gap in quantum computing, and indicates that systematic integration of quantum concepts at the high school level is both feasible and impactful.**

Keywords*— *Quantum Computing Education, High School STEM Curriculum, Simulation-Based Learning, STEAM Education, STEAM, Quantum Computing

I. Introduction

With the advent of the Fourth Industrial Revolution, advanced technologies such as artificial intelligence, big data, and the Internet of Things have rapidly progressed. In parallel, quantum computing has emerged as a next-generation technology capable of overcoming the limitations of classical digital computing [1], [2]. Based on fundamental quantum principles such as superposition and entanglement, quantum computing enables data processing that is significantly faster and more efficient than that of conventional computers. Its potential applications span a wide range of domains, including cryptanalysis, drug discovery, materials science, and financial modeling, positioning it as a core element in the ongoing global technology race. Leading companies such as Google and IBM are at the forefront of this field, contributing to the widening technological gap among nations [3]. Notably, Google recently announced the achievement of quantum supremacy, marking a critical milestone toward solving practical problems [10]. In South Korea as well, efforts to advance quantum technologies in the information and communication sector are accelerating in both research and industry domains [11].

Against this backdrop, the global need for early quantum education is increasingly recognized. Various countries, including the United States, Canada, and several European nations, have launched educational programs aimed at middle and high school students to foster foundational understanding and practical engagement in quantum computing. Notable initiatives such as Qubit by Qubit, the IBM Quantum Educators Program, and Canada's Quantum School underscore the importance of hands-on, concept-driven learning from an early age.

TABLE I. Comparative Analysis of Quantum Computing Education Status: Domestic vs. International

Category	USA, Canada, and Other Countries	South Korea
Key Programs	Qubit by Qubit, Quantum School, IBM Quantum Challenge	Selective short-term programs via science high schools, gifted schools, and university-sponsored camps
Target Audience	Elementary, middle, and high school students; pre-service teachers	Primarily students in science or gifted high schools; some teachers
Curriculum Content	Basics of quantum mechanics, quantum gates, algorithmic thinking, hands-on simulation	Mostly theoretical; limited use of simulation tools and applications
Educational Materials	Developed in-house by institutions; global resources in English	Heavy dependence on external materials; lack of standardized Korean-language materials
Field Application	Integrated within school curricula, after-school programs; both online and offline hands-on classes	Deployed irregularly through temporary camps and special lectures

In contrast, quantum mechanics and quantum computing are not explicitly addressed in the formal education curriculum in South Korea. At best, short-term, experience-based activities are offered in a limited number of science high schools and gifted education institutions [3]. This raises concerns regarding a potential gap in cultivating future domestic talent equipped with scientific and technological competitiveness. Furthermore, prior research indicates that hands-on and experiential quantum education is effective in enhancing learners' interest and self-directed learning capabilities [6], [9].

Accordingly, this study aims to identify key concepts in quantum computing that are suitable for high school-level learners, design a practice-oriented, interdisciplinary educational program based on those concepts, and analyze its effectiveness through implementation.

This paper is structured as follows: First, the theoretical background outlines the fundamentals of quantum computing, the necessity of quantum education, and the current status of related initiatives both domestically and internationally. Subsequently, the research methodology, instructional design process, and empirical findings are presented and discussed to explore future directions for quantum computing education targeting high school students.

II. Related work on Quantum Computing technology

Quantum computing fundamentally integrates the principles of quantum mechanics into computational technologies. Unlike classical computers, which process information using bits that exist in a state of either 0 or 1, quantum computers employ qubits, which can exist in a superposition of both 0 and 1 simultaneously. This allows quantum systems to compute multiple states at once [4], [5]. Moreover, the concept of entanglement—where the state of one qubit is intrinsically linked to that of another—enables the execution of highly complex computations at remarkable speed. Such characteristics have demonstrated exponential improvements in computational efficiency over classical algorithms through quantum algorithms such as Shor's and Grover's.

