ECE 405 Fall 2025

University of Illinois at Urbana-Champaign

ELECTRICAL AND COMPUTER ENGINEERING 498SB

Quantum Systems II

The course instructor is **Prof. Simeon I. Bogdanov** (bogdanov@illinois)

The course structure consists of three lecture/discussion meetings per week. Final course grades are based on the distribution of total points accumulated on the homework assignments, midterm exam and the final project.

The Course information listed below is included on the following pages:

Prerequisites are either of the following:

- ECE 305 or
- equivalent basic Quantum Mechanics class (for example, PHYS 486) or
- instructor consent (bogdanov@illinois)

Graduate and undergraduate credit: 4 graduate hours, 3 undergraduate hours

Purpose and scope of the course

The principal goal of this course is to introduce students to current issues in quantum technology and the physical realizations of quantum systems, including quantum processors, networks, sensors, and simulators. We will examine the use of physical systems such as single photons, superconducting qubits, neutral atoms, and ions to encode and manipulate quantum information at the elementary level. Using a semi-formal approach and classical analogies wherever they are relevant, we will introduce each platform's key metrics and limitations and show examples of state-of-the-art realizations. An overarching theme of the course is the universality of quantum formalism and its ability to describe diverse physical systems within the same framework.

Students will turn in several homeworks in the first half of the course and take a written midterm exam. The course will end with a literature review project. Students will make a final presentation and a written report, critically assessing a scientific quantum technology paper of their choice based on the knowledge acquired in class.

The course will consist of three parts:

PART I - Quantum physics primer, introducing the concepts of two-level systems, their interaction with fields, harmonic oscillators, relaxation, decoherence, and entanglement.

PART II - Quantum information basics, including basic architectures and protocols for quantum key distribution, quantum computing, and error correction.

PART III - Discussion of elementary quantum systems, their physical implementation, degrees of freedom, basic physical characteristics (interaction rates, dephasing rates), initialization, implementation of single and two-qubit gates, measurement and transduction mechanisms

Students can deepen their knowledge of quantum technology by taking more specialized courses such as

- ECE 406 "*Quantum Optics & Devices*",
- ECE 404 "*Quantum Information Processing*",
- PHYS 513 "*Quantum Optics & Information*",
- PHYS 514 "*Modern Atomic Physics*",
- PHYS 370 "*Quantum Information and Quantum Computing*", or
- PHYS 498SQD "*Superconductor Devices for Quantum Information Science*".

Learning objectives

After the class, the students should be aware of the current fundamental issues in the field, including the notion of quantum advantage and the fundamental limitations to the realization of scalable quantum information protocols. They will be able to classify different qubit implementations and explain their use for different tasks (e.g., transmitting, storing, and processing quantum information). The students will build elementary models describing physical qubits of various nature and compare their physical limitations. They will also critique current literature in the area of quantum technology and convey their analysis in written and oral form. This last objective is specifically designed to develop research and communication skills.

Class Organization

Course Instructor:	Prof. Simeon I. Bogdanov 3262 Holonyak Micro and Nanotechnology Laboratory 224-999-2484 bogdanov@illinois.edu
Course Website:	wiki.illinois.edu/wiki/display/ECE498SBFA21 **(temporary)** The main website is the course's Canvas space
Office hours:	TBD

Reference Texts

Main recommended text:	[IQC] *Introduction to Quantum Computing* R. LaPierre Springer, The Materials Research Society Series, 2021

Basic quantum mechanics:	[IQO] *Introduction to Quantum Optics*, G. Grynberg, A. Aspect, C. Fabre Cambridge University Press, 2010
	[IOQIP] *Introduction to optical quantum information processing,* P. Kok and B. Lovett Cambridge University Press, 2010
	[ORTLA] *Optical resonance and two-level atoms* L. Allen and J.H. Eberly Dover Publications, Inc., 1987
	[FLP] *Feynman Lectures on Physics, Vol. III Quantum Mechanics* R.P. Feynman, R.B. Leighton, M. Sands Available for free on the Caltech website.
	[TMQM] *The Theoretical Minimum: Quantum Mechanics* Leonard Susskind, Art Friedman Basic Books, 2014
Quantum information:	[QCQI] *Quantum Computation and Quantum Information* I. Chuang, M. Nielsen Cambridge University Press, 10th edition, 2010
Quantum technology:	[EAQC] *Experimental Aspects of Quantum Computing* Edited by Henry O. Everitt Springer, 2005

Lecture slides along with textbook and publication references will be made available to students.

