Quantum Game Club: Engaging with Quantum Computing Through Interactive Learning

Dongyang Li
School of Industrial Engineering
Purdue University
West Lafayette, Indiana 47906, USA
lidongyang@purdue.edu

Zirui Zhang
Department of Computer Science
Purdue University
West Lafayette, Indiana 47906, USA
zhan4192@purdue.edu

Xinzhe Xu
School of Aeronautics and Astronautics
Purdue University
West Lafayette, Indiana 47906, USA
xu1464@purdue.edu

Mahdi Hosseini
Department of Electrical and Computer Engineering
Northwestern University
Evanston, Illinois 60208, USA
mh@northwestern.edu

***Abstract*—With the rapid evolution of quantum computing, education in quantum technology should encompass both theoretical knowledge and practical applications relevant to industry and research. We aim to create an educational model that integrates learning, application, and research in quantum computing for students of all levels. Bridging the gap between coursework and active research, a club led by students provides comprehensive learning modules, followed by mini-challenges, which aim to engage students in active research in the field. These challenges have led to the development of web and standalone applications, contributing to both community and academic knowledge. Throughout its operation, the club has introduced a series of learning materials covering fundamental to advanced quantum computing topics, combined with hands-on challenges and projects that transitioned students from theoretical understanding to practical applications. This paper discusses the structure and outcome of the club activities, highlighting specific educational strategies taken and their educational and research achievements. Results indicate the practicality of the club's structure, evidenced by the members' contributions to the field through application development and publications. By detailing the club's methodology, achievements, and challenges, this paper aims to provide insight for educators looking to cultivate similar programs that encourage active learning and research in quantum computing.**

***Index Terms*—Quantum Computing, Quantum Algorithm, Quantum Art, Quantum Game, Quantum Pedagogy, Informal Learning, Course Design, Undergraduate Research**

I. Introduction

Quantum innovations are expected to usher in a new era in the history of technology. Reflecting on the 1960s, the notion of large-scale time-shared machines was the only practical future that engineers and scientists could foresee. However, this notion quickly changed when the significance of personal computers and human interaction with machines was revealed through demonstrations like Engelbart's ”Mother of All Demos” in 1968 [1]. The technology culture, initially shaped by communities of hobbyists in the early days of computers, eventually led to a profound social impact and, in turn, a digital revolution that met society's needs. Early computer games such as Spacewar! [2] eventually led to the launching of a new industry whose effects we still feel today. Perhaps more significant than the creation of the new industry was the resulting cultural movement that introduced the general public to the potential of new technology. This movement lowered the threshold to entry through open-access interface innovations that emerged within the community itself.

We believe that quantum technology stands at a similar critical juncture. It is perhaps not an exaggeration to say that quantum technologies have the potential to unleash a similar economic revolution. Bridging the gap between developing quantum technologies and the public's STEM literacy and interest in such technologies is essential. Similar to Xerox PARC [3], where the first personal computers and interfaces were built, there is a need to create a thriving community of students, hobbyists, engineers, and scientists. This can be achieved by providing the necessary education and resources to design games, interfaces, software, and communication hardware to interact with quantum technologies, including quantum networks, quantum sensors, and quantum computers.

Accordingly, we pose the question: How can we create a quantum culture of creativity and invention similar to the one that drove the digital revolution, empowering the general public while avoiding technology institutionalization? How can we empower quantum learning communities to develop, both figuratively and literally, the first Quantum “Tennis for Two” game played with trapped atoms used to build quantum computers? How does innovation within quantum communities translate to technological advancement?

Quantum concepts and quantum engineering are typically difficult to teach to non-physicists, and the threshold for entering the field is high, preventing broader education. On the other hand, there is a danger in mystifying a new technology that may impact every aspect of our lives, such as communication security, AI-assisted technologies, and big data. It is about access to information and shaping the future information-centric society. Recognizing these challenges, we have es-

979-8-3315-4137-8/24/$31.00 ©2024 IEEE
DOI 10.1109/QCE60285.2024.20470

tablished the Quantum Game Club, a student organization aimed at demystifying quantum thought. Our goals include developing user-friendly interfaces and providing free access to cutting-edge technology, enabling learners to abstract, visualize, and innovate with quantum concepts.

The club goes beyond an extracurricular activity by becoming a comprehensive educational model integrating learning with hands-on research projects. Doing so, extending the knowledge taught to the students to practical applications that engage students directly with topics they are interested in, involving real-world applications.

The Quantum Game Club approaches education in two directions. First, we provide a structured learning path that progresses from basic principles to advanced concepts. Through a series of presentations and workshops, the material targets students of all levels and fields. Second, the club encourages students to apply their knowledge in practical settings through a selection of mini-challenges, assisting in their transition from theoretical understanding to active development in quantum research. The mini-challenges frequently evolve into larger-scale projects, leading to standalone applications and contributions to academic publications and conferences.

This paper details the formulation, methodology, and outcomes of the Quantum Game Club, highlighting a structure for high-level quantum computing education. The organization of the paper is as follows: Section II offers an overview of the club's background, formation, and prior educational approaches in quantum computing. Section III outlines the club's objectives, focusing on its educational and research goals. Section IV details the club's methodology, including educational frameworks and curriculum design. Section V showcases the club's projects, illustrating the application of theoretical knowledge through mini-challenges and student-led initiatives. Section VI explores projects in quantum games and art, highlighting creative explorations in the field. Section VII addresses the challenges faced by the club and the adaptations made. Section VIII proposes future enhancements for expanding the club's activities. The paper concludes with final remarks in Section IX.

II. Background

The initiative at Purdue University and Northwestern University, Innovation in Pedagogy Application and Relation to Culture (IQ-PARC) [4], was established to address the education and access gap in quantum technologies through a multi-pronged approach:

- Undergraduate Quantum Education: Our Quantum Game Club (a student organization) is a learning community catalyzing peer-to-peer education and community innovation by bringing together students with little to no knowledge of quantum mechanics. It empowers students to use existing quantum computers to develop games, create art, and even attempt to solve pressing problems in their field of engineering [5].
- K-12 Education: We bring teachers to the university to work with our students and faculty to develop lesson plans for specific grades. We create hands-on activities, implement the lesson plans in classrooms engaging 1000+ students, collect data, and iterate the lesson plans so they can be widely adopted by other schools [6].
- General Public: We develop high-quality outreach videos for the general public that introduce some of the most counter-intuitive quantum concepts using little to no math.

There is an element of intellectual activism in democratizing quantum technology. Our program, along with many others across the country, aims to empower individuals to innovate and this helps to steer technology away from centralized information hubs encouraged by corporate culture [7], [8]. In addition, there are many quantum courses offered online for students of broad backgrounds, making education available to a wide audience [9], [10]. What sets our program apart from existing ones is our hands-on approach and continuous learner engagement, where students define projects of interest and collaborate to develop and evolve them.

Traditional courses on quantum computing are typically offered within academic institutions [11]–[13] and require physical attendance or enrollment in specific programs. Whether conducted in-person or virtually through scheduled classes, this format inherently limits accessibility. Participants are often required to be present at designated times and locations, which can be a significant barrier for those outside the institution or with conflicting commitments, leading to discouragement away from the subject.

Furthermore, these courses usually have prerequisites that may exclude those who do not have a background in related fields like mathematics or physics, thereby narrowing the potential students [14]–[18]. The structured format of such courses, while beneficial for systematic learning, lacks flexibility needed for the general public interested in the subject.

