Developing an Undergraduate Quantum Workforce

Dongyang Li
School of Industrial Engineering
Purdue University
West Lafayette, United States
lidongyang@purdue.edu

Priyam Gupta
Department of Computer Science
Purdue University
West Lafayette, United States
gupta751@purdue.edu

Yi Lin Yang
Department of Computer Science
Purdue University
West Lafayette, United States
yang2501@purdue.edu

Eric Christopher Broyles
School of Aeronautics and Astronautics
Purdue University
West Lafayette, United States
ebroyles@purdue.edu

Lakshay Goel
Elmore Family School of ECE
Purdue University
West Lafayette, United States
goel67@purdue.edu

Zirui Zhang
Department of Computer Science
Purdue University
West Lafayette, United States
zhan4192@purdue.edu

C. Robert Kenley
School of Industrial Engineering
Purdue University
West Lafayette, United States
kenley@purdue.edu

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***Abstract*—To fulfill the growing demand for the future workforce in quantum, we need to come up with workforce development programs at the undergraduate level. This paper reflects on discussions with industry professionals and academics that have indicated the need for a future quantum workforce, including all levels of post-secondary education, and it presents an exploration of an experiential learning pedagogy aimed at teaching quantum concepts to undergraduate students. The challenge is the intricate and often abstract domain of quantum mechanics. Due to their complexity, quantum concepts pose a unique challenge in educational settings, making hands-on demonstration and accessible understanding a formidable task. We review the pedagogical approach of project-based learning in The Quantum Game Club at Purdue, a student-led organization that is a community from diverse academic backgrounds, such as Computer Science, Physics, and Engineering, who work on fun and creative quantum computing projects. The club aims to introduce students to quantum and provide the necessary resources to work on projects by utilizing curated assignments that help students understand basic information about quantum circuits and algorithms. After the introductory learning phase, the students are assigned to different teams working on projects related to their interests. Club students successfully completed projects resulting in publications and web apps and went on to win quantum hackathons. To further enhance the learning experience, the VIP (Vertically Integrated Projects) team QuantAlgo was established to provide students with a more immersive industrial experience by facilitating collaboration with companies on more research-heavy projects.**

***Index Terms*—Quantum information science, Engineering education, Educational programs**

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I. Introduction

This paper presents an exploration of the experiential learning pedagogy aimed at teaching quantum concepts to people with little to no experience with quantum. The focus of the pedagogical approach is on fostering scientific literacy, critical thinking, and innovation through the intricate and often abstract domain of quantum mechanics. Quantum concepts pose a unique challenge in educational settings due to their complexity, making hands-on demonstration and accessible understanding a formidable task.

Innovation in Quantum Pedagogy, Application, and its Relation to Culture (IQ-PARC) is a team of Purdue faculty, graduate, and undergraduate students who collaborate and are funded by the National Defense Education Program (NDEP) for Science, Technology, Engineering, and Mathematics (STEM) education, outreach, and workforce initiative programs [1].

The IQ-PARC project supported the initiatives mentioned in this paper in an effort to provide training for Purdue students to prepare them for the future of quantum computing. The initiatives include the Quantum Game Club, which engages undergraduate students at Purdue University, and the Vertically Integrated Projects course offered at Purdue, which aims to educate interested students about quantum information and technology through peer-to-peer learning and both short and long-term projects centered on quantum computing [2].

II. Identifying the Gap

Successful methods for teaching quantum concepts have been documented in the literature [3]. It is important to make quantum concepts relevant to everyday events, through a combination of active learning strategies, reduced mathematical formulations, leading to more conceptual understanding.

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"Using strategies such as project-based, inquiry-based, hands-on experiment, and game-based learning to engage students [4]." An analysis of the literature review dataset was conducted using VOSviewer [5], revealing bibliometric networks in the literature related to teaching quantum concepts and workforce development. The literature reviewed is from Google Scholar searches using the keywords quantum games, quantum education, and quantum pedagogy. The search was broadened by applying the "related" feature to several top search results.

The entire text corpus of the abstract and keywords was processed using VOSviewer co-occurrence analysis. Figure 1 depicts VOSviewer's results, showing the topics that appear across a variety of studies and journal articles.

