WIP: *Building a Research Experience for Undergraduates in Quantum Machine Learning*

Jean Larson
Sustainable Engineering and the Built Environment
Arizona State University
Tempe, AZ
Jean.Larson@asu.edu

Deep Pujara
SenSIP Center, Electrical, Computer & Energy Engrg.
Arizona State University
Tempe, AZ
dpujara1@asu.edu

David Ramirez
SenSIP Center, Electrical, Computer & Energy Engrg.
Arizona State University
Tempe, AZ
dframire@asu.edu

Leslie Miller
SenSIP Center, Electrical, Computer & Energy Engrg.
Arizona State University
Tempe, AZ
lmille42@asu.edu

Tanay Patel
SenSIP Center, Electrical, Computer & Energy Engrg.
Arizona State University
Tempe, AZ
tpatel53@asu.edu

Niraj Anil Babar
SenSIP Center, Electrical, Computer & Energy Engrg.
Arizona State University
Tempe, AZ
nbabar@asu.edu

Andreas Spanias
SenSIP Center, Electrical, Computer & Energy Engrg.
Arizona State University
Tempe, AZ
spanias@asu.edu

***Abstract*—This work in progress research-to-practice study describes the development of a new undergraduate research training site on Quantum Machine Learning (QML), hosted at Arizona State University, a large Hispanic-Serving Institution. The objectives of this project are to a) recruit and prepare students from diverse pathways to increase representation of those traditionally underrepresented in QML research, b) increase awareness of career opportunities in the QML field, c) engage students in theoretical and experimental quantum information processing and machine learning (ML), d) motivate students to continue QML research into graduate school, and e) provide professional development training including presenting to stakeholders, developing publications/patents, and building an awareness on social implications, ethics, and privacy.**

The project adopts an integrative theory, application, and hands-on training approach by immersing undergraduate students in ML algorithm and quantum computing studies with hands-on quantum circuit design tasks. Participants are embedded in research labs, guided by graduate students and faculty mentors on quantum computing research studies.

The program is evaluated by both the Center for Evaluating the Research Pipeline (CERP) and an independent evaluator. Formative and summative assessments include pre- and post-surveys, a mid-point check-in survey, and a document review of program deliverables. Findings are described in a final evaluation report.

This paper describes the importance of introducing QML research at the undergraduate level, methods for recruiting a diverse group of participants, program format, research projects, and preliminary program evaluation results.

Keywords—undergraduate research, electrical engineering, quantum computing

I. Introduction

Participation in a research experience at the undergraduate level can strengthen a student's preparation for careers in various science, technology, engineering, and mathematics (STEM) fields [1]. The fields of Quantum Information Science (QIS) and Artificial Intelligence (AI) are recognized as important areas for research and workforce development, as evidenced by presidential-level announcements and significant corporate investments [2-4]. Quantum Computing (QC) has the potential to accelerate information processing relative to classical computers, providing efficient real-time solutions to computationally complex problems. Although access to quantum computers is currently limited and expensive, several organizations offer quantum simulators, including Amazon, Google, IBM, Microsoft, and Rigetti [5-12].

A new Research Experience for Undergraduates (REU) Site has been developed to bring this area of research related to quantum computing with an emphasis on quantum machine learning to undergraduate students. This program aims to immerse undergraduate students in QML projects, engage students in QML studies involving quantum noise and qubit precision tradeoffs, and provide skills in quantum simulation of signal processing and AI algorithms. Training and research activities for the program focus on the intersection of quantum information processing, ML, and signal/data classification (Fig. 1).

Fig. 1. *Quantum Computing, Bloch sphere, qubit and AI concepts promise improved speed in QML, Quantum AI implementations, signal classification, and big data processing.*

Fundamental research and education problems in this area include understanding the statistics of quantum bits (qubits), introducing quantum noise models, understanding tradeoffs between qubit precision and quantum noise, and provisions for access to facilities for quantum computing. Specific QML applications introduced to program participants include audio recognition, homomorphic encryption, PV fault detection, quantum Fourier transforms for QML feature extraction, and QML for radar imaging classification.

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II. BACKGROUND

The Quantum Machine Learning Algorithm Design and Implementation REU Site was awarded in early 2024 and hosted by the Sensor Signal and Information Processing (SenSIP) Center, an Industry/University Cooperative Research Center. The center operates as an industry-university consortium, and industry mentors will participate in the REU training process and serve as mentors on some projects. The Co-PIs recruited nine students from different universities and community colleges to spend the summer working in research laboratories on our campus.