On the other hand, many resources, ranging from complete courses to specific tutorials on quantum computing, exist on the Internet. These resources, often developed by institutions or industries, provide flexibility and self-paced learning opportunities. These materials often exist in two formats: either as standalone material aimed at very specific topics within the subject or full-fledged courses designed to cover the subject in its entirety. For fully developed courses, companies such as Qubit by Qubit [19], Microsoft [20] or Brilliant [21] have developed courses targeting students with diverse educational backgrounds, ranging from middle school to universities [22]. As for specific topics within quantum computing, companies such as IBM and Microsoft have created informative YouTube videos covering various quantum algorithms [23], [24].

However, this format also contains drawbacks. Students usually face challenges such as a lack of support, which is essential for learning complex topics. Without the ability to engage in discussion or ask for clarification, students might find themselves isolated without any support, which can slow down their understanding and progression. Additionally, the quality of online learning materials can vary significantly, combined with the lack of accreditation, often making it difficult for learners to assess the reliability and relevance of the materials available.

III. Objective

The Quantum Game Club was established to enhance the quantum computing scene in an educational environment, particularly at the undergraduate level, while collaborating with industry leaders. These objectives were designed to encompass fundamental quantum computing knowledge while fostering a community of enthusiasts and professionals alike.

A. Educational Enhancement and Accessibility

The primary aim of the Quantum Game Club is to deliver accessible and comprehensive quantum computing education to students across diverse disciplines and skill levels. Often, existing resources vary from overly simplistic overviews to complex, detailed explanations covering both hardware and software. By abstracting key concepts and utilizing a peer-to-peer teaching method, the club makes quantum computing accessible to all students.

The club adopts a modular approach, organizing learning materials from basic concepts to advanced applications in a linear progression. This structure allows students from any background to tailor their learning journey based on interest and prior knowledge. By incorporating interactive simulations and mini-challenges as checkpoints, the club keeps the material engaging and enhancing student retention.

B. Community Building

Creating a thriving community remains a critical objective of the Quantum Game Club. The club aims to foster a nurturing environment where students can explore their interests and enthusiasm for quantum computing. Regular virtual and in-person meetings provide a platform for sharing project ideas and collaboration, while workshops and guest lectures from industry experts offer deep dives into specialized topics. To ensure a diverse student population, we hold workshops specifically for underrepresented students. These workshops introduce students to our club activities and quantum technologies. This community-centric approach facilitates peer learning and mentorship, with more experienced members guiding new project directions. The intention is for students from different disciplines, such as physics, computer science, and electrical engineering, to collaborate on projects while simultaneously learning from and teaching their peers. Social events and collaborative projects also foster the community, creating a network of quantum computing enthusiasts in academic and professional fields. The community enhances learning and maintains a sustained interest in the rapidly evolving field of quantum computation.

C. Application and Research

The objective of the Quantum Game Club for its students is to transition from theoretical knowledge to practical implementation. The club encourages students to explore projects that apply quantum computing principles to real-world problems. These projects are integral to the club's development as a capstone for the theoretical knowledge acquired through coursework and extracurricular lessons. They also provide tangible outcomes that can be showcased to prospective employers or academic programs, further assisting members in their careers in quantum computation. Collaborations on these projects also serve as an introduction for newer members to critical skills such as problem-solving and teamwork, all while contributing to the field through publication and conference presentations.

D. Collaborations with Industry

The quantum computing industry allocates considerable resources toward education. Many companies and providers have offered their resources to the Quantum Game Club either for free or through collaboration. Microsoft Azure Quantum is a collaborator that supported the development of some Q# Development SDK notebooks [25] while providing access to QPUs through Azure [26]. In addition, Xanadu is another provider that collaborated with the club in developing course materials based on PennyLane [27]. Our industry collaborators engage in both informal and formal learning activities with the club by presenting workshops and seminars to our students and even mentoring some of them. These track records show the collaborative nature of the field and how the industry is pushing the adoption of quantum programming skills by supporting collaborative projects.

E. Accessibility in Education

The Quantum Game Club is committed to making its material accessible to students of all levels and disciplines. This commitment is established with the creation of entry-level modules requiring little to no prior knowledge and a selection of more advanced topics that challenge experienced students. By continuously adapting and creating new curricula based on student feedback and emerging architectures, the club ensures that it remains both accessible and relevant. This approach fosters a diverse learning environment and prepares students from various backgrounds for future careers in quantum technologies, supported by their interests.

IV. Methodology

The Quantum Game Club operates on a structured academic year cycle designed to maximize its members' learning and development opportunities. This methodology section outlines the comprehensive framework for how the club recruits, educates, and engages students in the area of quantum computing. From initial recruitment efforts in the fall semester to the development of projects in the summer, each phase of the club's activities builds on the previous, ensuring a cohesive and progressive learning experience. The following subsections detail each stage of the club's operational cycle, highlighting the educational methods employed.

A. Club Structure and Academic Year Cycle

Each fall semester, the club participates in multiple recruitment events at our institutions to attract new members.

Through various promotional activities such as workshops, talks, and flyers, the club aims to attract students interested in quantum computing and research. These events are designed to pique students' interest regardless of discipline, offering them a glimpse into what quantum computing is capable of. It should be noted that despite the majority of promotional and recruitment events occurring in the fall, similar events also occur in other semesters.

Once new members join, the club starts with a series of presentations by senior club members aimed at teaching the fundamentals of quantum computing. This educational phase is structured around a progression system where students advance through the curriculum by completing the checkpoint tasks after each presentation. These are critical in ensuring members grasp the fundamental concepts before moving on to more complex applications. This approach helps build a solid foundation while providing direct feedback to the instructor on the quality of the material. Details of the system can be found in the Subsection B.

B. Progression System and Learning Material

The majority of the club's presentation content is split into four subsections covered over the span of four weeks. The exact time frame for the presentation phase may be adjusted to accommodate for holidays and feedback. These presentations cover the fundamentals of gate-based quantum computing, starting with mathematical expression and advancing to algorithms.

Prior to the first presentation, students are instructed to set up their respective programming environments either locally or using online solutions. For the presentation phase, students are encouraged to use IBM's quantum computing programming package Qiskit [28], whereas previously, the club has also used the Q# development SDK package [25] as instructional material. Python, the programming language [29], was selected for its simplicity relative to other options like C and C++ used by Intel [30].

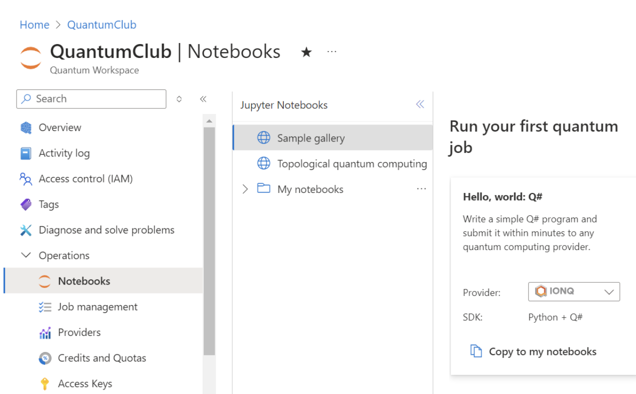

Fig. 1. Online Jupyter Notebook environment within Azure development workspace

For local installations, students had the option to select from a wide range of development environments, from Pycharm [31] to Visual Studio Code [32], as long as it is capable of running Python and installing the Qiskit Package. For online environments, students were encouraged to pick from Microsoft Azure [26], Google Colab [33], and IBM Quantum Lab [34] as their Jupyter notebook [35] environments. As of May 15th, 2024, the IBM Quantum Lab development environment [34] has been deprecated and will no longer be used by the club. As a benefit of being a member of the Quantum Game Club, students are given access to a selection of quantum computer hardware through cloud service. The interface is shown in Fig. 1, where students can choose the hardware. As opposed to submitting via API token, the club encourages its students to use the interactive web GUI provided by Microsoft. Members may access these QPUs through the Microsoft Azure platform, either directly through notebooks within the workspace or their respective resource ID, which can be used within their local environments to submit jobs to QPUs. Through Azure, we are able to provide students with Rigetti [36], Quantinuum [37], and IonQ [76] hardware access. Within the Azure portal provided to students, they are given a selection of examples and tutorials provided by Microsoft, guiding them through the steps of submitting jobs to quantum hardware.

