Proposal for Virtual Lab on Quantum Computing

Submitted by:
Dr. B. Rajathilagam
Department of Computer Science and Engineering
Amrita Vishwa Vidyapeetham, Coimbatore
b_rajathilagam@cb.amrita.edu
Contact: 9600648032

I. Objective

Quantum computing addresses challenging problems in chemistry, optimization, and machine learning, offering computation at higher speeds and reduced energy consumption. Major companies like Google, IBM, and Microsoft have made significant strides in this domain. Quantum technologies are forecasted to become a core innovation engine of the 21st century, with widespread industrial applications.

Despite the availability of simulators and online courses, no existing platform allows **step-by-step visualization of quantum algorithm execution**. This proposal aims to develop a **Quantum Computing Virtual Lab** to complement lectures and programming labs by allowing students to:

1. Visualize data representation in quantum computers.
2. Visualize quantum computations and algorithm execution.
3. Interactively run computations using multi-qubit configurations.
4. Explore quantum measurement techniques interactively.

Currently, vlab.co.in lacks a dedicated virtual lab for quantum computing. This lab fills that gap by providing interactive experiments in fundamental quantum principles and sample quantum programs.

II. List of Experiments

Experiment 1: Expectation Value Calculation in Quantum Systems

Aim:
To compute the expectation value of an observable for a given quantum state.

Objective:
Understand how to represent observables and quantum states and evaluate $\langle\psi|O|\psi\rangle$.

Simulation Steps:

- Input quantum state $|\psi\rangle$ and observable O (e.g., Pauli matrices).
- Simulate measurement probabilities.
- Display expected value using slider/toggle for basis change.

Learning Component:
Interactive Bloch sphere visualization and slider-based expectation computation.

Experiment 2: Factorization Using Shor's Algorithm

Aim:
To demonstrate integer factorization using a quantum algorithm.

Objective:
Understand the use of quantum Fourier transform and periodicity to solve factorization problems.

Simulation Steps:

- Select a number to factor.
- Visualize the superposition and modular exponentiation.
- Display classical post-processing step to derive factors.

Learning Component:
Step-by-step visualization of Shor's algorithm with circuit simulation.

Experiment 3: Variational Quantum Eigensolver (VQE) Optimization

Aim:
To compute ground state energy of a molecule using VQE.

Objective:
Understand hybrid quantum-classical optimization in chemistry.

Simulation Steps:

- Select a molecule (e.g., H_2).
- Show ansatz circuit and variational parameters.
- Visualize energy minimization via iteration.

Learning Component:
Energy vs. iteration plot and parameter tuning interface.

Experiment 4: Quantum Measurement and Result Interpretation

Aim:
To understand quantum measurement postulates and simulate output analysis.

Objective:
Demonstrate how measurement collapses a quantum state and how repeated runs yield probabilistic results.

Simulation Steps:

- Prepare quantum states.
- Choose measurement basis.
- Simulate repeated measurements and show histograms.

Learning Component:
Randomized sampling visualization and measurement statistics.

Experiment 5: Quantum Linear Algebra – Matrix and Vector Operations

Aim:
To simulate basic linear algebra operations (addition, multiplication, tensor product) in quantum computing.

Objective:
Understand how quantum gates are represented and how they operate on qubits using matrix algebra.

Simulation Steps:

- Choose gate matrices or vectors.
- Perform selected operations and view results.
- Visualize action of matrices on qubit states.

Learning Component:
Matrix operation calculator with gate transformation animation.

Experiment 6: Applied Linear Algebra – Quantum Gates in Action

Aim:
To apply linear algebra concepts to real quantum gates and circuits.

Objective:
Demonstrate unitary operations using sample circuits.

Simulation Steps:

- Select predefined circuits (e.g., Bell state, GHZ).
- Show matrix representation and transformation at each step.
- Visualize final state vector and measurement outcome.

Learning Component:
Matrix decomposition of quantum gates with simulation animation.

Experiment 7: Quantum Kernel Alignment in Machine Learning

Aim:
To visualize how quantum kernels can transform data into higher-dimensional spaces.

Objective:
Understand quantum kernel methods in ML classification.

Simulation Steps:

- Upload/choose a 2D dataset.
- Apply quantum feature maps.
- Visualize inner product matrix and kernel alignment score.

Learning Component:
Kernel matrix animation and accuracy comparison with classical kernel.

Experiment 8: Quantum Support Vector Machines (QSVM)

Aim:
To perform binary classification using QSVM.

Objective:
Explore how quantum computing enhances classical SVM.

Simulation Steps:

- Choose a dataset (e.g., XOR).
- Show quantum circuit-based feature mapping.
- Display margin, support vectors, and prediction accuracy.

Learning Component:
Real-time decision boundary visualization and prediction output.

III. Syllabi of Quantum Computing Courses in Other Institutions

1. **NEAT-AICTE** – Quantum Computing
2. **St. Petersburg University** – Quantum Computing: Less Formulas, More Understanding
3. **MOOC Platforms** – Courses from EdX, MIT, Coursera, FutureLearn, Udemy

---

IV. Existing Virtual Labs

- **IBM Quantum Lab:** https://quantum-computing.ibm.com/lab

V. Target Group of Users

- Undergraduate and Postgraduate students in Computer Science, Physics, and related disciplines.

VI. Student Feedback and Learning

1. Feedback Collection:

- Paper feedback forms during workshops.
- Online feedback integrated into each experiment.

2. Learning Components:

- Concept Definition & Procedure

- Concept Example (via animation and simulation)
- Concept Practice (Input exercises with Replay option)
- Reinforcement via Multiple Choice Quizzes

VII. Required Components for Virtual Experiments

1. **Online Manual:** Accessible via the lab's webpage.
2. **Step-by-step Procedure:** Included within the Concept Definition & Procedure section.
3. **Quiz for Self-Evaluation:** Three assessment strategies:

a) Pre-test

- 5 MCQs on prerequisites.
- **Feedback Strategy:**
  - 100%: Prompt to proceed.
  - <100%: Suggest review with learning resources. User can still continue if they choose.

b) Formative Assessments (End of Module Quizzes)

- 5 MCQs with immediate feedback on correct/incorrect choices.
- **Feedback Strategy:**
  - "Check Your Performance" option with progression advice based on score.

c) Post-assessment

- 5 MCQs covering all modules.
- **Feedback Strategy:**
  - 100%: Congratulatory message.
  - 80%: Positive reinforcement with suggestion to review.
  - <80%: Encouraged to review and reattempt.

This virtual lab aims to build conceptual clarity through **guided simulations**, **interactive visualizations**, and **practice-based learning**, bridging the gap between quantum theory and practical implementation.