From an educational perspective, understanding these principles extends beyond the domain of physics; it requires an interdisciplinary approach encompassing mathematics (e.g., linear algebra, probability theory), computer science (e.g., coding, algorithms), and ethics (e.g., the societal implications of quantum technologies). Reflecting this recognition, many countries have begun to implement quantum education programs targeted at adolescents [6]. For instance, the U.S.-based Qubit by Qubit program introduces the principles of quantum computing to thousands of high school students and teachers annually through simulations, hands-on workshops on quantum algorithms, and interactive modules. The Institute for Quantum Computing (IQC) at the University of Waterloo in Canada offers intensive programs for secondary school students through its Quantum School initiative. Similarly, European educational systems are incorporating STEAM-based quantum learning modules into their curricula.

In contrast, in South Korea, even the 2015 and 2022 revised national curricula only mention the concept of "quantum" briefly and exclusively within the high school Physics II course. The connection to computational principles or algorithmic thinking is scarcely addressed. While some science high schools and gifted education institutions have initiated short-term experiential or inquiry-based programs, challenges remain regarding accessibility, continuity, and teacher expertise. Consequently, there is a growing need to define a clear direction for quantum computing education for Korean high school students and to develop concrete pedagogical strategies tailored to this emerging field.

III. Quantum Computing Education Program

In this study, a quantum computing education program was developed for high school students and implemented in an actual classroom setting to analyze its effectiveness. The instructional design followed the ADDIE model—one of the most widely used frameworks in curriculum development [7], [9]. During the Analyze phase, the learners' expected proficiency level, prior knowledge, and learning environment were assessed. Based on this analysis, instructional objectives and content were formulated in the Design phase, followed by the development of learning materials and program components in the Develop phase. The program was then implemented in a pilot class (Implement), and its outcomes were systematically evaluated in the final Evaluate phase. This sequential process served as the foundation for constructing and delivering the instructional intervention.

TABLE II. Lesson Design Matrix for Quantum Computing Education Program

Lesson Hour	Learning Objectives	Key Activities	Assessment Methods
1st Session	Understand fundamental concepts of quantum systems: superposition and entanglement	Watch introductory videos; case discussions; concept quizzes	Pre-program survey; concept-based quiz
2nd Session	Explore quantum gate operations and circuit design	Use Hello Quantum app for gate manipulation; group-based circuit tasks	Practical observation; activity sheets
3rd Session	Investigate simple quantum algorithms and real-world relevance	Group discussion and presentation on applications (e.g., cryptography, logistics)	Post-program survey; group presentation evaluation

The program was structured into three instructional sessions, focusing on key concepts such as understanding the superposition of qubits, visualizing and practicing quantum gate circuits, and exploring the basic principles of simple quantum algorithms. Instructional materials included IBM's Hello Quantum app and a Python-based quantum circuit visualizer, both of which provided intuitive graphical user interfaces (GUIs) to facilitate the manipulation of quantum gates and visualization of qubit state changes [8], [9].

A total of 34 first- and second-year students from a science-focused high school in Seoul participated in the program. To assess changes in their understanding, interest, and career awareness related to quantum computing, self-reported surveys were administered before and after the sessions. In addition, learning activity sheets, open-ended response forms, and classroom portfolios were collected throughout the program to analyze students' engagement and cognitive development in detail.

The developed instructional program comprised three sessions (totaling six hours). The first session introduced fundamental concepts of quantum computing, highlighting the differences from classical computing, and presented the notions of superposition and entanglement using visual aids and video materials. The second session guided students through simulations of quantum gates (X, H, Z) using the Hello Quantum app, allowing them to directly observe changes in qubit states. Students engaged in activities such as drawing circuit diagrams and solving guided problems in small groups to infer the transformations of quantum states.

In the final session, students were presented with real-world scenarios—such as supermarket inventory optimization or cryptographic decryption—and were encouraged to understand and discuss the logic of basic quantum algorithms through group discussion and presentation. Each session incorporated collaborative group activities and included pre-lesson prompts, concept quizzes, hands-on exercises, and reflective activities. Based on the activity sheets, students' conceptual understanding was compared across pre-, during-, and post-lesson phases. Outcomes were further examined through student presentations and qualitative feedback [9].

Assessment focused on formative evaluation and employed a multi-dimensional framework, incorporating student self-assessment, peer evaluation within groups, and observational assessment by the instructor.

IV. RESULT AND DISCUSSION

A comprehensive analysis of the pre- and post-program surveys, student activity sheets, and classroom participation observations revealed that the quantum computing education program had a positive impact on students' conceptual understanding and engagement. In the pre-program survey, students demonstrated relatively low levels of familiarity with basic quantum computing terminology—such as qubit, superposition, and entanglement. However, in the post-program survey conducted after the three instructional sessions, there was a statistically significant improvement in scores related to the understanding and definition of key concepts.