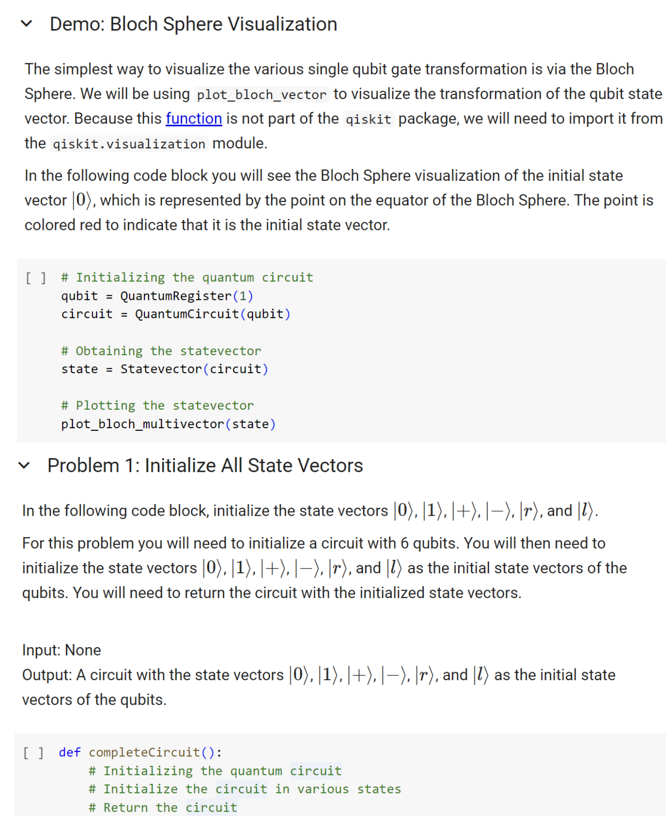

Fig. 2. Sample Jupyter notebook given to students each week, including code sections for demo and sample question based on demo.

During a presentation, students are invited to follow along with the given Jupyter Notebook file, demonstrated in Fig. 2, distributed prior to each week's presentation [38]. These notebooks include sample codes that are covered during the meeting and a problem for each section that the student should complete as part of the checkpoint system. Links referencing additional resources or source code can be found alongside each code sample and question.

Student responses are evaluated directly within the notebooks as self-evaluation functionalities have been implemented within. These functions evaluate the output of the student response as opposed to evaluating the student code directly, ensuring that students are not able to reverse-engineer the evaluation tools to obtain the answers.

Problem 2-1

Given a circuit containing 1 qubit in the state vector $|1\rangle$, transform the qubit into the state vector $|0\rangle$

Input: Circuit containing 1 qubit in the state vector $|1\rangle$
Output: Circuit object with transformation applied to the qubit

```
[ ] def circuit21(circuit):
        # TODO
```

Use the following code block to check your implementation

```
[ ] def check21():
        qubit = QuantumRegister(1)
        circuit = QuantumCircuit(qubit)
        circuit.initialize('1', qubit)
        circuit = circuit21(circuit)
        if Statevector(circuit) == Statevector.from_label('0'):
            print("The states are correct!")
        else:
            print("The states are incorrect.")
    check21()
```

Fig. 3. Sample questions with evaluation functionality.

Additionally, the question checkpoints do not have a standard answer and, therefore, can be completed through different methods. As seen in Fig. 3, the qubit rotation question can be answered with various rotational gates, allowing for multiple correct answers. After the students have completed the checkpoint for the week, they are encouraged to submit these tasks for further evaluation. This indicates that they are capable of advancing to the next task.

Each semester, depending on the number of total presentations, the number of tasks may be adjusted to fit within the time constraint. Despite the difference in the total task numbers, the fundamental topic covered does not change drastically. A sample structural education format can be seen as follows:

1) This week introduces new members to the club's objectives and plans. Previous members begin researching potential projects for the upcoming semester. Additionally, mini-research projects, or mini-challenges, are developed to help new members start specializing. During this period, new members are also expected to familiarize themselves with the programming environment, Python, and Qiskit.
2) Week 2: It is important to take a week to fill in the knowledge gaps for all incoming members, including mathematical knowledge required for gate calculation, such as matrix manipulation or eigenvalues. Checkpoint formats are also introduced to the students, allowing for self-evaluation for the weekly challenge.
3) Week 3: Building on their foundational mathematical knowledge, students learn about single-qubit gates such as Hadamard and rotational gates, with a focus on superposition using the Hadamard gate. Whenever possible, participants are encouraged to run their circuits on an actual quantum computer rather than through simulations.
4) Week 4: This week focuses on common multi-qubit gates like CNOT and Toffoli while introducing ideas like entanglement using CNOT. Due to the complexity of multi-qubit gates, it is advised that the checkpoint include hand-written portions for manual calculation of gates on qubits to understand entanglement mathematically.

While these notebooks are handed out on a weekly basis, prior notebooks are accessible directly through the club's GitHub page [38]. This assists students who may have missed a presentation due to time constraints or other reasons. As the club aims to provide resources for students whenever possible, all of the presentation material, along with the presentation recordings, can be found on the IQ-PARC website [39] or through the club's YouTube channel [40], ensuring accessibility at all times. Students may also contact leadership within the club directly for assistance with both the content presented and questions within the Jupyter Notebook. Whereas the presentations are structured as informational sessions, students are encouraged to collaborate on the material, sharing their understanding of the content along with ideas for potential applications.

C. Mini-Challenges and Conceptual Application

After gaining a basic understanding of the fundamental quantum computing concepts and completing the necessary tasks, students are offered a selection of mini-challenges. Often, these project-like tasks are designed by members from prior semesters who are relatively more experienced. These mini-challenges allow newer members to apply their newly acquired knowledge in a controlled, conceptual framework that focuses on understanding more than practical application. Additionally, these challenges allow for prior members to identify and mentor a cohort of students who can assist in future, larger-scale projects. A selection of mini-challenges includes:

- Max Cut with QAOA: This particular challenge focuses on optimization and graph theory. The goal is to solve the max-cut with QAOA through optimization while introducing the idea of hybrid iterative models, specifically focusing on optimization. Since many classical problems can be solved as a combinatorial optimization problem, this challenge can transition into other optimization problems, which will likely require knowledge of QAOA and other optimization models [41].

- Ciruict Compiler: This challenge aims to create a simple compiler that optimizes the gates used within a circuit. As certain machines may not have certain gates, such as CX, the user needs to compile the CX gate with various combinations of CZ gates. This challenge helps with understanding how quantum computers can be simulated and how the software optimizes the circuit input [42] while providing practice on critical gate sequences.
- Maximum Independent Set: This challenge aims to solve the maximum independent set using the adiabatic method [43] instead of QAOA. Students are introduced to neutral atom platform quantum computing instead of only learning about gate-based quantum computing. Due to the physics knowledge needed, this challenge will likely be more involved relative to others. However, it will act as a good introduction to other platforms and those who want to learn about quantum computers at the lowest level.

D. Transition to Large-Scale Projects

Mini-challenges set the stage for larger projects that students begin by the end of the fall semester. During winter break, students form groups based on their interests from these challenges to prepare for spring semester projects, which tend to be more specialized and field-specific.

