EE515: Quantum Sensing: Machine Learning, Inference, and Information

Units: 4
Time: Mon, Wed 2:00-3:50pm

Location: DMC 155

Instructor: Quntao Zhuang

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Teaching assistant: TBD

Office: TBD
Office Hour: TBD
Contact info: TBD

Catalogue Description

Basics of quantum mechanics, basics of quantum sensing, quantum theory of inference, information, and machine learning.

Course Description

It is a 4-unit course to introduce the basics of quantum sensing---the quantum theory of inference, information, and machine learning. Quantum information science and engineering has shown great promise in achieving better-than-classical performance in computing, communication, and sensing. Sensing is an arena where quantum technologies can achieve advantages over classical sensing technologies for practical applications in the near term. Quantum sensing and metrology studies the use of nonclassical resources to enhance the performance of measurements for a variety of sensing applications. As a prominent example, the Laser Interferometer Gravitational-wave Observatory (LIGO) injects nonclassical squeezed light into its Michelson interferometer to surpass the standard quantum limit (SQL) due to laser shot noise. Apart from LIGO, quantum metrology has also been exploited in target detection, microscopy, biological sensing and phase tracking. More recently, quantum sensing has found application in machine learning tasks, for example with intelligent quantum sensor networks. This course will introduce the theoretical foundation of quantum sensing and provide canonical examples of quantum advantages in different practical sensing scenarios.

The course starts from basic quantum mechanics, including both qubit systems and quantum optical systems modeled as harmonic oscillators. Then we will cover the basics of classical inference and classical machine learning, as a preliminary to the quantum versions that follows that. Finally, we will talk about some physical systems for quantum sensing. This course will introduce the basic tools and methodology to model and analyze quantum sensing protocols and apply those on realistic examples. Targeted at students with mature knowledge of complex linear algebra, this course provides students with state-of-the-art overview of quantum sensing and prepares them for further studies of the topic.

Learning Objectives

By the end of this course, students will be able to

- apply various paradigms of quantum sensing and quantum machine learning to applications

- analyze quantum sensing performance using acquired quantitative tools.
- analyze the advantage from entanglement and squeezing in sensing optical phase, including the case of multipartite entanglement leading to Heisenberg scaling in measurement precision using acquired skills.

Prerequisite(s): None

Recommended Preparation: Basic quantum mechanics on the level of EE 539. Linear algebra on the level of EE 141. Probability on the level of EE 364.

Course Notes

The course website will be on Brightspace or equivalent set-up to allow online access.

Technological Proficiency and Hardware/Software Required

None.

Required Readings and Supplementary Materials

Course notes will be distributed.

Optional Readings and Supplementary Materials

Carl W. Helstrom, Quantum Detection and Estimation Theory, Mathematics in Science and Engineering, Academic Press (February 11, 1976). ISBN 0-12-340050-3

Nielsen and Chuang, Quantum Information and Quantum Computation, Cambridge University Press. ISBN 978-1-107-00217-3

Sakurai, Modern Quantum Mechanics, Addison-Wesley or Cambridge University Press (any edition is fine) ISBN-10. 0805382917

John Preskill's lecture notes.
http://www.theory.caltech.edu/~preskill/ph219/index.html#lecture

Jon Watrous's lecture notes
https://cs.uwaterloo.ca/~watrous/LectureNotes.html

Umesh Vazirani's lecture notes
https://people.eecs.berkeley.edu/~vazirani/quantum.html

Andrew Childs's lecture notes
http://www.math.uwaterloo.ca/~amchilds/teaching/w08/co781.html

Seth Lloyd's notes
http://web.mit.edu/2.111/www/notes09/spring.pdf

Participation

Attendance is mandatory.

Grading Breakdown

Assessment Tool (assignments)	% of Grade
Participation	5
Homework problems	15
Quiz	10
Midterm exam	20
Final exam	35
Project presentation	15
TOTAL	100

Grading Scale

Course final grades will be determined in a rescaled fashion. Your final grade will depend on the relative scores in the class.

Description and Assessment of Assignments

Assignment will be submitted in person on date of due before class starts every two weeks. Six assignments will be given. The grades of homework will usually be returned in two weeks.

Project Presentation

Work in groups of 2-3 and choose one of the following papers and find related papers (use google scholar citation function to find papers citing it, or find it in the references), and present the results of the paper and related works. Each presentation is about 10 minutes. Other papers are also possible with approval of the instructor. The presentation will be graded based on the depth and breadth of the presentation, as well as the application of course materials and acquired tools to interpret the results in the works. A 2-page summary report will be handed in after presentation. All members in the same group are expected to work with equal contribution and receive the same score for project presentation.

(1) LIGO Collaboration, A gravitational wave observatory operating beyond the quantum shot-noise limit, Nature Physics volume 7, pages962–965 (2011)

(2) Backes et al, A quantum enhanced search for dark matter axions, Nature volume 590, pages238–242 (2021).

