EE599, Introduction to quantum sensing: inference and information

Units: 4

Spring 2023—Mon, Wed—Time: 4:00-5:50

Location: TBD

Instructor: Quntao Zhuang

Office: PHE 606 (temporary office PHE 620)
Office Hours: Wed 3-4
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Teaching Assistant: TBD

Office: TBD
Office Hours: TBD
Contact Info: TBD

Course Description

It is a 4-unit course to introduce the basics of quantum sensing---the quantum theory of inference and information. Quantum information science and engineering has shown great promise in achieving better-than-classical performance in computing, communication and sensing. In particular, sensing is an arena that 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. This course will introduce the theory 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 basic of classical inference, 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 prepare them to start research in quantum sensing.

Related courses: EE 520 Introduction to Quantum Information Processing, PHYS 513 Applications of quantum computing and EE 514: Quantum Error Correction

Learning Objectives

By the end of this course, students will develop a basic understanding of various paradigms of quantum sensing and acquire quantitative tools to analyze quantum sensing performance. Students will understand how entanglement and squeezing can enhance sensing optical phase, and how multipartite entanglement can lead to Heisenberg scaling of error.

Prerequisite(s): None, but students need to understand complex linear algebra and probability theory
Co-Requisite(s): None
Concurrent Enrollment: None
Recommended Preparation: Some experience with quantum mechanics is preferred.

Course Notes

Standard A/B/C/D/F with + and -. The course will be blackboard 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

Nielsen and Chuang, Quantum Information and Quantum Computation.

Sakurai, Modern Quantum Mechanics

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

Description and Assessment of Assignments

Homework problems will be assigned and graded.

Grading Breakdown

Table 1 Grading Breakdown

Assessment Tool (assignments)	Points	% of Grade
Homework problems	20	20
Quiz	10	10
Midterm exam	20	20
Final exam	35	35
Final project	15	15
TOTAL	100	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. The grades of homework will usually be returned in two weeks.

Academic Integrity

The University of Southern California is foremost a learning community committed to fostering successful scholars and researchers dedicated to the pursuit of knowledge and the transmission of ideas. Academic misconduct is in contrast to the university's mission to educate students through a broad array of first-rank academic, professional, and extracurricular programs and includes any act of dishonesty in the submission of academic work (either in draft or final form).

This course will follow the expectations for academic integrity as stated in the USC Student Handbook. All students are expected to submit assignments that are original work and prepared specifically for the course/section in this academic term. You may not submit work written by others or "recycle" work prepared for other courses without obtaining written permission from the instructor(s). Students suspected of engaging in academic misconduct will be reported to the Office of Academic Integrity.

Other violations of academic misconduct include, but are not limited to, cheating, plagiarism, fabrication (e.g., falsifying data), knowingly assisting others in acts of academic dishonesty, and any act that gains or is intended to gain an unfair academic advantage.

The impact of academic dishonesty is far-reaching and is considered a serious offense against the university and could result in outcomes such as failure on the assignment, failure in the course, suspension, or even expulsion from the university.

For more information about academic integrity see the student handbook or the Office of Academic Integrity's website, and university policies on Research and Scholarship Misconduct.

Please ask me if you are unsure about what constitutes unauthorized assistance on an exam or assignment, or what information requires citation and/or attribution.

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.

Violation of academic integrity will lead to failure of the course and other consequences according to the university policy.

Course Content Distribution and Synchronous Session Recordings Policies

USC has policies that prohibit recording and distribution of any synchronous and asynchronous course content outside of the learning environment.

Recording a university class without the express permission of the instructor and announcement to the class, or unless conducted pursuant to an Office of Student Accessibility Services (OSAS) accommodation. Recording can inhibit free discussion in the future, and thus infringe on the academic freedom of other students as well as the instructor. (Living our Unifying Values: The USC Student Handbook, page 13).

Distribution or use of notes, recordings, exams, or other intellectual property, based on university classes or lectures without the express permission of the instructor for purposes other than individual or group study. This includes but is not limited to providing materials for distribution by services publishing course materials. This restriction on unauthorized use also applies to all information, which had been distributed to students or in any way had been displayed for use in relationship to the class, whether obtained in class, via email, on the internet, or via any other media. (Living our Unifying Values: The USC Student Handbook, page 13).

Course Evaluations

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

Course Schedule

Table 2 Course schedule

	Topics/Daily Activities	Readings /Preparation	Deliverables
Week 1	(1) Introduction lecture; (2) Review of quantum mechanics: quantum states (superposition, density matrix)		HW1
Week 2	Review of quantum mechanics: (1) quantum operations (unitary, quantum channel, measurement); (2) quantum systems: qubits, qdits (Pauli operators, gates, basic noise model: depolarizing, phase flip, bit flip)		HW2
Week 3	Review of quantum mechanics: (1) quantum systems: harmonic oscillators (annihilation operators, Wigner function, P function, Q function (2) Gaussian states and operations, homodyne, heterodyne, number measurement. Basic noise model: loss, phase)		
Week 4	(1) Review of quantum mechanics: Distance Measure of quantum states (Trace distance, Fidelity) (2) Quiz		Quiz
Week 5	Basic classical inference: (1) Probability, Prior probability and posterior probability, Bayes rule (2) Parameter estimation: estimator, deviations, classical Cramer-Rao bound, maximum likelihood estimator.		
Week 6	(1) Basic classical inference: Hypothesis testing, hypothesis/guess, error probability, maximum-likelihood decision (2) Quantum parameter estimation: basic paradigm. Single parameter estimation, basic theory. Cramer-Rao bound and Quantum Fisher information		HW3
Week 7	Examples of quantum parameter estimation (theory and experiment review) (1) Standard quantum limit and Heisenberg scaling (2) displacement estimation		
Week 8	(1) magnetic field sensing (2) optical phase estimation		
Week 9	(1) Summary lecture (video recording due to instructor attending APS March meeting) (2) Midterm		Midterm
Week 10	Quantum parameter estimation: (1) Multi-parameter estimation, basic theory. Complex displacement sensing (2) Quantum lidar: range and velocity estimation		
Week 11	(1) Distributed quantum sensing: displacement sensing (2) Distributed quantum sensing: general review		HW4
Week 12	Quantum Hypothesis testing (1) Quantum Hypothesis testing. Basic theory. Helstrom limit, quantum Chernoff bound (2) Example: coherent state discrimination		

Week 13	Brief introduction to microwave cavity sensing		Project reminder
Week 14	Brief introduction to opto-mechanical sensing		Project presentation slides due
Week 15	Project presentation		
FINAL			Refer to the final exam schedule in the USC *Schedule of Classes* at classes.usc.edu.

*Course project: choosing one of the following paper, and find related papers (use google scholar citation function to find papers citing it, or find it in the references), present the results of the paper, and related works. Each presentation is about 10 minutes.

(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)

Statement on Academic Conduct and Support Systems

Academic Integrity:
The University of Southern California is a learning community committed to developing successful scholars and researchers dedicated to the pursuit of knowledge and the dissemination of ideas. Academic misconduct, which includes any act of dishonesty in the production or submission of academic work, comprises the integrity of the person who commits the act and can impugn the perceived integrity of the entire university community. It stands in opposition to the university's mission to research, educate, and contribute productively to our community and the world.

All students are expected to submit assignments that represent their own original work, and that have been prepared specifically for the course or section for which they have been submitted. You may not submit work written by others or "recycle" work prepared for other courses without obtaining written permission from the instructor(s).

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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.