In the spring semester, students engage in the research and development phase of these projects. Experienced members lead these efforts, applying their knowledge to guide project progression and maintain high standards, ensuring projects meet their objectives and deliverables.

E. Final Deliverables and Summer Continuation

Students are expected to produce partial deliverables by the end of the spring semester. These are then prepared for submission to relevant publications and conferences, providing the student with an opportunity to gain recognition for their work and contribute to the field of quantum computing. As many new members do not possess publication experience, this allows them to learn about the publication process. Some examples of platforms where students publish their work include The Journal of Purdue Undergraduate Research (JPUR) [44], Tools on nanoHUB [45], etc.

Students who wish to refine their projects further or those whose projects require additional work can continue their development during the summer semester. The club supports these efforts by continuously providing necessary resources such as scholarships and access to QPUs. Simultaneously, the summer semester is also a period for feedback on the club's operation, allowing for adjustment and improvement in the upcoming academic cycle.

This cycle of recruitment, education, project development, and feedback system ensures that the Quantum Game Club continuously enhances its educational impact while staying relevant and up-to-date with the latest developments in quantum computing.

F. Student Incentives and Retention

To motivate and support our members, the Quantum Game Club offers a range of incentives designed to provide tangible benefits for active participation. One of the primary incentives for club members is the availability of scholarship funding. These scholarships are awards based on active participation in activities and projects. Additionally, the club also allocates funding to assist members in traveling to significant events such as industry talks [46] and hackathons [47]. As a testament to our efforts, students within the club have received first place at the MIT iQuHack hackathon [48]. This opportunity allows students to learn from and network with leading professionals in the field.

In addition to club participants, the club actively fosters relationships with industry professionals to arrange internships and mentorship opportunities [49]. These connections are essential as they provide students with firsthand experience in the industry, helping them build a professional network. By providing students with opportunities outside of the club, it prepares them for future challenges within the quantum computing industry.

V. Projects

A key aspect of the Quantum Game Club's mission is transforming theoretical knowledge into practical solutions. This section showcases projects ranging from web applications to standalone software and academic publications, all developed by club members. These projects demonstrate how students apply quantum computing concepts in diverse fields, producing tangible results. We also provide insight into some of the projects initiated by the students along with some technical details of selected projects to demonstrate the depth of understanding of the topics. We detail the objectives, development processes, subjects addressed, and outcomes of these projects in Table 1.

TABLE I
OVERVIEW OF PROJECTS PRESENTED IN SEC. V

Title	Category	Outcome	License
Procedural Optimization [50]	Optimization	Conference publication	MIT
Hamiltonian Simulation [51]	Simulation	Journal publication	MIT
Quantum Bayesian Network [52]	Machine learning	Journal publication	MIT
Prisoners Dilemma [53]	Simulation	Standalone application	MIT
Quantum Galaxies [54]	Machine learning	Standalone application	MIT
Maze Optimization [55]	Optimization	Standalone application	MIT
Shape VQC [56]	Machine learning	Standalone application	MIT
Stir it up! [57]	Simulation	Web application	MIT
Quantum Education [58]	Course	Online resources	MIT

Over the last three years, the Quantum Game Club has developed a multitude of projects covering a wide range of subjects. In the rest of this section, we provide a selection of the work demonstrated in Table 1 with a description detailing the idea and outcome of the work. Please note the following subsections only contain a selection of projects recently completed and do not include every project completed by members of Quantum Game Club.

A. *Procedural Optimization*

The Procedural Optimization project adapts the classical wave function collapse algorithm [59] to address its limitations in handling large-scale, high-dimensional datasets, where runtime increases exponentially with dataset complexity. By reformulating this algorithm as a constraint-satisfaction problem and using quantum computation techniques—specifically quadratic unconstrained binary optimization (QUBO) optimized with the quantum approximate optimization algorithm (QAOA)—we enhance its efficiency and applicability.

Algorithm 1 Wave Function Collapse via QUBO Optimization

Define a set of tiles T, each with a unique identifier.
Define adjacency rules for each tile in T, encoded as constraints on their edges.
Represent the problem space as a grid of cells C, each cell $c \in C$ to be filled with one tile from T.
Formulate a QUBO matrix Q where:
- Each variable x_{ct} represents whether tile $t \in T$ is placed in cell $c \in C$.
- Quadratic terms in Q encode the constraints that adjacent cells in C must satisfy adjacency rules according to tile types in T.
- Linear terms in Q enforce that each cell $c \in C$ must contain exactly one tile from T.
- Additional constraints can be added to Q to enforce specific tiling patterns or restrictions.

Initialize the QUBO solver with the matrix Q.
while not converged **do**
    Use the QUBO solver to find the minimum energy configuration of tile placements.
    Check if the solution meets all constraints (all cells $c \in C$ filled correctly according to rules).
    if solution is valid **then**
        Break.
    else
        Modify constraints or penalties in Q to guide the search.
    end if
end while
Output: Optimized tile placement for the entire grid.

1) Problem setup: The wave function collapse algorithm, reconfigured into a QUBO formulation, tackles the problem of tiling a 2D grid by applying specific adjacency rules to each tile, conceptualized as a small matrix. The grid consists of cells, C, where each cell $c \in C$ is required to host exactly one tile from a set, T, with each tile $t \in T$ having predefined adjacency rules.

The objective function, minimized through a QUBO matrix Q, penalizes incorrect configurations with quadratic and linear terms. Quadratic terms in Q penalize adjacent incompatible tiles, directly enforcing the adjacency rules, while linear terms ensure each cell contains only one tile, imposing a high cost for empty or multiple filled cells.

The implementation employs QUBO and QAOA to find the tile configuration that minimizes the system's energy, indicating an optimal arrangement under specified constraints. A QUBO matrix Q is constructed with constraints derived from adjacency rules and penalties related to the tiling problem, incorporating both quadratic and linear terms to enforce these rules. The algorithm is summarized in Algorithm 1.

Initially, the solver is initialized with matrix Q, containing all possible tile configurations. It then operates iteratively, adjusting tile configurations by applying unitary transformations linked to Hamiltonians H_C and H_B, which represent the cost and mixing terms, respectively. Each iteration involves measuring the system state in the computational basis and calculating the expectation value of H_C to assess alignment with the constraints. Details of these steps are outlined in Algorithm 1.

After each iteration, the configuration is checked against the constraints. The algorithm terminates if the configuration satisfies all rules and ensures every cell contains a tile. If not, the algorithm adjusts the QUBO matrix Q by modifying penalties or constraints, adjusting towards a valid solution.

2) Results: The algorithm's output is an optimized tile placement across the grid, denoted by the binary vector $x* = (x_1^*, \ldots, x_n^*)$, indicating specific tiles' presence in specific cells. This configuration minimizes the objective function Q and adheres to all adjacency and placement rules while providing a valid solution to the problem.

As a demonstration, a dataset containing four different types of tiles was used to generate a three-by-three output. Artistic elements have been added to demonstrate its use in computer graphics, inspired by artist Piet Mondrian, as seen in Fig. 4.

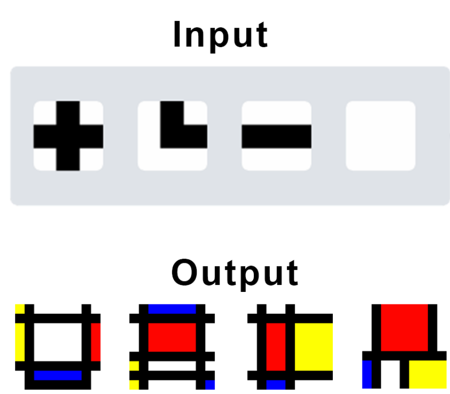

Fig. 4. Sample output from the algorithm given the ruleset. Four different tiles have been used as the ruleset input, generating sample output on a 3 by 3 grid, with an artistic post-processing effect applied.