A. *Student Recruitment*

The program seeks to broaden participation in engineering by targeting recruitment efforts at underrepresented groups (URGs) and supporting students from diverse educational backgrounds to enter engineering. Several strategies were used for recruitment, retention, and developing a pathway for REU graduates to graduate research. Applications for the program were collected through the NSF Education and Training Application (ETAP) portal. Additional questions were added to the ETAP to allow participants to share further information and aid in the selection process. To improve on the inclusiveness and equity of the selection process, a rubric was used, which helps prioritize students: 1) who had fewer opportunities for research at their home institutions, 2) demonstrated the ability to overcome adversity (whether academic or personal), and 3) who would contribute to the culture of inclusion and diversity at the REU Site through their unique life or academic experiences or their commitment to equity and justice. In addition to these questions, applicants included a personal statement, resume, unofficial transcripts, and a letter of recommendation. The REU program was advertised through various mechanisms, such as the National Broadening Participation Listserv, educational partner community colleges, and over 1000 engineering faculty contacts at Minority Serving Institutions nationwide.

B. *Student Selection*

Of the 315 applicants received through the ETAP portal, nine REU participants were selected. The applications were evaluated individually, after which the REU team held a meeting to finalize admissions. Selected students were interviewed and placed on projects. Several factors guided placement, including team building, diversity, inclusivity, and students' specific interests obtained from a statement of purpose and interviews.

Of the nine REU participants, three identified as female, and six identified as male. The group was made up of the following racial/ethnic identities: Native American (1), Asian (2), White (4), Other (1), Hispanic/Latino (4). Two participants received a Pell Grant, one has a moderate disability, and one is a first-generation student. The participants currently attend a variety of colleges and universities. Two students attend local Hispanic Serving community colleges (Phoenix College and Glendale Community College), two are currently attending Arizona State University (or will be transferring in the fall), and the others attend Massachusetts Institute of Technology, University of California Berkeley, Princeton University, University of Notre Dame, and Carnegie Melon University. The majors of the participants included computer science (4), electrical engineering (2), mathematics (1), and finally, two were double majoring in computer science – one with statistics and one with electrical engineering. Of the nine REU participants, six have never participated in undergraduate research, and zero have participated in an REU program.

C. *Format and Content*

REU participants were trained in designated project labs where they were provided guidance and freedom to develop and test ideas. The advisors established weekly milestones and an end goal, with the challenge of creating and understanding QML algorithm design and simulation emphasized in all projects. Faculty and graduate mentors guided students through experiments with quantum simulation circuits and analysis of data with QML and signal processing tools. The students used Python and quantum simulation platforms such as the IBM Quantum Computing Software Development Kit (QISKIT) [9,13]. REU students gained privileged access to quantum simulators and quantum hardware as ASU is an IBM Quantum Hub.

The QML program includes structured training with modules in quantum computing systems, including video-streamed modules on various quantum topics, quantum simulation software, and algorithm training with hands-on sessions.

1) Orientation Boot Camp: During the initial boot camp training, faculty provide an introductory theory module on QC by briefly introducing basics of the interaction of quantum objects (electrons, photons, etc.) and the notion of qubits. This module, which embeds an online boot camp tutorial, explains how qubit processing enables exponential growth in computing speed. It also gives examples of how a two-qubit processor enables four simultaneous computations by leveraging quantum mechanics principles of *superposition* and *entanglement*. The students then receive training through simple examples of qubit processing and its relation to QC in terms of quantum gates and circuits. Discussions include how quantum circuits are designed to realize quantum computations, which can be implemented on an IBM quantum simulator or on actual quantum hardware. Qualitative and graphical explanations of QC are provided, explaining *superposition*, *quantum measurement*, and *entanglement*. Faculty then introduce the notion of a quantum state, measurement uncertainty with noise, and how qubit computations and noise are modeled in modern quantum simulation models such as IBM's Qiskit. Quantum gates through quantum circuit examples are described [14-17], with a sequence of quantum gates and measurements. Elements of quantum circuits, qubit precision, and quantum noise are introduced. The quantum gates are described through quantum circuit examples with a sequence of quantum gates and measurements. The symbols H and Ry in Fig. 2 represent the quantum gates. The diagram shows that both qubits, q_0 and q_1, are measured. Elements of quantum circuits, qubit precision, and quantum noise are introduced.