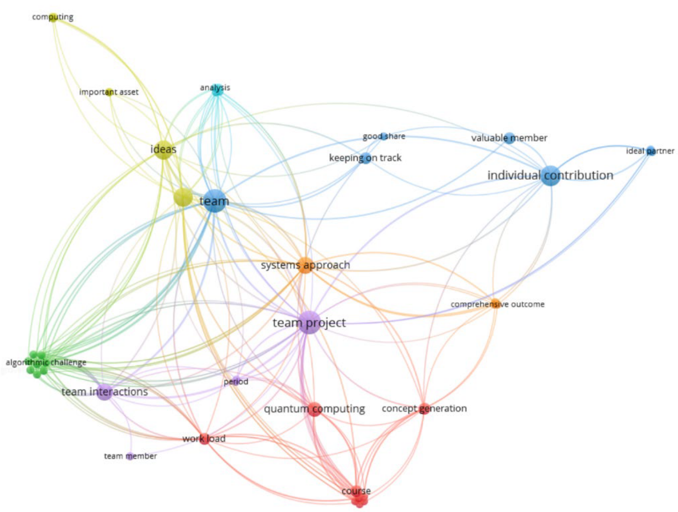


Fig. 1. Literature Review Visualization.

The authors had a round table discussion with industry and academic professionals involved in quantum education and workforce development. Based on the discussion, we identified three groups where quantum education could happen: (1) public outreach and broad awareness, (2) traditional education paths (K-12, undergraduate), and (3) current workers. The following topics were mentioned, and we have annotated them with literature that supports them.

- Access and Equity:
  A lot of companies have hands-on workshops, but they are not free nor available for everybody [6].
  Faculty indicates: Inclusive ecosystem, learn from failures from early computer science. Taking initiatives to encourage minorities to pursue quantum, giving them access [7].
- Lack of interest in Quantum Education:
  A faculty member researching quantum algorithm development mentioned that CS and engineering education still have huge gaps.
  No quantum computing education [8].
  One faculty member mentioned that the Quantum mechanics class in physics has only 5-6 students taking that course, which is a relatively low enrollment compared to a college physics class.
- Professors believe that Quantum is intimidating for undergraduates and need to show that it's not magic [9]. It just uses basic programming and linear algebra, basic knowledge.
- Professors indicate that there is a Lack of initiative by universities [10]. Value the teaching to the next generation of science (quantum computing community value is not good enough)
- More people need access to quantum education (at a wider level) [11]. Right now, only a few get highly specialized.
- Long term, we will need more people to build machines: technicians [12].

The discussions often mentioned gamified abstractions of physics, quantum, and computer science concepts, as games are helpful in recruiting students.

People from the industry indicate that they value student clubs greatly because students go out of their way to participate in quantum and are passionate about it. Companies prefer recruiting from a motivated pool of students who have experience in quantum.

From the discussions, we identified a gap in undergraduate-level quantum training to support the growing need for a quantum workforce.

III. Approaching the Problem Situation

The Quantum Game Club at Purdue was founded to provide a solution to the problem of quantum physics's steep learning curve. The club presents a novel approach as a multidisciplinary organization working on hands-on projects that help students understand concepts from physics, quantum physics, and computer science [13].

The club first provides a set of learning materials for newcomers. These include an introduction to quantum concepts and educational materials from industry, such as IBM Qiskit, that could be useful to students. After students are proficient with the basic quantum concepts, they become eligible to participate in a project group organized by the club and led by senior students, where they can contribute to research projects with real-life impact. There are multiple opportunities throughout the year for students to participate in team-building and hands-on activities, such as quantum hackathons, for which the club has won multiple first places at MIT [14] and recognition at Yale [15].

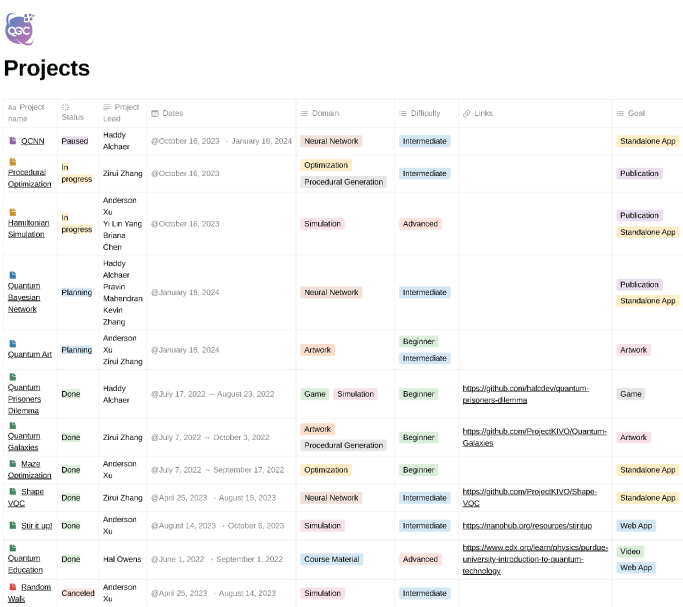
Inspired by the success and methodologies of the Quantum Game Club (QGC), a Vertically Integrated Projects (VIP) team named QuantAlgo was launched under the supervision of Prof. Hadiseh Alaeian [2]. QuantAlgo uses a more serious research-based approach to quantum computing. By collaborating on projects with companies like Xanadu Quantum Technologies [16], the project provided students with the opportunity to engage in high-level research and development. This partnership allowed students to work on cutting-edge quantum computing problems, enhancing their understanding and skills in this field. The practical experience gained through these collaborations not only prepares students for future careers in quantum technologies but also demonstrates the significant impact of integrating academic learning with real-world applications.