The algorithm demonstrates the ability to generate the correct output that fits within the constraint. While the result may differ depending on the specific architecture of the quantum computer, by using QUBO formulations sampled with QAOA, the algorithm aligns well with the current NISQ technology [60].

B. Hamiltonian Simulation

Hamiltonian simulation is a fundamental task in quantum computing which involves replicating the time evolution of the quantum system described by the Hamiltonian. Simulating Hamiltonian classically is inherently challenging to due to the exponential growth of the state space with the numbers of particles in the system. On the other hand, quantum computers are well-suited for such task due to their abilities to leverage the fundamental priciples for quantum mechanics.

Our project focuses on the development of an interactive tool that simulates the Hamiltonian of the Transverse Field Ising Model (TFIM) using Qiskit. This tool is designed to help students and researchers visualize and understand the dynamics of the TFIM, leveraging the power of quantum simulations to explore the effects of various parameters on the system's behavior. The transverse field Ising model is a well-studied and relatively simple quantum spin model that exhibits rich physical phenomena, making it an interesting candidate for demonstrating the power of quantum simulations for a general audience. In this model, spins are subject to both interaction with their neighbors and an external transverse magnetic field, leading to a non-trivial Hamiltonian that captures both local interactions and external perturbations.

$$H = -J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z - h \sum_i \sigma_i^x \tag{1}$$

where:

- J is the coupling constant between neighboring spins.
- h is the strength of the transverse magnetic field.
- σ_i^z and σ_i^x are the Pauli matrices representing the spin operators in the z and x directions, respectively.
- The summation $\sum_{\langle i,j \rangle}$ runs over pairs of nearest-neighbor spins.

To implement the Hamiltonian simulation, we employed the Trotterization method, which approximates the continuous time evolution of the Hamiltonian by breaking it into discrete steps. The Trotter-Suzuki decomposition approximates the time evolution operator e^{-iHt} by breaking it into a series of smaller steps. For the Transverse Field Ising Model, the Trotterized time evolution operator is given by:

$$e^{-iHt} \approx \left(e^{-iH_z t/n} e^{-iH_x t/n}\right)^n \tag{2}$$

where:

$$H_z = -J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z$$
$$H_x = -h \sum_i \sigma_i^x$$

In this approximation:

- H_z is the part of the Hamiltonian representing the interaction between neighboring spins.
- H_x is the part of the Hamiltonian representing the effect of the transverse magnetic field.
- t is the total time for which the system evolves.
- n is the number of Trotter steps, with higher n leading to a more accurate approximation.

Using Qiskit, we constructed quantum circuits that simulate the TFIM for various parameters J, h, and the number of Trotter steps.

VI. Quantum Games and Arts

Quantum games [61]–[64] and visual quantum arts [65] can be powerful tools for conveying challenging quantum concepts. These virtual experiences make abstract ideas more tangible and relatable for students. At the Quantum Game Club, we focus on creating interfaces and interactive modules to help the general public understand complex quantum concepts.

Take randomness, for example. It's a core concept in encoding messages or measuring quantities, yet it's challenging to explain. It is also fundamental to quantum computing and communication. By developing algorithms to extract quantum data from hardware, we can leverage its inherent randomness and visualize it through visual arts, providing profound educational value. By incorporating quantum mechanics concepts like superposition and entanglement into games and art, the club enhances educational materials and fosters creative expression. These efforts make quantum computing more accessible, extending its reach beyond traditional academic environments [66].

Quantum games offer a unique way to illustrate and interact with quantum concepts, providing both developers and players with valuable insights. Studies have shown that quantum games can facilitate an engaging and intuitive learning experience without requiring deep mathematical knowledge [67].

Furthermore, quantum games apply quantum computing algorithms to game development challenges like procedural generation and post-processing [68], which are often limited by the computational capacities of classical computers. Leveraging quantum properties like true randomness and potential computational speed-ups, these games introduce innovative mechanics and enhance game design possibilities previously unachievable with classical computing.

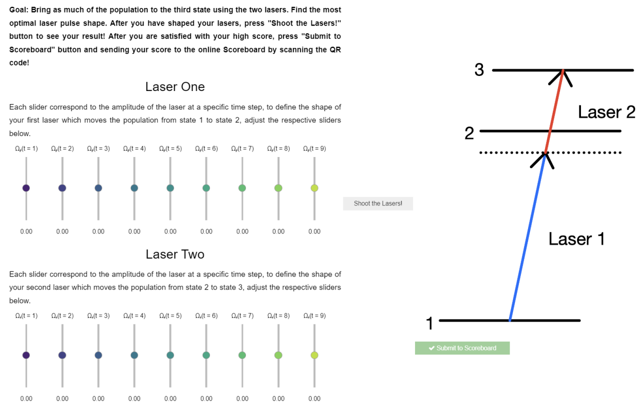

Fig. 5. Screenshot of Stir it up! A quantum game that explores the optimal laser pulses which transition an atom with three electronic states from an initial to a final state.

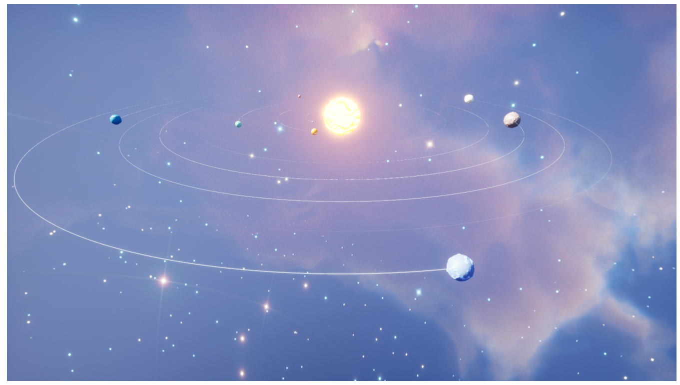

Fig. 6. Screenshot of Quantum Galaxy art project, generated with Microsoft Q# development SDK [25] and IonQ Harmony [71], designed to recreate solar system with correct aspect ratio through regression and noise.

Within the Quantum Game Club, the development of quantum games challenges the club members to think creatively about how to incorporate quantum mechanics into games, enforcing a deeper understanding of the theoretical aspect through programming challenges.

A recent project developed by club students under faculty supervision is an interactive game based on the quantum optics phenomenon Stimulated Raman Adiabatic Passage (STIRAP), designed to educate players through hands-on interaction [57]. STIRAP, a technique for transferring population between quantum states coherently without populating intermediate states, is the central theme of the game. Players aim to transfer a quantum particle from state $|1\rangle$ to $|3\rangle$ by controlling two virtual laser pulses, which simulate the pump and Stokes pulses used in the actual STIRAP process. This game not only educates but also provides an engaging way to explore quantum mechanics.

Quantum art is a creative direction explored by the club, interpreting quantum mechanics principles through artistic mediums. This art form visualizes concepts such as wave-particle duality, quantum entanglement, and the uncertainty principles, making them accessible and engaging to the general public without requiring detailed quantum knowledge [69].

Additionally, artistic interpretations serve educational purposes, provoking curiosity and interest in quantum computing. Exhibitions of quantum art [65] act as visual essays that encourage viewers to explore and question the underlying scientific principles.

By employing modern quantum computing technologies like generative algorithms [70], the club aims to showcase technological advancements and demonstrate how art and technology intersect. This approach both enhances public engagement and attracts new members and collaborators, extending the club's reach beyond traditional academic boundaries.