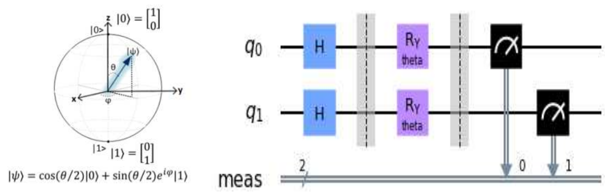

Fig. 2. *Qubit representation and Quantum circuit measurement.*

2) Research Projects: All projects have assigned faculty and graduate student mentors. Research projects have been inspired by previous studies and sponsored projects at the host university and other institutions [18-42]. Students report on their projects weekly to the research team and other program participants. Examples of the projects include:

a) Signal Analysis and Feature Extraction using the Quantum Fourier Transform (QFT): Quantum circuits (Fig. 3) are designed for a QFT and an inverse QFT (IQFT) and their effectiveness is tested with simulations on signal analysis and reconstruction for possible use in speech compression and recognition applications.

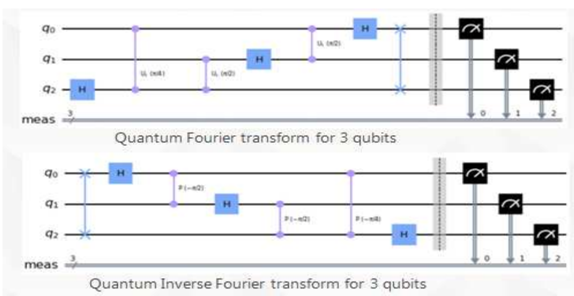

Fig. 3 The QFT and Inverse QFT simulation models.

b) QML for Audio Classification for Health Diagnostics: Students compute spectrograms using QFTs and then use Quantum Neural Networks (QNNs) to classify sounds.

c) Quantum Computing and Encryption Algorithms: An encryption scheme for a quantum perceptron is introduced for securing QNN parameters.

d) QML for Solar Array Fault Detection: Students study photovoltaic fault detection using a QNN simulation system and compare it against a classical computer NN simulation.

e) Quantum Linear Prediction of Speech: Students study how to design quantum linear prediction algorithms and evaluate them with speech signals.

f) Image Classification and Tumor Detection using ML: In collaboration with a teacher from a Research Experience for Teachers (RET) program, students focus on deep learning and QNN for tumor detection and SAR image classification applications.

g) Quantum Networking: Students learn to analyze quantum networks. They design and implement feedback control to compensate for polarization.

3) Deliverables: Throughout the program, students work with their mentors to complete several deliverables, including:

a) Weekly Updates: Due each Friday, students present 2-3 slides summarizing work completed and next steps.

b) Project Report: Students write a one-page project summary and expand it to a four-page IEEE-style report.

c) Research Poster: Using a provided template and training support, students develop a poster based on the research, which they present at an industry meeting.

d) Elevator Pitch: Students receive training and examples, and are supported in creating a one-slide elevator pitch.

e) Final Presentation: During the last week of the program, a final presentation (10 slides), including background, methods and materials, results, and discussion is shared.

III. Evaluation

An external evaluation team works with the REU faculty and staff to ensure program components are being implemented as described. Feedback loops are regularly instituted while activities are being delivered to address challenges as they occur and modify program elements to meet program requirements. Descriptive participant information and participation in activities will be reported.

A. Program Goals

The overarching goal of the QML REU Program is to create an inclusive culture to develop a globally competitive and innovative workforce that is knowledgeable in research related to quantum circuit design issues and QML algorithm functional operation. Through collaboration between faculty and graduate student mentors, engineering education experts, and industry partners, programming and activities are designed to motivate and educate students from all backgrounds and inspire a new generation of diverse and innovative engineers interested in pursuing graduate degrees and careers in QC and ML. The goals of the program include: 1) Providing integrative training in QML algorithm design and implementation, 2) Recruiting and training a culturally and gender diverse cohort of students, 3) Motivating students to pursue research careers that require graduate education in STEM, 4) Building awareness and skills in the areas of entrepreneurship, intellectual property, innovation, and industrial practice and ethics, 5) Offering a rich, mentored experience for students, and 6) Providing a high-quality research program.

B. Key Impact Outcomes

The QML REU Program aims to engage and prepare students through the following key impact outcomes: 1) Gain in knowledge and skills, 2) Demonstration of a diverse and inclusive culture in STEM, 3) Enrollment in STEM graduate program or career, 4) Preparedness to enter the engineering workforce, 5) Satisfaction with the quality of mentorship received during the program, and 6) Overall satisfaction with program experiences.

