Frontiers of Quantum Complexity

CS 598QC (Spring 2024)

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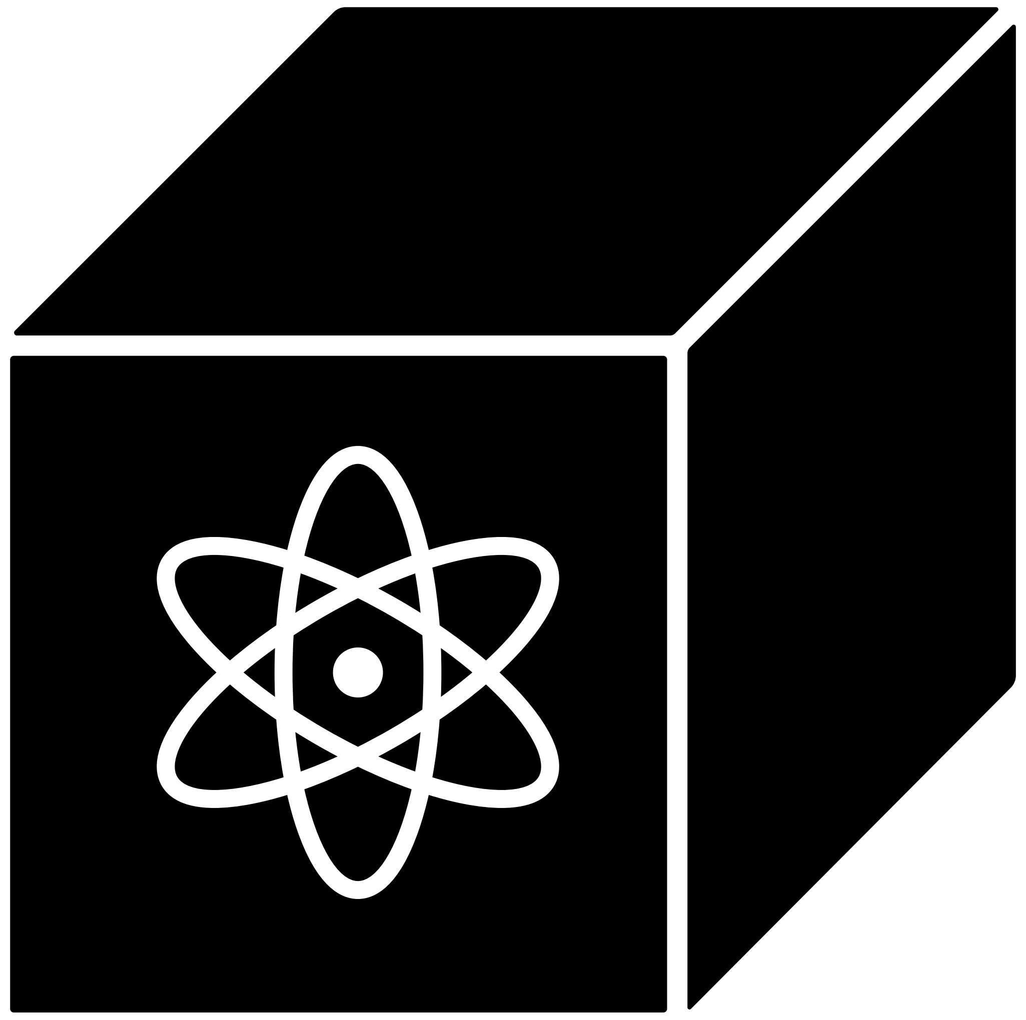


What is this course about?

