MATH 595: Quantum Learning Theory

Spring 2026 — University of Illinois, Urbana-Champaign

Instructor: Jacob Beckey (jbeckey@illinois.edu)

Meeting Times: Tues/Thurs, 3:30-4:50pm, 132 Davenport Hall

Course Overview

This course will survey the burgeoning field of *quantum learning theory* (QLT) which lies at the intersection of mathematics, theoretical computer science, and quantum information theory. This an exciting and extremely active subfield of theoretical computer science and quantum information theory. QLT can be viewed as a quantum generalization of classical statistical learning theory, and many of these connections will be made throughout the course. At its core, the goal of QLT is to quantify the resources (samples, measurements, memory, time, etc) needed to test or learn a desired quantity. In this course, we will place a particular emphasis on understanding the effects that randomness, adaptivity, and measurement restrictions have on the sample complexity of various quantum state learning and testing tasks.

The goal of this course is *not* to give a comprehensive review of the entire field, but to help students deeply understand a subset of carefully selected, canonical testing/learning problems and the associated mathematical techniques. Thus, in the first half of the course, we will focus primarily on important results in state discrimination, quantum state tomography, shadow tomography, and property testing. Then, in the second half we will cover more recent results in the field and discuss open problems. All students will do a final project that distills a QLT paper into a guided tutorial-style problem that their peers could complete by that point in the course, highlighting open questions left by the paper. The hope is that motivated students may use this course as a starting point for conducting research in the field.

Prerequisites

- **(Required)** Math 416 Abstract Linear Algebra (or equivalent)

- **(Preferred)** Intro to Quantum Mechanics/Information (e.g. Phys 486/487, Phys 513, or ECE 404)

- **(Preferred)** Math 595 Representation-theoretic methods in quantum information

Course Outline

- Quantum State Discrimination

    - Quantum info crash course
    - Quantum state discrimination

- Quantum State Tomography

    - Representation theory crash course
    - Mixed state tomography with multi-copy measurements
    - Mixed state tomography with restricted measurements

- Shadow Tomography

    - Classical shadow tomography
    - Exponential separations in classical shadow tomography
    - Summary of applications and open questions

- Quantum Property Testing

    - State certification
    - Purity testing
    - Exponential separations in purity testing
    - Entanglement testing

- Open problems and class-voted topics

Assignments and Grading

There will be no mandatory homework or exams. We will work through tutorial-style problems in some classes and optional problem sheets to solidify core concepts will be provided. Grading will be based upon a final group project.

Literature

- John Wright's *Quantum Learning Theory* course notes. Taught Spring 2024 at UC Berkeley. Available online.

- Sitan Chen and Jordan Cotler's *Quantum Learning Theory* course notes. Taught Fall 2025 at Harvard. Available online.

- Ashley Montanaro and Ronald de Wolf. *A Survey of Quantum Property Testing.* Theory of Computing Graduate Surveys 7, 2016. Available online.

- Anurag Anshu and Srinivasan Arunachalam. *A Survey on the Complexity of Learning Quantum States.* Nature Reviews Physics. January 2024. Available online.

- Felix Ledizky's *Representation-theoretic methods in quantum information theory* course notes. Available online.

- Antonio Anna Mele. *Introduction to Haar Measure Tools in Quantum Information: A Beginner's Tutorial.* July 2023. Available online.

Classroom Climate, Inclusivity, and Anti-Harassment

People learn mathematics best when they feel respected and comfortable asking questions. In this course, we are committed to creating a supportive environment where everyone can engage fully in discourse and grow as mathematical thinkers.

Expectations for Our Classroom Community

- All students are expected to treat one another with respect, patience, and kindness in class discussions, group work, and online communication.

- Questions, confusion, and mistakes are a normal and valuable part of learning mathematics. We will celebrate curiosity and persistence, not just quick answers.

- Disruptive, dismissive, or disrespectful behavior (including but not limited to harassment based on race, gender, sexual orientation, religion, ability, or background) will not be tolerated.

Commitment to Inclusivity

- Our classroom welcomes students from all backgrounds and levels of preparation.

- Diversity of perspectives strengthens mathematical conversations, and your contributions are valued.

- If something in the course environment makes it harder for you to participate or feel included, I encourage you to let me know so we can work together to address it.