(3) Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone, Quantum Metrology, Phys. Rev. Lett. 96, 010401 (2006)

(4) Guo X, Breum C R, Borregaard J, Izumi S, Larsen M V, Gehring T, Christandl M, Neergaard-Nielsen J S and Andersen U L, Distributed quantum sensing in a continuous-variable entangled network, Nat. Phys. 16 281–4, 2020

(5) Mankei Tsang, Ziv-Zakai Error Bounds for Quantum Parameter Estimation, Phys. Rev. Lett. 108, 230401 (2012)

(6) Zheshen Zhang, Quntao Zhuang, Distributed quantum sensing, Quantum Sci. Technol. 6 043001 (2021)

(7) Zhou, S., Zhang, M., Preskill, J. et al. Achieving the Heisenberg limit in quantum metrology using quantum error correction. Nat Commun **9**, 78 (2018).

(8) J. M. Taylor et al, High-sensitivity diamond magnetometer with nanoscale resolution, Nature Physics volume 4, pages810–816 (2008).

(9) Si-Hui Tan et al, Quantum Illumination with Gaussian States, Phys. Rev. Lett. 101, 253601 (2008)

(10) Anthony J. Brady, Christina Gao, Roni Harnik, Zhen Liu, Zheshen Zhang, Quntao Zhuang, Entangled sensor-networks for dark-matter searches, PRX Quantum 3, 030333 (2022)

Course Evaluations

Course evaluation occurs at the end of the semester university-wide. Lecturer will ask for feedback in class as well.

Course Schedule

	Topics/Daily Activities	Readings/Preparation	Deliverables
Week 1 (Aug 25, 27)	Introduction lecture. Review of quantum mechanics: states (superposition, density matrix)	lecture slides provided ahead of time Preskill Notes Chapt 2 Nielsen and Chuang Chapter 2	
Week 2 (Sep 3,8) **[Sep 1 is** labor day**]**	Review of quantum mechanics: states (superposition, density matrix) Review of quantum mechanics: operations (unitary, quantum channel, measurement)	lecture slides provided ahead of time Preskill Notes Chapt 3, part of 4&10 Nielsen and Chuang Chapter 8, part of Chapter 11	**HW 1 due**
Week 3 (Sep 10,15)	Quantum systems: finite dimensional (qubits, qdits, Pauli operators, gates, basic noise model: depolarizing, phase flip, bit flip) quantum systems: harmonic oscillators (annihilation operators, Wigner function, P function, Q function)	lecture slides provided ahead of time Gaussian quantum information, Weedbrook et al.	
Week 4 (Sep 17,22)	Gaussian states and operations (homodyne, heterodyne, number measurement. Basic noise model: loss, phase) Review of quantum mechanics: Distance Measure of quantum states (Trace distance, Fidelity. Symplectic diagonalization)	lecture slides provided ahead of time Nielsen and Chuang Chapter 9	**HW2 due**

	Topics/Daily Activities	Readings/Preparation	Deliverables
Week 5 (Sep 24,29)	Summary of QM Basic classical inference: Bayes rule Hypothesis testing (Probability, Prior probability and posterior probability)	lecture slides provided ahead of time	
Week 6 (Oct 1,6)	Non-Bayesian hypothesis testing. Classical radar target detection. Parameter estimation (estimator, deviations, classical Cramer-Rao bound)	lecture slides provided ahead of time	**HW3 due**
Week 7 (Oct 8, 13)	Basics of classical machine learning **Quiz (open book)**	lecture slides provided ahead of time	
Week 8 (Oct 15, 20)	Quantum state hypothesis testing. (Basic theory. Helstrom limit, quantum Chernoff bound) Quantum Hypothesis testing example (coherent state discrimination: Kennedy receiver, Dolinar receiver)	lecture slides provided ahead of time	
Week 9 (Oct 22, 27)	Coherent state discrimination: beyond the binary case (Conditional nulling) Quantum channel hypothesis testing (Basic theory, entanglement advantage)	lecture slides provided ahead of time	**HW4 due**
Week 10 (Oct 29, Nov 3)	Bosonic quantum channel discrimination (Quantum Chernoff bound, receiver design) Quantum illumination target detection: I	lecture slides provided ahead of time	
Week 11 (Nov 5, 10)	**Review for midterm** **Midterm (open book)**	lecture slides provided ahead of time	**Project begins**

	Topics/Daily Activities	Readings/Preparation	Deliverables
Week 12 (Nov 12, 17)	Quantum illumination target detection: II Quantum parameter estimation (basic paradigm. Single parameter estimation, basic theory. Cramer-Rao bound and Quantum Fisher information)	lecture slides provided ahead of time	**Project: narrow down paper selection and let instructor know**
Week 13 (Nov 19, Nov 24) [Nov 26 is thanksgiving]	Standard quantum limit and Heisenberg scaling Quantum sensing application: spectroscopy (Entanglement advantage)	lecture slides provided ahead of time	**HW 5 due** **Project: start making slides**
Week 14 (Dec 1, Dec 3) [Dec 5 is last day of class]	Quantum machine learning Intro to quantum machine learning Project Presentation	lecture slides provided ahead of time	**Presentations in class, turn in report**
FINAL (Friday, Dec 12, 2-4 p.m.)	**Final Exam**		Refer to the final exam schedule in the USC *Schedule of Classes* at classes.usc.edu.