IV. RESULTS

A. Quantum Game Club learning outcomes

The Quantum Game Club mainly consists of undergraduate students majoring in Computer Science, Physics, and Electrical Computer Engineering. For the past academic year, they have been divided into three separate teams, each independently working on a separate Quantum project selected from the set of projects displayed in Figure 2.

Apart from the projects, the Quantum Game Club also offers students different academic and professional growth opportunities, including supporting travel to hackathons at the Chicago Quantum Exchange, MIT, and Yale Quantum Institute. Students also landed internships at companies collaborating with the IQ-PARC project. This is useful to show the importance of the Quantum Game Club being open and free to everyone.


Projects

Project name	Status	Project Lead	Dates	Domain	Difficulty	Links	Goal
QCNN	Paused	Haddy Alchaer	@October 16, 2023 → January 18, 2024	Neural Network	Intermediate		Standalone App
Procedural Optimization	In progress	Zirui Zhang	@October 16, 2023	Optimization, Procedural Generation	Intermediate		Publication
Hamiltonian Simulation	In progress	Anderson Xu, Yi Lin Yang, Briana Chen	@October 16, 2023	Simulation	Advanced		Publication, Standalone App
Quantum Bayesian Network	Planning	Haddy Alchaer, Pravin Mahendran, Kevin Zhang	@January 18, 2024	Neural Network	Intermediate		Publication, Standalone App
Quantum Art	Planning	Anderson Xu, Zirui Zhang	@January 18, 2024	Artwork	Beginner, Intermediate		Artwork
Quantum Prisoners Dilemma	Done	Haddy Alchaer	@July 17, 2022 → August 23, 2022	Game, Simulation	Beginner	https://github.com/halcdev/quantum-prisoners-dilemma	Game
Quantum Galaxies	Done	Zirui Zhang	@July 7, 2022 → October 3, 2022	Artwork, Procedural Generation	Beginner	https://github.com/ProjectKIVO/Quantum-Galaxies	Artwork
Maze Optimization	Done	Anderson Xu	@July 7, 2022 → September 17, 2022	Optimization	Beginner		Standalone App
Shape VQC	Done	Zirui Zhang	@April 25, 2023 → August 15, 2023	Neural Network	Intermediate	https://github.com/ProjectKIVO/Shape-VQC	Standalone App
Stir it up!	Done	Anderson Xu	@August 14, 2023 → October 6, 2023	Simulation	Intermediate	https://nanohub.org/resources/stiritup	Web App
Quantum Education	Done	Hal Owens	@June 1, 2022 → September 1, 2022	Course Material	Advanced	https://www.edx.org/learn/physics/purdue-university-introduction-to-quantum-technology	Video, Web App
Random Walk	Canceled	Anderson Xu	@April 25, 2023 → August 14, 2023	Simulation	Intermediate		

Fig. 2. Overview of Projects Within the Quantum Game Club.

It is important to give everyone a chance to develop skills without introducing financial barriers. The results of the past projects have been published in various research-focused publication services, including nanoHUB. Some of the projects were invited to be published in The Journal of Purdue Undergraduate Research (JPUR). Students were part of the teams that won the first place of IonQ and Quera's challenges at the MIT iQuHack quantum hackathon 2024. Club students got the honorable mention at Yale Quantum Hackathon 2024 for the Quantinuum challenge.

B. Integration of VIP Research Projects

The VIP program further enhances the hands-on research experience for undergraduate students by allowing them to engage in long-term, multidisciplinary projects over several semesters, thereby deepening their understanding and expertise in quantum computing and related fields.