C. *Evaluation Questions*

Table I contains the evaluation questions, which have been aligned with the project goals and key impact outcomes.

TABLE I. EVALUATION QUESTIONS

Project Goal	Provide integrative training in QML algorithm design and implementation.
Impact Outcome	Gain in knowledge and skills
Evaluation Question	To what extent does the REU program provide strong QML skill building and research experience?
Project Goal	Recruit and train a culturally and gender-diverse cohort of students.
Impact Outcome	Demonstration of a diverse and inclusive culture in STEM
Evaluation Question	To what extent do the QML project teams include a diverse cohort of students?
Project Goal	Motivate REU students to pursue research careers that require graduate education in STEM.
Impact Outcome	Enrollment in STEM graduate program or career
Evaluation Question	To what extent are the REU participants considering/pursuing graduate school and a career in STEM?
Project Goal	Build awareness and skills in entrepreneurship, intellectual property, and ethical industrial practice.
Impact Outcome	Preparedness to enter the engineering workforce
Evaluation Question	To what extent do the students display interest in entrepreneurship and innovation?
Project Goal	Offer a rich, mentored experience for students.
Impact Outcome	Satisfaction with the quality of mentorship received during the program
Evaluation Question	To what extent are the students satisfied with the mentoring received?
Project Goal	Provide a high-quality research experience.
Impact Outcome	Overall satisfaction with program experiences
Evaluation Question	To what extent are the students satisfied with the quality of the program?

D. *Evaluation Methods*

As part of the REU Site, three surveys were conducted by the Center for Evaluating the Research Pipeline (CERP). Data collected from these surveys contributed to understanding how similar undergraduate research programs can direct participants' education and career pathways. Pre- and post-surveys were used to measure participant demographics and backgrounds, how students changed during the program, and perceptions of the overall REU experience. The pre-survey was administered on the program's first day, and students completed the post-survey once they completed the program. Program participants also completed a mid-point check-in survey halfway through the program to gather formative feedback to address any immediate needs. The program PIs and graduate student mentors completed a document review of all drafts and final deliverables.

IV. PRELIMINARY RESULTS

Formative feedback from the mid-point check-in survey, along with highlighted key findings, was shared with the program team after the first few weeks, so that any necessary changes could be made while the program was still in session.

The REU participants were satisfied with their experiences after a few weeks in the program. The survey data showed that 100% of the REU students were *satisfied* or *highly satisfied* with the following program activities so far, including the overall schedule of the program, collaboration with other participants, research experience, interaction with project staff, and interaction with their mentor. When asked about successful experiences, one student responded, "Developed new algorithm that shows promise." Another student responded, "I have learned a lot about quantum computing as a whole, and it is great to write quantum code that runs successfully. I have also had a positive experience working with my mentor to get code working." Students were then asked to describe any overwhelming experiences over the first few weeks. One student responded, "Sometimes I feel like I wish I knew more about quantum computing coming into the experience." Finally, students were asked to share anything that would improve their summer research experience. One student suggested, "I would say it would be helpful if we could have been provided with some quantum computing resources before the program."

Findings from the pre- and post-surveys, which include student characteristics, self-perceptions, skills and knowledge gained, support received, and future computing research interests and intentions will be shared in a final report provided by the evaluation team. Overall the first year of this summer experience worked out well in terms of research outcomes. Students presented their final reports around mid-July and submitted recently their final technical reports in IEEE format. Highlights of the technical presentations and a summary of research outcomes will be presented at the conference.

V. CONCLUSIONS AND NEXT STEPS

In this work in progress research-to-practice study, the data from the pre- and post-surveys conducted by CERP have yet to be shared. However, the mid-point check-in survey provided immediate feedback that could be addressed to improve the students' experience before the program ended. For example, the mentors reassured participants who were feeling insecure about lack of prior knowledge of quantum computing by providing additional lectures and/or recitations to clarify certain concepts. For the students feeling isolated, some projects that were similar in scope were able to be combined so students could collaborate together on the research.

Future analysis and reporting will focus on the program goals of providing integrative training in QML algorithm design, implementation, recruiting and training a diverse cohort of students, motivating students to pursue graduate school and research careers in the field, building awareness and skills in entrepreneurship and innovation, and providing a high-quality, mentored research experience for participants.

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