Physics 272 / CS 2233 – Quantum Learning Theory (Fall ’25)

Schedule	MW 3:00 - 4:15, Pierce 209
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Course page	`https://harvard-quantum-learning.github.io/`
Canvas	`https://canvas.harvard.edu/courses/158126`
Gradescope	`https://www.gradescope.com/courses/1113067`
Edstem	`https://edstem.org/us/courses/85742/`

Course Description and Learning Objectives

This course covers *quantum learning theory*, a contemporary subject at the intersection of quantum mechanics, quantum computing, statistical learning theory, and machine learning. The core question of the subject is: how can we use quantum computation to efficiently learn properties of quantum mechanical systems? Answering this question helps us understand the power of quantum computers in assisting experimental physicists with studying quantum materials and quantum chemical systems, while also providing valuable tools for quantum machine learning to develop algorithms based on quantum data. Quantum learning theory has become a core subject in quantum information and computation, and this course is one of the first of its kind to present quantum learning theory in its entirety. We will explore the theory of learning quantum states and quantum dynamics, the theory of quantum memory and quantum replica-learning, random and pseudo-random quantum circuits, and many applications to quantum many-body physics.

The following is a tentative schedule, with each bullet point corresponding to a 75-minute lecture.

(1) **Introduction and toolkit**
- (A) Vignette: Learning an unknown rotation
- (B) Quantum basics I (states, channels, measurements, circuits, Hamiltonians, goals)
- (C) Quantum basics II (tensor networks)

(2) **Learning general quantum states**
- (A) State tomography I: Pauli measurement protocol
- (B) State tomography II: optimal bounds via representation theory
- (C) Shadow tomography I: classical shadows
- (D) Shadow tomography II: online learning

(3) **Learning structured quantum states**
- (A) Gibbs states I: high temperature
- (B) Gibbs states II: low temperature
- (C) Shallow circuit states I: local inversion, 2D
- (D) Shallow circuit states II: three and higher dimensions
- (E) Stabilizer states, Bell difference sampling
- (F) Agnostic tomography

(4) **Learning quantum channels**
- (A) Noise characterization I: Pauli channel estimation
- (B) Noise characterization II: gate set tomography
- (C) Learning shallow quantum circuits

  (D) Learning from time evolution I: basics, Heisenberg limit
  (E) Learning from time evolution II: Heisenberg limit cont'd
(5) **Lower bounds**
  (A) Quantum memory I: probability basics, learning tree, Pauli shadows separations
  (B) Quantum memory II: entangled versus unentangled protocols for tomography
  (C) Quantum memory III: replica complexity
(6) **Quantum pseudorandomness**
  (A) Designs and pseudorandomness I: random quantum circuits and unitary designs
  (B) Designs and pseudorandomness II: pseudorandom states and computational hardness
  (C) Designs and pseudorandomness III: pseudorandom unitaries and applications

The goal is that by the end of the course, students will be sufficiently up to date with the modern literature on quantum learning theory that they are ready to engage in original research.

Prerequisites

Strong mathematical maturity and proficiency with proofs, probability at the level of Stat 110, and linear algebra are required. Prior exposure to quantum mechanics or quantum computing, e.g. at the level of Physics 143a or QSE 210a / Physics 260a, strongly encouraged but not required.

Course Materials

The schedule on the course webpage will include a list of relevant papers for each lecture, as well as a set of preliminary lecture notes and/or slides. We will not be following any particular textbook.

Course Format

Each class will feature a combination of slides and blackboard lecture.

The Teaching Fellows will also hold a weekly section, which will provide students the opportunity to ask more questions and explore additional examples of the concepts covered in the course.

Coursework and Grading

- 20% class participation
- 80% problem sets

The pacing and content of the lectures will be guided by student questions and comments, so it is heavily encouraged for students to ask questions not just about technical steps in the proofs presented but also about the overarching context and modeling assumptions implicit in the material. Class participation will be evaluated holistically based on the student's level of engagement in these class discussions, as well as discussions on Ed. **In-person attendance at lectures is mandatory to receive full participation credit.** In the event of unavoidable conflicts (illness, travel, etc.), the student will not be penalized provided that they write to the instructors prior to the lecture in question.

The problem sets will be challenging, so you are encouraged to start them early. There will be ample opportunities for extra credit in the form of submitting suggestions for exercises as well as substantive edits of the lecture notes.

Expections and Course Policies

- **Laptop policy**: Since laptops tend to be distracting and dampen class participation, the use of laptops in class is not permitted. Students who need to use a laptop in class for accessibility reasons should contact the instructor for approval. Tablet devices like iPads are generally allowed without prior approval if they are used exclusively for handwriting with a stylus.
- **Office hours** are optional but intended for students both to get help with coursework and to engage more deeply with the material.

- **Assignments and collaboration policy:** All assignments will be submitted on Gradescope, so students should either have a scanner available or become familiar with LaTeX.

  The student is responsible for understanding Harvard policies on academic integrity. For problem sets, students are encouraged to collaborate with each other, but they must write their final solutions independently and list their collaborators in their submissions. For all assignments, it is acceptable to consult outside sources, but the student must cite whatever is used and synthesize the information in these references in their own words. Use of generative AI for assignments is strongly discouraged, but if the student chooses to use it, they must provide a full transcript of the prompts used and write the final solutions in their own words.
- **Late days:** Students have **8** late days in total for the semester, which may be used for the problem sets. For exceptions beyond this, students must have their senior tutor (for undergrads) or their advisor (for graduate students) contact me.
- **Accommodation requests:** We acknowledge the value of every individual's unique perspective and experiences. If you ever feel hesitant to share your thoughts openly in class, or if something was said in class that made you uncomfortable (either by us or anyone else), please do not hesitate to reach out. The same goes if you find that external experiences are impacting or have the potential to impact your performance in the course. The University Disability Office also offers accommodations and services for students with documented disabilities. We will do our best to create an inclusive and supporting learning environment that respects accessibility and promotes diversity, inclusion, and belonging, and we welcome any and all feedback if you feel there are areas in which we can improve.
- **Student well-being:** We deeply care about your physical and mental well-being. In case you run into any problems in this course or feel that you are falling behind due to external circumstances, please don't hesitate to reach out to the course staff or your resident dean. Other resources we recommend taking advantage of in such cases include Harvard services such as Counseling and Mental Health Services, Room 13, and the Academic Resource Center. Additionally, if you have a serious emergency, medical or otherwise, please contact the instructor. In all of these cases, we will make sure to accommodate you as best as possible.