As another potential area of exploration, students within the Quantum Game Club have attempted to create artwork with quantum computing hardware. One such project, known as the Quantum Galaxies [72], seen in Fig. 6, utilizes the concept of noise alongside quantum machine learning models to create solar systems similar to ours. The regressor model [73] used aims to recreate the solar system through many iterations, with each iteration altering the parameter of the regressor. This art piece is created through Blender [74] and Unreal Engine 5 [75], with data generated with QPU hardware from IonQ [76].

By embracing both quantum games and quantum art, the Quantum Game Club aims to create additional directions of exploration for its members, enhancing the educational experience and extending quantum computing beyond the academic scene. This integration of science, art, and technology hopes to demonstrate a multidisciplinary approach to quantum computing education.

VII. Management and Challenges

Establishing the Quantum Game Club presented numerous challenges. Despite its innovative approach to quantum computing education, the club encountered obstacles ranging from curriculum development to member retention. This section outlines these challenges and the trial-and-error strategies employed to refine the club's operations. The experiences and solutions discussed here are intended to inform and guide similar educational initiatives in related fields.

A. Initial Establishment and Curriculum Development

When the Quantum Game Club was first established, it encountered significant challenges due to the absence of similar clubs in our institution. Developing a balanced curriculum that was both complex and accessible proved difficult, leading to frequent revisions based on student feedback to simplify the content without losing depth [38].

Over three years, this iterative process, assisted by contributions from former students who identified unnecessary complexities, significantly enhanced the curriculum's quality and relevance to current industry standards. These efforts streamlined the content creation process, focusing on essential concepts.

B. Educational Backgrounds and Entry Requirements

The Quantum Game Club strives for inclusivity without entry prerequisites, fostering a diverse membership, which also presents challenges. Members often have varied educational backgrounds, sometimes lacking key skills in linear algebra, quantum mechanics, or basic programming necessary for quantum computing.

To address this, the club simplified complex content and used software libraries that abstract advanced computations into user-friendly functions. For example, tools simplifying the QAOA algorithms were used, enabling members to focus on applications by adjusting parameters without deep mathematical complexities. Industry-standard packages like IBM's Qiskit [28], and Xanadu's Pennylane [27] were also employed.

For those seeking deeper or advanced knowledge for projects, the club offers structured learning paths with supplementary materials and mini-challenges tailored to various skill levels, allowing gradual and self-paced learning.

VIII. Future Expansions

The field of quantum computing demands continuous adaptation, especially in educational settings. Recognizing this, the club has identified several areas for enhancement to expand its education offerings, strengthen industry connections, and increase its academic research capabilities. These planned changes intend to enhance the educational experience of current members and also to ensure the club remains relevant in cultivating future quantum computing professionals and researchers. This section outlines specific approaches that can lead to sustainable and engaging educational efforts in the field of quantum technology.

A. Expansion on Learning Material

To support a greater community of learners and continuity of education in this domain, there is a significant demand for more specialized and advanced educational content. By providing diversified and focused learning modules for specific quantum computing applications, students who have mastered the fundamentals can explore how quantum computing can be applied in various specialized fields.

In addition, the club is exploring expansion into advanced modules such as quantum optimization techniques and hybrid approaches to machine learning, reflecting recent growth in these areas. Research directions include financial portfolio optimization [77], where real-world economic models are integrated with quantum techniques, applicable to industries needing large-scale optimization. Furthermore, the club aims to develop modules on using quantum computation for machine learning, specifically to create classifiers and regressors. These efforts will equip students with the tools to apply hybrid-quantum models to various tasks, from data classification to predictive analytics [78], [79].

These advanced topics are intended for a selective curriculum tailored for members deeply committed to the club, ensuring that as they advance, they are given the necessary resources and challenges to further their education and careers in quantum computation.

B. Academic Research Structure

Understanding the importance of academic contributions, the club is committed to creating a structured approach to research. We aim to give students the necessary skills and knowledge to conduct research with different faculty members and contribute to the quantum technology field through scholarly publications and conference presentations. Our club members have already co-authored refereed publications [44], [80]–[82] advancing research in the field.

As the club continuously gains new members, we understand that a large portion does not have prior research experience. Resources can be developed and faculty connection can be established aiming to guide students through the process of designing research projects and developing them, combined with preparing reports to disseminate their results.

C. Broadening Participation

As the Quantum Game Club continues to grow, one of our key objectives for the future is to extend the reach of our education resources beyond the club. We aim to cultivate a broader community of quantum computing enthusiasts by creating learning materials and project examples. This initiative aims to share knowledge with a larger audience while fostering a collaborative environment that goes beyond our club and university.

To achieve this, all educational materials developed within the club are open source and accessible to all at any time [38]. This repository will be designed to serve both beginners and advanced learners interested in quantum computing, regardless of their affiliation. We also aim to keep all projects developed within the club licensed as open source and accessible through our website [39]. Throughout the club's lifetime, all projects developed are under the MIT license [83], allowing anyone to access, modify, or re-distribute our work.

IX. Conclusion

In a community-centric effort, we have established a club for post-secondary learners and intellectuals to explore and contribute to quantum technology, particularly quantum computing and programming. By providing a social setting, access to hardware, and facilitating collaboration with industry leaders and faculty, we created a self-driven learning community. Initially comprising members with little to no background in quantum mechanics, this community has engaged in creating quantum art, games, interfaces, and applications. Through multifaceted experiences and iteratively designed hands-on activities, students have learned to abstract quantum concepts, code quantum hardware, find novel applications and problems, and disseminate their results to broader communities. We believe the Quantum Game Club can serve as an educational model for teaching complex topics to young learners and intellectuals, thereby helping to avoid the institutionalization of technology and fostering innovation.

ACKNOWLEDGMENT

We acknowledge the support provided by the National Defense Education Program (NDEP) for Science, Technology, Engineering, and Mathematics (STEM) Education, Outreach, and Workforce Initiative Programs under Grant No. HQ0034-21-1-0014. The views expressed here do not necessarily reflect the official policies of the Department of Defense nor does mention of trade names, commercial practices, or organizations imply endorsement by the U.S. Government. We thank IonQ for providing us with credits to use their quantum processor and Microsoft for their support in developing quantum course assignments.

In addition, we would like to thank Hadiseh Alaeian, Erica Carlson, Muhsin Menekse, Valentin Walther, Nicholas Dang, Hal Owens, Mariia Mykhailova, Haddy Alchaer, Hiram Enrique Diaz Berrios for their contributions to the Quantum Game Club.

REFERENCES

[1] S. L. Center, "The Mother of All Demos," Lemelson Center for the Study of Invention and Innovation. Accessed: May 24, 2024. [Online]. Available: https://invention.si.edu/mother-all-demos

[2] S. Russell, "Spacewar!", Massachusetts Institute of Technology, 1962.

[3] Palo Alto Research Center Incorporated, "Xerox PARC", Apr. 29, 2024. https://www.parc.com (accessed May 24, 2024).

[4] Z. G. Akdemir, D. Li, M. Menekse, M. Hosseini, E. W. Carlson, and N. Dang, "Innovation in Quantum Pedagogy, Application, and Its Relation to Culture (IQPARC)," in "ADVANCING STEM WITH STUDENTS," Purdue University, 2023. doi: 10.5703/1288284317594.

[5] D. Li et al., "Developing an Undergraduate Quantum Workforce," 2024 IEEE International Conference on Quantum Computing and Engineering (QCE), 2024.