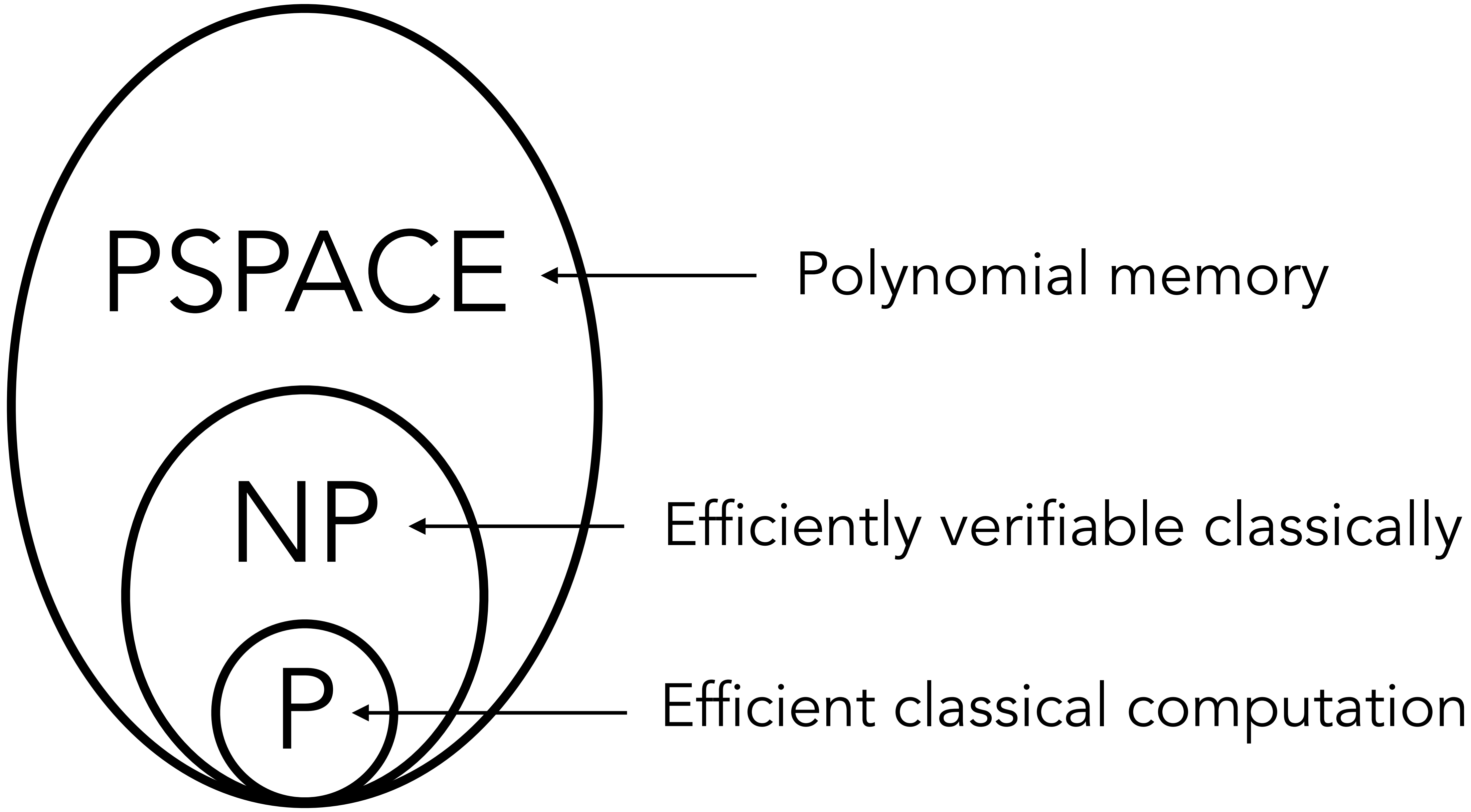
What are the fundamental capabilities of quantum computers?

- Research-level course covering emerging topics
- Very theoretical, math-based course!

