Course Syllabus

Course Name: *Many-body Physics of Information*
Instructor: Prof. Jong Yeon Lee

January 15, 2025

Course Information

- **Instructor:** Prof. Jong Yeon Lee
- **Office:** ESB 3113
- **Email:** jongyeon at illinois dot edu
- **Location and Time:** Tuesday and Thursday, 9:30 AM - 10:50 AM at Loomis 136
- **Office Hours:** Thursday 11:00 AM - 12:00 AM

Course Description

Information is not just an abstract concept—it's a fundamental cornerstone of the physical universe. In thermodynamics and quantum mechanics, information emerges as a tangible and measurable entity that profoundly influences the behavior of complex systems. As quantum information science propels the frontiers of modern physics, understanding its deep connections with many-body physics becomes essential.

This course offers a unified and coherent exploration of the intersection between quantum information theory and quantum many-body physics. You will delve into how information underpins physical phenomena, uncovering the profound ways it shapes our understanding of the quantum world. Through a blend of theoretical frameworks and practical applications, we'll journey into topics like entanglement in many-body systems, quantum phase transitions, and the role of information in thermodynamic processes.

By the end of this course, you will have a robust foundation in the core principles of quantum information theory and a comprehensive grasp of how these principles apply to cutting-edge research in quantum many-body physics. This course is particularly valuable for those intrigued by quantum computing, condensed matter physics, and theoretical physics, equipping you with the knowledge and tools to contribute to these exciting fields.

Course Schedule

- **Week 1-2:** Classical information theory. Shannon's theory of information compression and transmission. Classical linear codes. Maximum likelihood decoder.
- **Week 3-4:** Quantum information theory, covering key concepts such as quantum channels, quantum data processing inequality, quantum error correction codes, and the implications of entanglement for information processing in quantum systems.
- **Week 5-6:** Various quantum error correction code constructions and decoding protocols, such as *toric codes, fractons, quantum LDPCs, etc.* Their connections to topological orders.

- **Week 7-9:** Symmetry Protected Topological (SPT) phases: We will classify SPT phases using tools like tensor networks, understanding their significance in the broader landscape of quantum matter. Also, its information-theoretic aspects that enable measurement-based quantum computation will be discussed.
- **Week 10-11:** Topological orders under Decoherence: Exploration of how decoherence affects topological phases and the robustness of topological quantum computing.
- **Week 12-13:** Quantum Circuits and Non-equilibrium Dynamics: Analysis of quantum circuits with measurements, symmetries, and non-equilibrium dynamics, focusing on recent developments in this rapidly evolving field.
- **Final Presentation** Scheduled during exam week

Textbooks and Resources

- **Course Website:** `https://sites.google.com/view/jongyeonlee/teaching`
- **Recommended:** (*i*) John Preskill's lecture note: `http://theory.caltech.edu/~preskill/ph219/index.html#lecture` (*ii*) John McGreevy's lecture note: `https://mcgreevy.physics.ucsd.edu/w23/index.html` (*iii*) Amazing book on information theory (pdf): `https://www.inference.org.uk/mackay/itila/book.html`

Grading Policy

- **Homework:** 60%
- **Final Presentation:** 30%
- **Participation:** 10%

Final Presentations

Choose any topic that interests you and prepare a 20-minute presentation. Below, you will find a few suggestions, but feel free to explore beyond this list. If you already have a paper in mind that is relevant to your research, go for it! Some of the suggestions can be quite challenging to understand–before choosing topic, please consult with me (send me an email or visit my office hour).

As physicists, we value both the novelty and the importance of the topic—so be sure to motivate why your chosen subject matters. You should also provide clear intuitions and demonstrate correctness. Your presentation should distill the most essential ideas and steps for conveying your key message, ideally with motivating contexts and illustrative examples. The references provided below are intended to serve as entry points to the literature, rather than exhaustive citations. For each paper you investigate, be sure to look at the papers it cites and those that cite it, to form a well-rounded view of the research landscape.

1. (Asymptotically) good quantum LDPC codes Panteleev and Lin.
2. LDPC as a stable phase of matter Yin and Lucas or Khemani
3. Randomized measurement toolbox and Shadow tomography Huang and Elben
4. Not all area law states are ground states of local Hamiltonian Ge and Eisert
5. Eigenstate Thermalization Hypothesis. There are myriad of references, so please dig into them. Some examples are Grover or Choi
6. SPT and Measurement-Based Quantum Computation Stephen
7. Quantum-Classical Cross Correlation Garrat
8. Random quantum circuit with measurements review article
9. Quantum Celluar Automata this and that
10. Area law for gapped one-dimensional quantum system Hastings
11. Quantum Bottleneck Theorem this
12. Gacs Automaton this
13. Local Automation of 2D toric code this
14. Pseudorandom Unitaries this
15. Topological Quantum Spin Glass and qLDPC this
16. Shor's algorithm and quantum Fourier transform: note and Aaronson's post