[6] Z. G. Akdemir, M. Menekse, E. W. Carlson, N. Dang, M. Hosseini, and D. Li, "Supporting Middle School Students' Learning Outcomes and Engagement with NGSS-Aligned Quantum-Infused Science Curriculum," presented at the 2024 ASEE Annual Conference & Exposition, Portland, Oregon, Jun. 2024. [Online]. Available: https://peer.asee.org/48039

[7] A. Goff, D. Lehmann, and J. Siegel, "Quantum Tic-Tac-Toe, Spooky-Coins & Magic-Envelopes, as Metaphors for Relativistic Quantum Physics," in 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, American Institute of Aeronautics and Astronautics. doi: 10.2514/6.2002-3763.

[8] T. Liu, D. Gonzalez-Maldonado, D. B. Harlow, E. E. Edwards, and D. Franklin, "Qupcakery: A Puzzle Game that Introduces Quantum Gates to Young Learners," in Proceedings of the 54th ACM Technical Symposium on Computer Science Education V. 1, in SIGCSE 2023. New York, NY, USA: Association for Computing Machinery, Mar. 2023, pp. 1143–1149. doi: 10.1145/3545945.3569837.

[9] D. L. Tucker, "Leveraging Dual Enrollment Programs to Expand Secondary Education in Quantum Computation," Sep. 2023, doi: https://doi.org/10.1109/qce57702.2023.20319.

[10] Y. He, S. Zha, and W. He, "A literature review of quantum education in K-12 level," presented at the Innovate Learning Summit, Association for the Advancement of Computing in Education (AACE), Nov. 2021, pp. 418–422. Accessed: Sep. 14, 2023. [Online]. Available: https://www.learntechlib.org/primary/p/220311/

[11] M. Ivory et al., "Quantum Computing, Math, and Physics (QCaMP): Introducing Quantum Computing in High Schools," Sep. 2023, doi: https://doi.org/10.1109/qce57702.2023.20318.

[12] P. P. Angara, U. Stege, A. MacLean, H. A. Müller, and T. Markham, "Teaching Quantum Computing to High-School-Aged Youth: A Hands-On Approach," IEEE Transactions on Quantum Engineering, vol. 3, pp. 1–15, 2022, doi: 10.1109/TQE.2021.3127503.

[13] S. Kumar, T. Adeniyi, A. Alomari and S. Ganguly, "Design of Quantum Machine Learning Course for a Computer Science Program," 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), Bellevue, WA, USA, 2023, pp. 68-77, doi: 10.1109/QCE57702.2023.20326.

[14] G. P. Temporao, S. Guerreiro, Pedro, and Ana, "Teaching Quantum Computing without prerequisites: a case study," 2022 IEEE International Conference on Quantum Computing and Engineering (QCE), Sep. 2022, doi: https://doi.org/10.1109/qce53715.2022.00090.

[15] J. Liu and D. Franklin, "Introduction to Quantum Computing for Everyone: Experience Report," in Proceedings of the 54th ACM Technical Symposium on Computer Science Education V. 1, in SIGCSE 2023. New York, NY, USA: Association for Computing Machinery, Mar. 2023, pp. 1157–1163. doi: 10.1145/3545945.3569836.

[16] K. Gordon, "Improving Quantum Computing Education for Undergraduate Students".

[17] S. Seegerer, T. Michaeli, and R. Romeike, "Quantum Computing As a Topic in Computer Science Education," in The 16th Workshop in Primary and Secondary Computing Education, in WiPSCE '21. New York, NY, USA: Association for Computing Machinery, Oct. 2021, pp. 1–6. doi: 10.1145/3481312.3481348.

[18] Tunde Kushimo and B. Thacker, "Investigating Students' Strengths and Difficulties in Quantum Computing," Sep. 2023, doi: https://doi.org/10.1109/qce57702.2023.20322.

[19] "QubitxQubit — Programs," www.qubitbyqubit.org. https://www.qubitbyqubit.org/programs

[20] SoniaLopezBravo, "Get started with Azure Quantum - Training," learn.microsoft.com. https://learn.microsoft.com/en-us/training/paths/quantum-computing-fundamentals/

[21] "Learn Quantum Computing on Brilliant," brilliant.org. https://brilliant.org/courses/quantum-computing/

[22] "QubitxQubit — Middle School Summer Camp," www.qubitbyqubit.org. https://www.qubitbyqubit.org/middle-school-camp (accessed May 26, 2024).

[23] Qiskit, "Grovers Algorithm — Programming on Quantum Computers — Coding with Qiskit S2E3," YouTube, Oct. 30, 2020. https://www.youtube.com/watch?v=0RPFWZj7Jm0&t=357s (accessed May 26, 2024).

[24] Microsoft Azure, "Exploring the Azure Quantum Development Kit — Azure Friday," YouTube, Mar. 01, 2024. https://www.youtube.com/watch?v=PD0wHX6edIg (accessed May 28, 2024).

[25] Microsoft, "Azure Quantum Development Kit," GitHub, May 24, 2024. https://github.com/microsoft/qsharp (accessed May 24, 2024).

[26] Azure, "Microsoft Azure Cloud Computing Platform & Services," Microsoft.com, 2019. https://azure.microsoft.com/

[27] V. Bergholm et al., 'PennyLane: Automatic differentiation of hybrid quantum-classical computations', arXiv [quant-ph]. 2018.

[28] A. Javadi-Abhari et al., 'Quantum computing with Qiskit', arXiv [quant-ph]. 2024.

[29] Python Software Foundation, "Python," Python.org, May 29, 2019. https://www.python.org/

[30] G. G. Guerreschi, J. Hogaboam, F. Baruffa, and N. P. D. Sawaya, 'Intel Quantum Simulator: a cloud-ready high-performance simulator of quantum circuits', Quantum Science and Technology, vol. 5, no. 3, p. 034007, May 2020.

[31] JetBrains, "PyCharm," JetBrains, 2019. https://www.jetbrains.com/pycharm/

[32] Microsoft, "Visual Studio Code," Visualstudio.com, 2024. https://code.visualstudio.com/

[33] Google, "Google Colaboratory," Google.com, 2019. https://colab.research.google.com/

[34] IBM, IBM Quantum Lab, https://quantum.ibm.com, accessed 4/18/2024

[35] Jupyter, "Project Jupyter," Jupyter.org, 2019. https://jupyter.org/

[36] "Rigetti Provider for Qiskit — QCS Documentation," Rigetti.com, Jul. 27, 2023. https://docs.rigetti.com/qcs/references/rigetti-provider-for-qiskit (accessed May 28, 2024).

[37] "Accelerating Quantum Computing — Quantinuum," www.quantinuum.com. https://www.quantinuum.com/

[38] "IQPARC-Spring-2023-Learning-Activities," GitHub, Apr. 27, 2023. https://github.com/IQPARC/IQPARC-Spring-2023-Learning-Activities (accessed May 24, 2024).

[39] "IQ-PARC – Innovation in Quantum Pedagogy, Application and its Relation to Culture," iqparc.northwestern.edu. https://iqparc.northwestern.edu/ (accessed May 24, 2024).

[40] "Quantum Game Club at Purdue by IQ-PARC - YouTube," www.youtube.com. https://www.youtube.com/@quantumgameclub (accessed May 24, 2024).