Complexity Theory

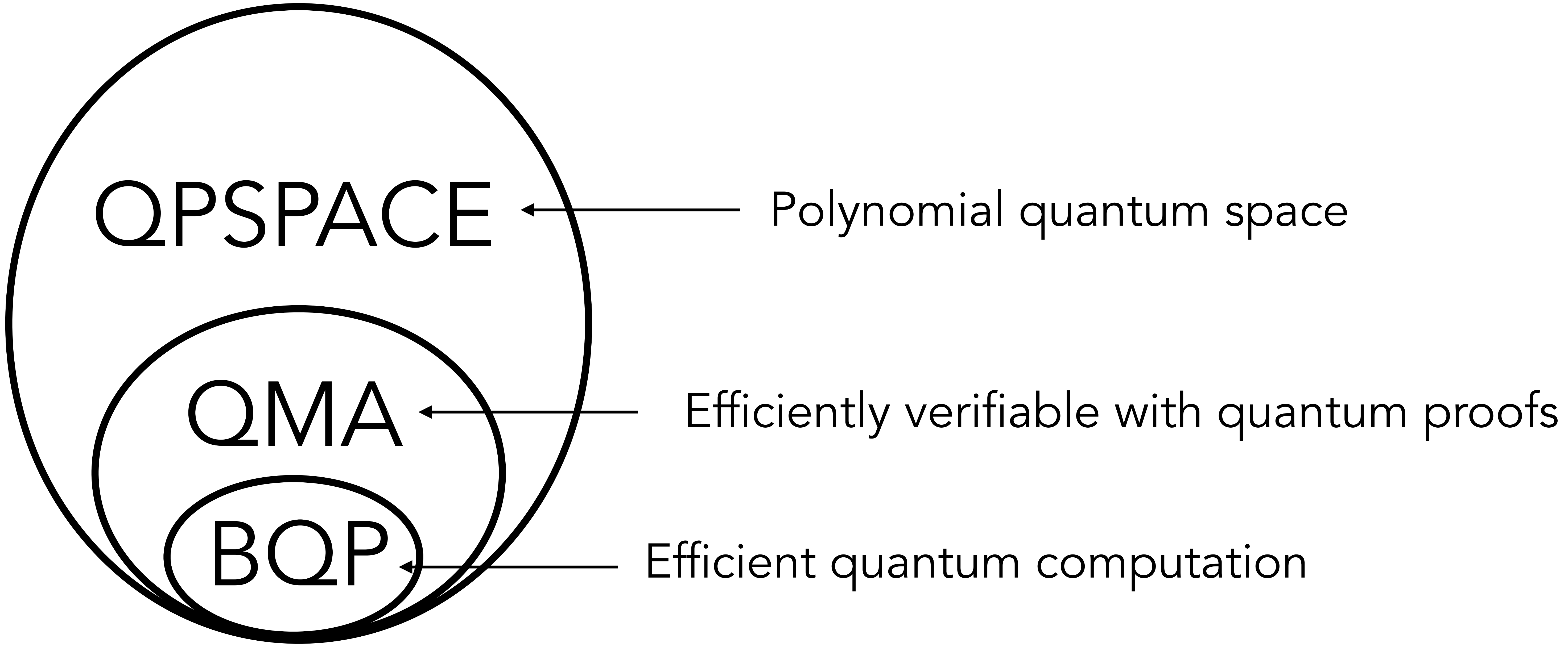
Study of computational resources needed
to solve different problems

Time? Memory?
Randomness?
Proofs? Interaction?



Quantum Complexity Theory

Understand the difficulty of solving problems with quantum resources (e.g. quantum computers, entanglement) vs classical resources



Fundamental Themes

Quantum Advantage

Quantum Proofs

Description of Physical systems

Quantum Pseduorandomness

Quantum Advantage

What problems have efficient quantum algorithms but not classical ones?

BQP vs classical complexity classes

Random circuit/ boson sampling

Do quantum speedups need structure?

Quantum Proofs

What is the power of a quantum witness?

QMA and its properties

Local Hamiltonian Problem

Friends of QMA

Description of Physical systems

Are ground states of Local Hamiltonians easy to describe?

Quantum PCP Conjecture

NLTS Conjecture

Area Laws

Quantum Pseudorandomness

How to efficiently construct quantum states and transformations that look random?

Pseudorandom States

Quantum Cryptography

Black Holes and Quantum Gravity

What this class is not

- Not an introduction to quantum computing or quantum information

  Take "**CS 498QC: Introduction to Quantum Computing**" instead!

- How to build or program a quantum computer

  Look at ECE or physics courses

- Not a course to learn quantum physics

Prerequisites

- **Basic Linear Algebra** Essential

  Vector space (subspaces, orthogonal complements, dimension, linear independence, basis, span,…). Inner products. Row vs column vectors. Linear operators (invertibility, matrix representation, composition of linear operators, transpose, adjoint). Eigenvalues and eigenvectors. Trace.

- **Basic Probability Theory** Essential

  Bayes' rule, conditional distributions. Joint probability spaces. Independent random variables. Mean, variance, etc. Normal distribution.

- **Theoretical Computer Science** Important

  Analysis and design of algorithms. Complexity theory. Discrete math.

Target Audience

- **Who this class is intended for**
  - Graduate students, postdocs, faculty, undergrads doing research in quantum information and theoretical computer science
  - People with a solid background in linear algebra, probability and higher-level mathematics
  - People who want to learn about the **frontiers** of quantum complexity

Expectations

- Most of the content exists in research papers

  One of the goals of the course is to distill out ideas from papers and produce lecture notes

  You will already be contributing to research by scribing lectures!