Statement on Academic Conduct and Support Systems

Academic Integrity
Unless otherwise noted, this course will follow the expectations for academic integrity as stated in the USC Student Handbook. The general USC guidelines on Academic Integrity and Course Content Distribution are provided in the subsequent "Statement on Academic Conduct and Support Systems" section.

For this class, we have the following specific rules.

Collaboration. In this class, you are expected to submit work that demonstrates your individual mastery of the course concepts.

Group work. Unless specifically designated as a 'group project,' all assignments are expected to be completed individually.

Computer programs. Plagiarism includes the submission of code written by, or otherwise obtained from someone else.

If found responsible for an academic violation, students may be assigned university outcomes, such as suspension or expulsion from the university, and grade penalties, such as an "F" grade on the assignment, exam, and/or in the course.

Please ask the instructor [and/or TA(s)] if you are unsure about what constitutes unauthorized assistance on an exam or assignment, or what information requires citation and/or attribution.

You may not record this class without the express permission of the instructor and all other students in the class. Distribution of any notes, recordings, exams, or other materials from a university class or lectures — other than for individual or class group study — is prohibited without the express permission of the instructor.

Use of Generative AI in this Course
Generative AI is encouraged: Any proper use of AI (e.g., ChatGPT and image generation tools) in this class is allowed. Learning to use AI is an emerging skill; this is an opportunity for you to discuss with the instructor appropriate use of these tools. Keep in mind the following:

- AI tools are permitted to help you brainstorm topics or revise work you have already written.
- If you provide minimum-effort prompts, you will get low-quality results. You will need to refine your prompts to get good outcomes. This will take work.
- Proceed with caution when using AI tools and do not assume the information provided is accurate or trustworthy If it gives you a number or fact: assume it is incorrect unless you either know the correct answer or can verify its accuracy with another source. You will be responsible for any errors or omissions provided by the tool. It works best for topics you understand.
- AI is a tool, but one that you need to acknowledge using. Please *include a paragraph at the end of any assignment explaining if, how, and why you used AI and indicate/specify the prompts you used to obtain the results*. Failure to do so is a violation of academic integrity policies.

Students and Disability Accommodations:

USC welcomes students with disabilities into all of the University's educational programs. The Office of Student Accessibility Services (OSAS) is responsible for the determination of appropriate accommodations for students who encounter disability-related barriers. Once a student has completed the OSAS process (registration, initial appointment, and submitted documentation) and accommodations are determined to be reasonable and appropriate, a Letter of Accommodation (LOA) will be available to generate for each course. The LOA must be given to each course instructor by the student and followed up with a discussion. This should be done as early in the semester as possible as accommodations are not retroactive. More information can be found at osas.usc.edu. You may contact OSAS at (213) 740-0776 or via email at osasfrontdesk@usc.edu.

Support Systems:

Counseling and Mental Health - (213) 740-9355 – 24/7 on call
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

988 Suicide and Crisis Lifeline - 988 for both calls and text messages – 24/7 on call
The 988 Suicide and Crisis Lifeline (formerly known as the National Suicide Prevention Lifeline) provides free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week, across the United States. The Lifeline is comprised of a national network of over 200 local crisis centers, combining custom local care and resources with national standards and best practices. The new, shorter phone number makes it easier for people to remember and access mental health crisis services (though the previous 1 (800) 273-8255 number will continue to function indefinitely) and represents a continued commitment to those in crisis.

Relationship and Sexual Violence Prevention Services (RSVP) - (213) 740-9355(WELL) – 24/7 on call
Free and confidential therapy services, workshops, and training for situations related to gender- and power-based harm (including sexual assault, intimate partner violence, and stalking).

Office for Equity, Equal Opportunity, and Title IX (EEO-TIX) - (213) 740-5086
Information about how to get help or help someone affected by harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298
Avenue to report incidents of bias, hate crimes, and microaggressions to the Office for Equity, Equal Opportunity, and Title for appropriate investigation, supportive measures, and response.

The Office of Student Accessibility Services (OSAS) - (213) 740-0776
OSAS ensures equal access for students with disabilities through providing academic accommodations and auxiliary aids in accordance with federal laws and university policy.

USC Campus Support and Intervention - (213) 740-0411
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity, Equity and Inclusion - (213) 740-2101
Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-1200 – 24/7 on call
Non-emergency assistance or information.

Office of the Ombuds - (213) 821-9556 (UPC) / (323-442-0382 (HSC)

A safe and confidential place to share your USC-related issues with a University Ombuds who will work with you to explore options or paths to manage your concern.

Occupational Therapy Faculty Practice - (323) 442-2850 or otfp@med.usc.edu
Confidential Lifestyle Redesign services for USC students to support health promoting habits and routines that enhance quality of life and academic performance.