Grading Criteria

Rubric	Sub-rubric	Comments	Weight
Homeworks	4×5%		20%
Midterm exam		Partial credit for problems is allowed	30%
Final project	Presentation	The grade will be issued based on the following aspects of the presentation: i) context (5%), ii) clarity of the narrative (5%), iii) slide quality (5%) iv) time limit (5%), v) addressing Q&A (5%)	30%
	Report	The grade will be issued based on the quality of the writing (5%), literature review (5%), technical depth (5%), figures (5%)	20%

Students will be assigned four homeworks accross the modules of PART I and II. The homeworks will count for 5% of the grade each. The homeworks will consist of a series of simpler problems, followed by more complex "asterisk" problems. Asterisk problems are compulsory for graduate students, while undergraduate students may solve them for additional credit. “Double asterisk” problems may be solved for additional credit by all students.

A midterm exam will test the knowledge of background material covered in Parts I and II, counting for 30% of the grade. It will consist of a succession of elementary problems relevant to quantum information devices, some with quantitative answers. An essential objective of the midterm is to lay the groundwork for the discussion of physical quantum information platforms.

The final project will count for 50% of the final grade, with 30% allocated to the evaluation of the final presentation and 20% - to that of the final report. A successful presentation will introduce the research context for the paper by discussing prior work and motivation. It will consist of 4-5 neatly organized, illustrated slides with annotated figures, arranged in a clear logical succession that can be easily followed by the classmates. Further grading criteria are adhering to the time limit, and the handling of the Q&A. The final report will be assessed based on the following criteria:

1. Quality of scientific writing: sentence length and simplicity, logical progression of the narrative
2. Literature review: citing key papers in the field,
3. Technical depth, i.e. the extent to which the report authors correctly understood the main message and the paper's significance.

Reports turned in late but not more than by three days will incur a penalty of 5% of the total course grade. To receive a full 20% credit, such late reports will need to supply an additional 1-page technical appendix with a detailed derivation of an equation from the paper based on the material taught in class. The instructor will determine this equation concurrently with the choice of paper. The grading of the technical appendix is entirely at the instructor's discretion. Reports + appendices not submitted within three days will receive a zero grade.

The final grade may contain "pluses" and "minuses". Any questions regarding course grading should be addressed to the course instructor. Essential material for this course is covered in textbooks listed on page 3, some of which are available in the Grainger Library and are on reserve for this class. If a subject is not understood clearly, be active in class, find a relevant textbook or review article, and attend office hours. Be resourceful!

<u>**Final project**</u>

Students will select a scientific paper of their choice either from a list of suggested papers or autonomously. The paper must deal with the physical issues of qubit fabrication/design/control/protection/transmission/transduction/storage/measurement, be published after the year 2000, and be transformative [e.g. Knill, Laflamme and Milburn, "A scheme for efficient quantum computation with linear optics," *Nature* 409, **49** (2001)]. Students are encouraged to select recently published papers over older ones.

Students will prepare a 5 min presentation + 5 min Q&A discussing the context of the paper, its significance for the field, the opportunities it creates, and offer a critical discussion of how it could (or has) transform(ed) the field. During the Q&A, students must be able to comment on the significance of the addressed problem, basic technical approach, competing technologies, and fundamental limitations.

In addition, students will prepare a written illustrated report of about three and no longer than five pages, summarizing the paper and explaining its significance. Students must use their formulations in the report. Copy-pasting from any existing published text <u>**is not**</u> allowed, but reproduction and adaptation of published figures <u>**are**</u> allowed. The report should contain i) the problem definition; ii) a review of pre-existing approaches, iii) Outstanding challenges not covered in literature at the moment of the paper publication iv) how the paper addresses the outstanding challenges v) technical details of the approach.

The report should also contain relevant literature references. Pairing with one other student from the class is allowed for the final project. The choice of paper and final presentation/report must be discussed in advance with the course instructor. The instructor will offer optional initial feedback for the drafts of the presentation and report. Detailed guidelines and tips will be given in class.