- Material spans many different mathematical fields

  We will introduce the minimal background to discuss the results and key ideas

  Discuss and read supplementary material to internalize ideas and fill in background knowledge

- We might omit some of the technical details for the more complicated topics or skip some of the topics listed

Grading

- **Homeworks 40%**

  3 to 4 Homeworks

  - Homework questions released on a rolling basis after each lecture/topic
  - Typeset submissions in groups of 3-5
  - 3 late submission tokens: extend deadline by 24 hours
  - Probabilistically checkable grading

- **Scribe 10%**

  Each student scribes one lecture and edits/proofreads one more

- **Participation 10%**

  Participate in student discussion groups weekly

- **Final Project 40%**

  Read a research paper/Work on a research problem

  Write a report and possibly give a short talk

Class Resources

- **Course Webpage:** https://courses.grainger.illinois.edu/cs598qc

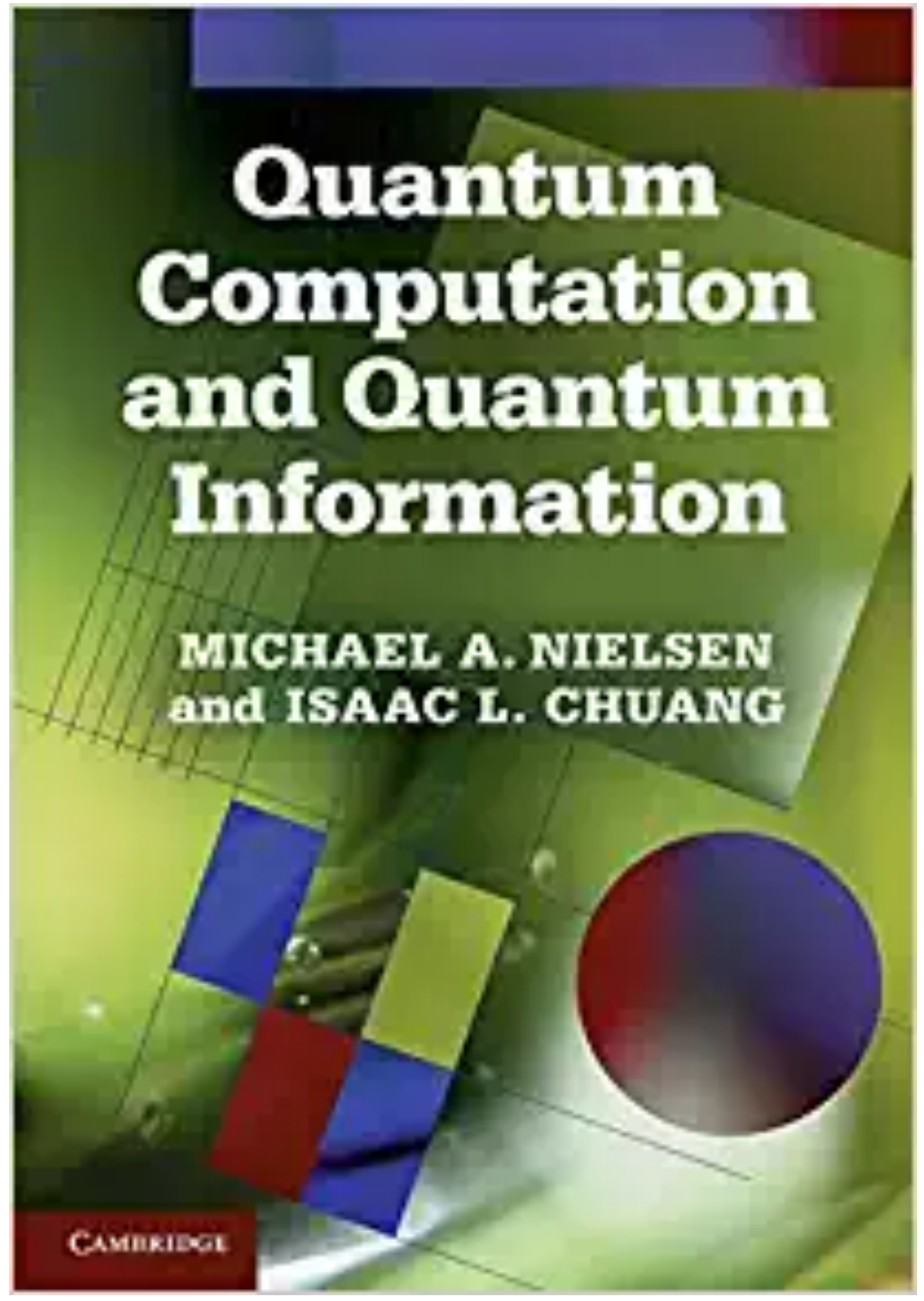
Basic Information
Lecture Notes
Additional Resources