Notably, students showed marked progress in explaining the roles of quantum gates, intuitively grasping the nature of superposition, and articulating the fundamental differences between classical and quantum computing. These findings suggest that targeted instruction in quantum computing, even at the high school level, can meaningfully enhance both conceptual clarity and student interest.

TABLE III. PRE- AND POST-PROGRAM SURVEY RESULTS (MEAN SCORES BY LEARNING DIMENSION)

Evaluation Dimension	Pre-Mean Score	Post-Mean Score	Score Change
Conceptual Understanding of Key Terms	2.1	4.0	+1.9
Interest and Career Awareness	2.5	4.2	+1.7
Perceived Applicability to Real Life	2.0	3.7	+1.7

In terms of student interest, the program led to a noticeable increase in positive perceptions regarding future career paths and occupations related to quantum computing. Additionally, students reported an enhanced willingness to engage in creative problem-solving. Many students responded that "concepts which initially felt difficult became more accessible through visual materials and hands-on simulations," and that "the coding exercises made the mathematical principles feel practically applicable."

Thematic analysis of students' activity sheets and open-ended responses revealed a qualitative shift in conceptual understanding. Prior to the program, students predominantly used general associative terms such as "quantum computer" or "quantum." However, after the sessions, more specific and conceptually central terms such as qubit, entanglement, quantum gate, superposition, and quantum algorithm appeared frequently in their responses. Topic modeling and word cloud analyses of student essays and group presentation documents further confirmed a marked increase in the use of technical terminology related to quantum computing, as well as references to its potential applications in future society.

Classroom observations highlighted several notable patterns. During the simulation activities, students actively engaged with the material by posing questions while manipulating qubit states, and spontaneous discussions and peer feedback frequently emerged during group missions. Student responses were characterized by curiosity toward unfamiliar domains, recognition of interdisciplinary connections with mathematics and science subjects, and an increased awareness of links between quantum computing and future career opportunities.

However, some challenges were also observed. A few students initially struggled to grasp abstract concepts due to the inherent complexity of the topic, while others experienced difficulties using simulation tools or were hesitant to participate in group discussions. These limitations may be attributed to the abstract nature of quantum principles and the students' lack of prior background knowledge. To address these issues, future instructional designs should adopt a more gradual approach, incorporate a broader range of visual media, and emphasize repeated hands-on practice to support conceptual understanding..

V. DISCUSSION

This study confirmed that a simulation- and practice-oriented quantum computing education program—designed to explain core quantum concepts at a level appropriate for high school students—significantly improved students' conceptual understanding and learning motivation. When compared to international cases, the findings suggest that foundational quantum computing education for high school students can also be effectively implemented in South Korea.

In particular, the program demonstrated that instructional design based on a STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach fosters students' self-directed inquiry, mathematical reasoning, and curiosity toward emerging scientific technologies. The active use of visual tools and hands-on platforms was found to be especially effective in facilitating intuitive understanding of otherwise abstract and complex quantum theories.

Moreover, the program helped students reframe "quantum" not merely as a difficult theoretical concept in physics, but as a practical technology connected to real-world applications and societal challenges. This shift in perception positively influenced their career awareness and motivation to pursue science and technology-related fields.

However, this study has certain limitations. As a short-term intervention conducted with a relatively small experimental group, the sample size and instructional duration limit the generalizability of the findings. In addition, variations in learning outcomes were observed depending on students' prior knowledge in mathematics and science, as well as their familiarity with educational tools and simulations.

Therefore, future efforts should aim to incorporate basic quantum computing concepts into the national curriculum, establish systematic teacher training programs and instructional resources, and develop level-appropriate educational content for diverse student groups. Longitudinal studies involving large-scale populations, as well as policy research focused on bridging regional and institutional disparities in access to quantum education, are also needed.

In conclusion, this study not only demonstrates the practical feasibility and effectiveness of quantum computing education for high school students in South Korea, but also proposes a new direction for innovation in science and technology education. Continued research into various models of integrated education will be essential for building a sustainable foundation for cultivating future talent in quantum technologies.

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