Volunteer students will act as chairs for the final presentations with the duties similar to those of conference chairs. The final reports and presentation will be assessed based on the expectations typical of "perspectives" published in scientific journals and conference presentations respectively. These expectations are differentiated between graduate and undergraduate students will be detailed in class.

Final project timeline

Date	Action due
09/26 - 10/10	Preliminary literature research to select a paper
10/10	Submit your team and choice of paper to the course instructor
10/17	Finalize choice of paper upon discussion with the course instructor
11/02	Send draft presentation recording to the instructor for initial feedback and sign up for presentation slots
11/14	Send draft report to the instructor for initial feedback
12/08 and **12/10**	Presentations
12/17	Final reports due by 11:59 PM

Fall 2024 ECE 498SB COURSE SCHEDULE AND OUTLINE

#		DATE	TOPIC	LECTURE CONTENT	READ
1	PART I	M 08/25	**Introduction**	Applications of quantum technology, platforms, and building blocks. Quantum supremacy.	Slides
2		W 08/27	**Quantum Formalism**	Hilbert spaces, wave functions. Operators.	IQC 1 IQC 4.1-9
3		F 08/29		Uncertainty principle, product, and entangled states.	FLP 1 IQC 4.10-13 IQC 5.1-5.4
		M 09/01		LABOR DAY. NO CLASS	
4		W 09/03		Schrodinger equation and time evolution.	FLP 6,7
		HOMEWORK 1 due on Friday 09/02			
5		F 09/05	**Quantum levels and hybridization**	Position and momentum spaces.	IQC 2.1–6 FLP 8
6		M 09/08		Quantum wells, optical waveguides, atomic levels.	IQC 2.7-14 FLP 16,19
7		W 09/10		Classical and quantum harmonic oscillators.	TMQM 10
8		F 09/12		Energy gaps. Semiconductors and photonic crystals.	FLP 8,13,14
	PART II	**HOMEWORK 2 due on Friday 09/09**			
9		M 09/15	**Two-level quantum systems**	Classical dipole interaction with driving fields. Bloch plane.	Slides
10		W 09/17		Classical dipole spontaneous emission and dephasing.	Slides
11		F 09/19		Two-level systems, **d**.**E** interaction Hamiltonian and Bloch sphere	IQC 16.1-2
12		M 09/22		Coherent manipulation of two-level systems	IQC 16.4-6
13		W 09/24		Relaxation and dephasing. T_1 and T_2.	IQC 25.1-4
		HOMEWORK 3 due on Friday 09/23			
14		F 09/26	**Interactions of quantum systems**	Strong dipolar interaction of two-level systems.	IQC 17
15		M 09/29		Adiabatic elimination.	IQO 2C.5
16		W 10/01		Lambda systems and electromagnetically induced transparency.	IQO 2D.2
17		F 10/03		Introduction to nonlinear optics: second-order nonlinear processes.	IQO 7.1-7.3
18		M 10/06		Spontaneous parametric down-conversion.	IQO 7.4
		HOMEWORK 4 due on Friday 10/07			
19		W 10/08	**Quantum Information**	Introduction to quantum computation. Qubits.	IQC 7
20		F 10/10		Grover search.	IQC 12
21		M 10/13		Introduction to quantum error correction.	IQC 25
22		W 10/15		Introduction to quantum communication.	IQC 6 IQC 5.7 – 11
23		F 10/17		Introduction to quantum metrology	Slides
24		M 10/20	**Review and problem solving**		
		MITDERM (tentative date: Tuesday 10/17, 6 – 8 PM, ECEB 3081)			