- **Recordings:** Mediaspace
- **Course Announcements, Policies, Homework, Q&A posted on EdStem**

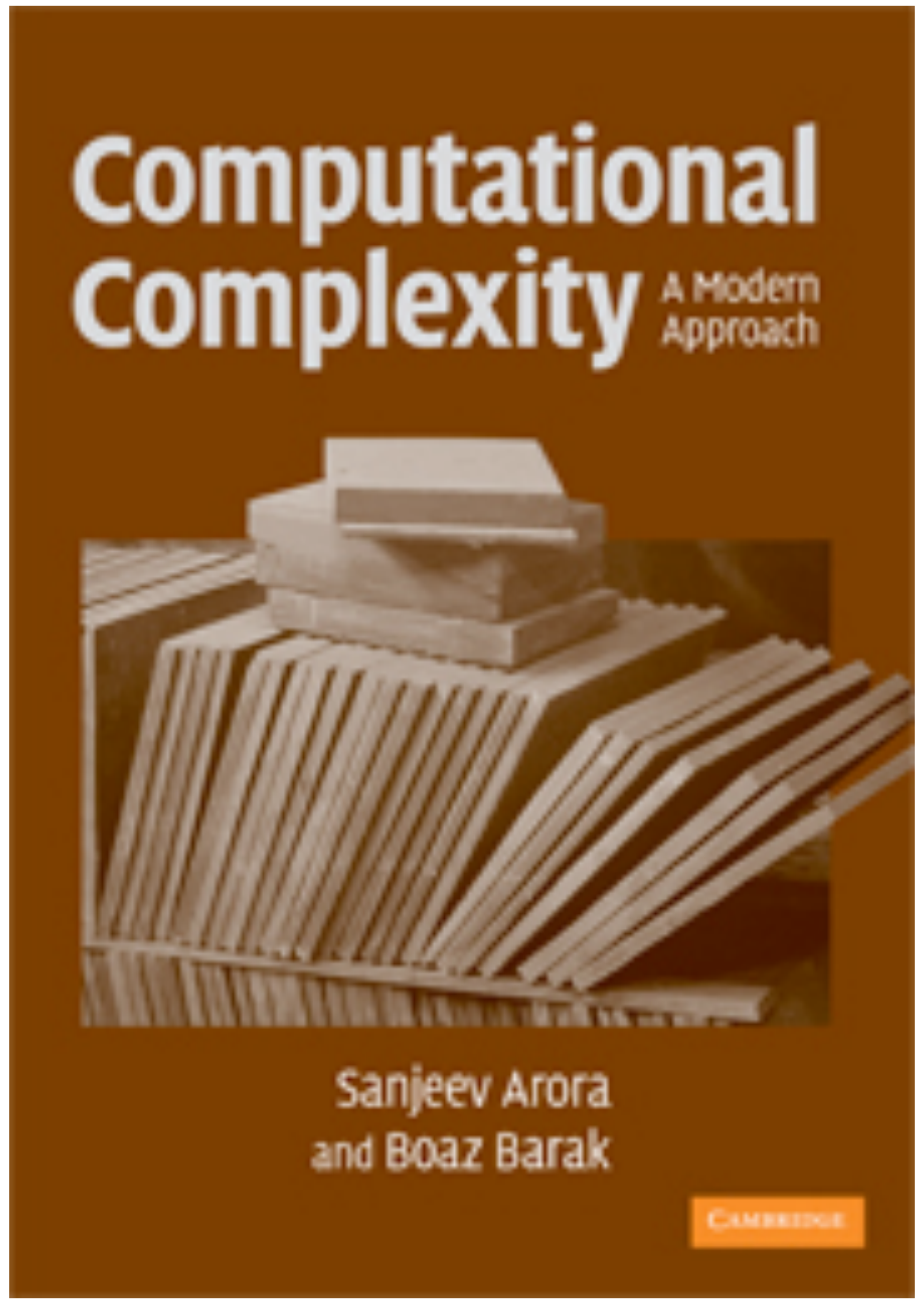
  Use the **chat feature** on EdStem to send a direct message to the instructor instead of email

- **Homework submission:** Gradescope
- **Office Hours:** after class or by appointment

Recommended Textbooks for Prerequisites



Quantum Computing



Computational Complexity