In the QuantAlgo research team, students work on a variety of quantum projects, collaborating closely with Xanadu Quantum Technologies on multiple projects. One notable project undertaken by the QuantAlgo team is the extension of the existing Deutsch-Jozsa algorithm to qutrits, a type of quantum system based on three-level quantum states rather than the traditional two-level qubits [17]. The Deutsch-Jozsa algorithm is designed to determine whether a given function is constant (producing the same output for all inputs) or balanced (producing different outputs for different inputs) with a single query, showcasing the potential speedup of quantum algorithms over classical ones [18].

Algorithm 1 is the extension developed by the VIP students. It provides a concise summary of the Deutsch-Jozsa algorithm's main steps and functionality when extended to qutrits, and Figure 3 shows the corresponding circuit representation developed by the VIP students illustrating its implementation.

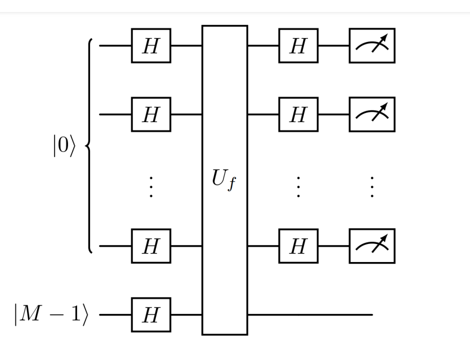


Fig. 3. Circuit Representation of the Deutsch-Jozsa Algorithm using Qutrits (M = 3 for qutrits.)

This project has yielded several interesting results, the most significant being that while the extended algorithm works fine with constant oracles, it does not perform as expected with balanced oracles. This unexpected outcome opens up new areas of discovery related to higher-dimensional systems, which are set to be further explored in collaboration with Xanadu in the upcoming semesters.

V. CONCLUSION AND FUTURE WORK

In the workforce round table discussion with industry partners, we identified issues and validated the approach of the club. This paper showcased the structure of the club and how it has helped club members in the pursuit of quantum professional opportunities.

Practitioners can apply the outcome of this study in their pursuit of a similar educational system that is structured

Algorithm 1 Deutsch-Jozsa Algorithm for Qutrits

Define the number of qutrits n.
Define the quantum device with $n + 1$ qutrits.
Define the CNOT gate for qutrits as a 9×9 matrix.
Define the Deutsch-Jozsa algorithm as a quantum node.
Initialize the output qutrit with T-Shift and T-Hadamard gates.
Initialize the input register with T-Hadamard gates for each qutrit.
Append the oracle gate:
if the case is "balanced" **then**
    Generate a random integer b and convert it to a base-3 string b_str.
    Apply T-Shift gates based on the digits in b_str.
    Apply the qutrit CNOT gate between each qutrit and the output qutrit.
    Apply T-Shift gates again based on the digits in b_str.
else if the case is "constant" **then**
    Generate a random output and apply T-Shift to the output qutrit if needed.
end if
Perform T-Hadamard gates again on each qutrit and measure the probabilities.
Run the algorithm for the desired case and store the result.
Display the probability distribution as a bar plot.

around a club approach and a VIP course research project. The implication of this study is to set an example of a successful implementation of teamwork, a hands-on approach, and an informal learning environment to promote quantum literacy at Purdue University.

Our findings indicate that the Quantum Game Club (QGC) has been instrumental in providing open and free access to quantum learning, significantly lowering financial barriers and fostering inclusive skill development. The projects undertaken by club members have not only provided practical experience but also led to substantial achievements, including hackathon wins, web app developments, and publications. This success underscores the importance of experiential learning and the positive impact of accessible educational resources.

In the future, we aim to foster a mutually beneficial exchange of ideas and expertise by integrating members of QGC into more research-focused projects alongside the QuantAlgo team. This collaboration not only enriches the research endeavors of QuantAlgo but also provides QGC members with valuable research experience and exposure to state-of-the-art quantum computing projects. The interesting results produced by projects like the VIP project on the Deutsch-Jozsa algorithm extension using qutrits will serve as a catalyst for initiating a collaborative environment between the Quantum Game Club (QGC) and the QuantAlgo VIP team.

We are constantly evolving the format of our approach. Future work includes collecting data from club participants and analyzing it to showcase statistical significance, which can include doing CATME peer review on project groups to evaluate effective teamwork and also comparing the results over semesters. CATME is a non-profit recharge center in the School of Engineering Education at Purdue University. The CATME system enhances team learning by teaching students how to contribute effectively to teamwork and creating accountability for team-member contributions [19] [20].

This paper lays the groundwork for the upcoming design of the data collection, and the subsequent data analysis will provide more insights into measuring the success of the initiative and point to the areas where more work can be done to support a future workforce in quantum information science.

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