[41] Farhi, E., Goldstone, J., & Gutmann, S. (2014). A Quantum Approximate Optimization Algorithm. ArXiv. /abs/1411.4028
[42] E. Younis and C. Iancu, 'Quantum Circuit Optimization and Transpilation via Parameterized Circuit Instantiation', in 2022 IEEE International Conference on Quantum Computing and Engineering (QCE), 2022.
[43] V. Choi, 'Adiabatic Quantum Algorithms for the NP-Complete Maximum-Weight Independent Set, Exact Cover and 3SAT Problems', arXiv [quant-ph]. 2010.
[44] "The Journal of Purdue Undergraduate Research — Scholarly Publishing Services Open Access Journals — Purdue University," docs.lib.purdue.edu. https://docs.lib.purdue.edu/jpur/ (accessed May 27, 2024).
[45] "nanoHUB.org - Simulation, Education, and Community for Nanotechnology," nanohub.org. https://nanohub.org/
[46] "DoD STEM Exchange," www.dodstem.us. https://www.dodstem.us/stem-exchange-23/ (accessed May 25, 2024).
[47] "Students partner with businesses for quantum hackathon in New Haven — Yale Quantum Institute," quantuminstitute.yale.edu. https://quantuminstitute.yale.edu/publications/students-partner-businesses-quantum-hackathon-new-haven (accessed May 25, 2024).
[48] "Unlocking the quantum future," MIT News — Massachusetts Institute of Technology, Mar. 18, 2024. https://news.mit.edu/2024/hackathon-unlocking-quantum-future-0318
[49] H. Owens, "Developing and using Azure Quantum assignments for quantum computing courses," Q# Blog, Dec. 20, 2022. https://devblogs.microsoft.com/qsharp/developing-and-using-azure-quantum-assignments-for-quantum-computing-courses/ (accessed May 25, 2024).
[50] Z. Zhang, "Procedural Optimization." Northwestern University, Oct. 16, 2023. doi: 10.21985/n2-s7q5-vx09.
[51] X. Xu, "Hamiltonian Simulation." Northwestern University, Aug. 01, 2023. doi: 10.21985/n2-synw-cg53.
[52] H. Alchaer, "QCNN." Northwestern University, Sep. 01, 2023. doi: 10.21985/n2-ryjp-ht56.
[53] L. A. OGUNFOWORA and H. E. ALCHAER, "Quantum Prisoner's Dilemma." [Online]. Available: https://doi.org/10.21985/n2-vmpg-7443
[54] K. Xiao, H. Owens, and Z. Zhang, "Quantum Generative Art." [Online]. Available: https://doi.org/10.21985/n2-4bp9-3b12
[55] X. Xu, "Quantum Maze Solver." [Online]. Available: https://doi.org/10.21985/n2-k52q-sq49
[56] Z. Zhang, "Shape VQC." Northwestern University, Aug. 09, 2022. doi: 10.21985/n2-tk32-xf25.
[57] V. Walther and Xu, "Stir it up!," 2023, doi: https://doi.org/10.21981/YVFY-7K57.
[58] H. Owens, "Quantum Education." Northwestern University, Aug. 01, 2022. doi: 10.21985/n2-9h12-x672.
[59] A. Bassi, K. Lochan, S. Satin, T. P. Singh, and H. Ulbricht, 'Models of wave-function collapse, underlying theories, and experimental tests', Rev. Mod. Phys., vol. 85, pp. 471–527, Apr. 2013.
[60] J. Preskill, "Quantum Computing in the NISQ era and beyond," Quantum, vol. 2, no. 2, p. 79, Aug. 2018, doi: https://doi.org/10.22331/q-2018-08-06-79.
[61] J. Eisert, M. Wilkens, and M. Lewenstein, 'Quantum Games and Quantum Strategies', Phys. Rev. Lett., vol. 83, pp. 3077–3080, Oct. 1999.
[62] K. Becker, 'Flying Unicorn: Developing a Game for a Quantum Computer', arXiv [quant-ph]. 2019.
[63] Khan, F.S., Solmeyer, N., Balu, R. et al. Quantum games: a review of the history, current state, and interpretation. Quantum Inf Process 17, 309 (2018). https://doi.org/10.1007/s11128-018-2082-8
[64] Z. C. Seskir et al., "Quantum games and interactive tools for quantum technologies outreach and education," Optical Engineering, vol. 61, no. 08, Jul. 2022, doi: https://doi.org/10.1117/1.oe.61.8.081809.
[65] R. Huffman, "Quantum art installation lands in New York City," Qiskit, Oct. 05, 2022. https://medium.com/qiskit/quantum-art-installation-lands-in-new-york-city-44edb8ea9291
[66] L. Nita, N. Chancellor, L. M. Smith, H. Cramman, and G. Dost, "Inclusive learning for quantum computing: supporting the aims of quantum literacy using the puzzle game Quantum Odyssey." arXiv, Jun. 13, 2021. doi: 10.48550/arXiv.2106.07077.
[67] M. L. Chiofalo, C. Foti, M. Michelini, L. Santi, and A. Stefanel, "Games for Teaching/Learning Quantum Mechanics: A Pilot Study with High-School Students," Education Sciences, vol. 12, no. 7, Art. no. 7, Jul. 2022, doi: 10.3390/educsci12070446.
[68] J. Wootton, "A quantum procedure for map generation." Accessed: May 24, 2024. [Online]. Available: https://arxiv.org/pdf/2005.10327
[69] Sanskriti Chitransh et al., "A Multidisciplinary, Artistic Approach to Broadening the Accessibility of Quantum Science," 2022 IEEE International Conference on Quantum Computing and Engineering (QCE), Sep. 2022, doi: https://doi.org/10.1109/qce53715.2022.00095.
[70] X. Gao et al. ,A quantum machine learning algorithm based on generative models.Sci. Adv.4,eaat9004(2018).DOI:10.1126/sciadv.aat9004
[71] "IonQ Harmony," IonQ. https://ionq.com/quantum-systems/harmony
[72] Z. Zhang, "ProjectKIVO/Quantum-Galaxies," GitHub, Oct. 04, 2022. https://github.com/ProjectKIVO/Quantum-Galaxies (accessed May 24, 2024).
[73] "Neural Network Classifier & Regressor - Qiskit Machine Learning 0.7.2," qiskit-community.github.io. https://qiskit-community.github.io/qiskit-machine-learning/tutorials/02_neural_network_classifier_and_regressor.html (accessed May 24, 2024).
[74] Blender Foundation, "blender.org - Home of the Blender project - Free and Open 3D Creation Software," blender.org, 2019. https://www.blender.org/
[75] "Unreal Engine — The most powerful real-time 3D creation platform," Epic Games. https://www.unrealengine.com
[76] IonQ — Trapped Ion Quantum Computing, "IonQ," IonQ, 2019. https://ionq.com/
[77] Marzec, M. (2016). Portfolio Optimization: Applications in Quantum Computing. In Handbook of High-Frequency Trading and Modeling in Finance (eds I. Florescu, M.C. Mariani, H.E. Stanley and F.G. Viens). https://doi.org/10.1002/9781118593486.ch4
[78] J. S. Otterbach et al., 'Unsupervised Machine Learning on a Hybrid Quantum Computer', arXiv [quant-ph]. 2017.
[79] O'Driscoll, L., Nichols, R. & Knott, P.A. A hybrid machine learning algorithm for designing quantum experiments. Quantum Mach. Intell. 1, 5–15 (2019). https://doi.org/10.1007/s42484-019-00003-8
[80] H. An, H. Owens, H. Ather, A. Shakouri, and M. Hosseini, "Intensity instability and correlation in amplified multimode wave mixing," Sci Rep, vol. 12, no. 1, p. 14784, Aug. 2022, doi: 10.1038/s41598-022-19051-5.
[81] H. Ather, H. An, H. Owens, S. Alajlouni, A. Shakouri, and M. Hosseini, "Quantum Sensing of Thermoreflectivity in Electronics," Phys. Rev. Appl., vol. 19, no. 4, p. 044040, Apr. 2023, doi: 10.1103/PhysRevApplied.19.044040.
[82] "Spring Conference Information - Office of Undergraduate Research - Purdue University," www.purdue.edu. https://www.purdue.edu/undergrad-research/conferences/spring/index.php (accessed May 27, 2024).
[83] "The MIT License," Open Source Initiative, Oct. 31, 2006. https://opensource.org/license/mit