Spring 2025 CSE/CEN 598, CSE 494

Special Topics: Quantum Computation

with focus on Quantum Machine Learning

Contact Information

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Office Hours

- T.B.D

Course Description

This course provides an introduction to Quantum Computing (QC), the mathematical framework behind classical machine learning (ML), and combines them to teach Quantum Machine Learning (QML).

Prerequisites:

There are no prerequisites for the course, but background in the following would be useful in better learning.

- **Linear Algebra:** A strong foundation in linear algebra, including vectors, matrices, determinants, eigenvalues, and eigenvectors, is essential.
- **Probability and Statistics:** Familiarity with probability theory, statistical distributions, and basic statistical inference is necessary.
- **Programming:** Proficiency in a programming language like Python is recommended, as it is widely used in quantum computing and machine learning.
- **Classical Machine Learning:** A foundational understanding of classical machine learning algorithms and techniques (e.g., linear regression, logistic regression, neural networks) would be beneficial.
- **Basic Complex Analysis:** Familiarity with complex numbers and their properties will be valuable.

Course Objective:

1. Understand the postulates of quantum mechanics.
2. Understand the working of single and multi-qubit systems.

3. Understand the bra-ket notation, bloch sphere, and state vector representation of quantum state.
4. Understand single-bit and multi-bit quantum gates, their matrix representations and universality of Pauli + CNOT gates.
5. Understand the basic concepts of superposition, entanglement, reversibility, and measurement.
6. Understand some of the basic quantum computing algorithms.
7. Understand Quantum feature spaces and main methods of data encoding.
8. Understand variational gates, function approximation, state similarity measurements, and gradient calculations in quantum circuits.
9. Understand data re-uploading, quantum kernels and Quantum generative models.
10. Understand the basics of adiabatic quantum computing.

Learning Outcomes:

Upon completion of this course, students will be able to -

- Explain the main physics experiments that helped develop quantum physics and understand the postulates of quantum computing.
- Demonstrate the evolution of quantum states in single-bit and multi-bit quantum circuits.
- Demonstrate understanding and operation of the main quantum computing algorithms.
- Explain the main sources of noise in quantum computation, and why NISQ devices exist.
- Explain the main methods of classical data encoding into quantum circuits.
- Demonstrate understanding of main quantum machine learning algorithms, including variational quantum circuits, data re-uploading, quantum kernels and quantum generative models.

Grade Components:

- Assignments (Math + Coding) - 40 pts
- Topic Presentation – 10 pts
- Finals (Open Book) - 30 pts
- Quizzes (In Class) - 20 pts
- Extra Credit Quizzes (In Class) - Pts T.B.D

Grade Policies:

The letter grade will be calculated using this formula

>=90 pts → A
>=80 pts , <90 pts → B
>=70 pts , <80 pts → C
>=60 pts , <70 pts → D
<60 pts → E

The +/- at each letter grade will depend on the score distribution in the letter grade.

Reference Materials :

QML Reading List

Absence Policies:

1. In general, no late submission of assignments will be accepted unless there is a genuine emergency backed up by official documents (such as a physician's note attesting the same).
2. Excused late submission related to religious observances/practices that are in accord with ACD 304-04, "Accommodation for Religious Practices".
3. Excused late submission related to university sanctioned events/activities that are in accord with ACD 304-02, "Missed Classes Due to University-Sanctioned Activities".
4. Excused late submission related to missed class due to military line-of- activities that are in accord with ACD 304–11, "Missed Class Due to Military Line-of-Duty Activities," and SSM 201–18, "Accommodating Active Duty Military".

List of Topics (subject to change):

1. **Quantum Mechanics**
    - 1.1. Stern Gerlach
    - 1.2. Mach-Zehnder Interferometer
    - 1.3. Postulates of Quantum Mechanics
    - 1.4. Schrodinger’s Equation
    - 1.5. X, P commutators and Heisenberger’s principle
    - 1.6. E-V Bomb
2. **Quantum Computation**
    - 2.1. Single Qubit Systems
        - 2.1.1. What is a qubit
        - 2.1.2. Superposition
        - 2.1.3. Braket Notation and Polar Form
            - 2.1.3.1. State vector form
            - 2.1.3.2. Probability Amplitudes (The Born Rule) [With proof]
        - 2.1.4. Bloch Sphere and 2-D plane
    - 2.2. Measurement I:
        - 2.2.1. The Measurement Postulate - State collapse on measurement
        - 2.2.2. Statistical Measurement
            - 2.2.2.1. QCs as a probability distribution
            - 2.2.2.2. Probability from sampling
    - 2.3. Single Qubit Gates
        - 2.3.1. Rotate-Compute-Rotate
        - 2.3.2. Unitary Gate Computation
        - 2.3.3. Universality of Pauli-Rotations
    - 2.4. Multi Qubit System I:
        - 2.4.1. Multi qubit superposition via tensor product.
        - 2.4.2. Multi-qubit gates
            - 2.4.2.1. Native (CNOT)
            - 2.4.2.2. Single qubit gate composition
            - 2.4.2.3. Pauli + CNOT Universality
        - 2.4.3. Deutsch-Jonza Experiment
        - 2.4.4. No Cloning Theorem
    - 2.5. Entanglement
        - 2.5.1. Bell States
        - 2.5.2. Density Matrices
        - 2.5.3. Mixed States
        - 2.5.4. Quantum Teleportation
    - 2.6. Measurement II:
        - 2.6.1. Quantum Operators
        - 2.6.2. Projective measurement

2.6.3. Positive-Operator-Valued Measures
2.6.4. Measurement in Arbitrary Basis
2.7. Quantum Algorithms:
2.7.1. Simons Algorithm
2.7.2. Grovers Algorithm
2.7.3. QFT
2.8. Quantum Errors and NISQ Devices

3. **Quantum Machine Learning**
3.1. Classical ML Background:
3.1.1. Vector Spaces
3.1.2. Distance Metrics
3.1.3. Kernel Classification
3.1.4. Single layer classifier
3.2. Quantum Feature Spaces:
3.2.1. Hilbert Space
3.2.2. Classification spaces
3.3. Classical Data Encoding:
3.3.1. Basis Encoding
3.3.2. Amplitude Encoding
3.3.3. Rotational Encoding
3.3.4. Comparing them
3.4. Variational Gates
3.4.1. Classically parameterized gates
3.4.2. Function Approximation
3.4.3. Intractable circuits.
3.4.4. Effect of entanglement
3.4.5. State Similarity Measurement:
3.4.5.1. SWAP Test
3.4.5.2. Inversion Test
3.5. Gradients:
3.5.1. Classical Gradients
3.5.2. Backpropagation - Computational graph
3.5.3. No-Cloning = No Backprop
3.5.4. Gradients on real devices:
3.5.4.1. Finite Difference
3.5.4.2. Parameter Shift
3.6. Data Re-Uploading
3.6.1. Single Qubit universal classifier
3.6.2. Weighted re-uploading
3.6.3. Multi-Qubit extension
3.6.4. Effect of Entanglement

3.7. Quantum Kernels
  3.7.1. Quantum Kernel Maps (QKM)
  3.7.2. Variational Models and Kernel Learning
  3.7.3. Exponentiality of QKM
3.8. Quantum Generative Models
  3.8.1. Intro
  3.8.2. Significance
  3.8.3. Q-VAE
  3.8.4. Q-GANs
3.9. Adiabatic Quantum Computing
  3.9.1. Time Evolution
  3.9.2. Quantum Annealing
  3.9.3. QAOA

4. **Topic Presentation** [Team Presentations]
  4.1. Post-variational quantum neural networks
  4.2. Quantum generative adversarial networks
  4.3. Learning to learn with quantum neural networks
  4.4. Approximating a classical kernel with a quantum computer
  4.5. Introduction to Geometric Quantum Machine Learning
  4.6. Multidimensional regression with a variational quantum circuit
  4.7. Why measuring performance is our biggest blind spot in quantum machine learning
  4.8. How to do measurements in PennyLane
  4.9. How to parallelize QNode execution
  4.10. How to simulate noise with PennyLane
  4.11. How to use noise models in PennyLane

Academic Honesty

This is a research-oriented course where collaboration is welcomed. But provide credit where it's due. Plagiarism or any form of cheating in assignments or projects is subject to serious academic penalties. To understand your responsibilities as a student read: ASU Student Code of Conduct and ASU Student Academic Integrity Policy. You may engage in intellectual discussions about reading assignments with your peers or course TAs/instructor, but all submissions must be your own, based on your understanding of the content. Your project report will resemble academic scholarly articles, where you must credit all sources, including your partners in brainstorming, published papers, and existing code repositories (e.g., from stackoverflow or github) that you have used in your implementation. Posting your projects online, including using a public Github repo, is expressly forbidden. The Github Student Developer Pack provides unlimited private repositories while you are a student.

Title IX

Title IX is a federal law that provides that no person be excluded on the basis of sex from participation in, be denied benefits of, or be subjected to discrimination under any education program or activity. Both Title IX and university policy make clear that sexual violence and harassment based on sex is prohibited. An individual who believes they have been subjected to sexual violence or harassed on the basis of sex can seek support, including counseling and academic support, from the university. If you or someone you know has been harassed on the basis of sex or sexually assaulted, you can find information and resources at https://sexualviolenceprevention.asu.edu/faqs. As mandated reporters, we are obligated to report any information we become aware of regarding alleged acts of sexual discrimination, including sexual violence and dating violence. ASU Counseling Services (https://eoss.asu.edu/counseling) is available if you wish to discuss any concerns confidentially and privately. ASU online students may access 360 Life Services at https://goto.asuonline.asu.edu/success/online-resources.html.

Policy against threatening behavior, per the Student Services Manual, SSM 104-02

Students, faculty, staff, and other individuals do not have an unqualified right of access to university grounds, property, or services. Interfering with the peaceful conduct of university-related business or activities or remaining on campus grounds after a request to leave may be considered a crime. All incidents and allegations of violent or threatening conduct by an ASU student (whether on- or off-campus) must be reported to the ASU Police Department (ASU PD) and the Office of the Dean of Students.