25		W 10/22	**Photons**	Producing, detecting and encoding single photons	IQC 24.1-3
26		F 10/24		Deterministic and linear quantum gates	IQC 24.4-8
27		M 10/27		Spin-photon interfaces. Quantum memories.	Slides
28		W 10/29		Teleportation. Repeaters. State-of-the-art quantum networks	Slides
29		F 10/31	**Trapped neutral atoms**	Magneto-optical traps. Atomic qubits.	IQO 8.1-3
30		M 11/03		Preparation and readout of atomic states;	Slides
31		W 11/05		Rydberg blockade and atomic quantum gates	Slides
32		F 11/07		Neutral atom quantum simulators.	Slides
33		M 11/10	**Trapped ions**	Quadrupole traps; hyperfine and optical qubits;	IQC 21.1-3
34		W 11/12		Cooling of the phonon modes. Optical state preparation and readout	IQC 21.4-9
35		F 11/14		Entangling ionic gates: a qualitative overview	Slides
36		M 11/17		Ion-based quantum computers	Slides
37		W 11/19	**Super-conducting qubits**	Resonators. Transmission lines. Introduction to superconductivity.	IQC 22.1-4
38		F 11/21		Josephson effect. Transmon qubits.	IQC 22.5-22.15
				FALL BREAK NOV 22 – 30	
39		M 12/01		Interaction between qubits in the fixed coupling regime Decoherence mechanisms	IQC 22.16-18
40		W 12/03		Superconducting quantum computers	Slides
41		F 12/05	Broader quantum ecosystem: transduction and control		
42		M 12/08	**FINAL PRESENTATIONS 1**		
43		W 12/10	**FINAL PRESENTATIONS 2**		
		W 12/17	Final reports due at 11:59 pm		

Class policy

We in the Illinois ECE community are committed to understanding, empathizing with, and respecting each other, embracing the many differences among us. The Grainger College of Engineering is committed to the creation of an anti-racist, inclusive community that welcomes diversity along a number of dimensions, including, but not limited to, race, ethnicity and national origins, gender and gender identity, sexuality, disability status, class, age, or religious beliefs. The effectiveness of this course is dependent upon each of us to create a safe and encouraging learning environment that allows for the open exchange of ideas while also ensuring equitable opportunities and respect for all of us. Everyone is expected to help establish and maintain an environment where students, staff, and faculty can contribute without fear of personal ridicule, or intolerant or offensive language. If you witness or experience racism, discrimination, micro-aggressions, or other offensive behavior, you are encouraged to bring this to the attention of the course director if you feel comfortable. You can also report these behaviors to Campus Belonging Resources (https://diversity.illinois.edu/diversity-campus-culture/belonging-resources/). Based on your report, Members of the Office of the Vice Chancellor for Diversity, Equity & Inclusion staff will follow up and reach out to students to make sure they have the support they need to be healthy and safe. If the reported behavior also violates university policy, staff in the Office for Student Conflict Resolution may respond as well and will take appropriate action. Faculty and staff members are required to report any instances of sexual misconduct to the University's Title IX Office. In turn, an individual with the Title IX Office will provide information about rights and options, including accommodations, support services, the campus disciplinary process, and law enforcement options. Information about resources and reporting is available via https://wecare.illinois.edu.

Family Educational Rights and Privacy Act (FERPA): Any student who has suppressed their directory information pursuant to Family Educational Rights and Privacy Act (FERPA) should self-identify to the instructor to ensure protection of the privacy of their attendance in this course. See https://registrar.illinois.edu/academic-records/ferpa/ for more information on FERPA

Mental Health: Significant stress, mood changes, excessive worry, substance/alcohol misuse or interferences in eating or sleep can have an impact on academic performance, social development, and emotional wellbeing. The University of Illinois offers a variety of confidential services including individual and group counseling, crisis intervention, psychiatric services, and specialized screenings which are covered through the Student Health Fee. If you or someone you know experiences any of the above mental health concerns, it is strongly encouraged to contact or visit any of the University's resources provided below:

- Counseling Center (217) 333-3704
- McKinley Health Center (217) 333-2700
- National Suicide Prevention Lifeline (800) 273-8255
- Rosecrance Crisis Line (217) 359-4141 (available 24/7, 365 days a year)
- If you are in immediate danger, call 911.

Students with Disabilities: To obtain disability-related academic adjustments and/or auxiliary aids, students with disabilities must contact the course instructor and provide the instructor with a Letter of Academic Accommodations from Disability from DRES located at 1207 S. Oak St., Champaign, 217-333-1970, e-mail disability@illinois.edu.

Religious Observances: Illinois law requires the University to reasonably accommodate its students' religious beliefs, observances, and practices in regard to admissions, class attendance, and the scheduling of examinations and work requirements. You should examine this syllabus at the beginning of the semester for potential conflicts between course deadlines and any of your religious observances. If a conflict exists, you should notify your instructor of the conflict and follow the procedure at https://odos.illinois.edu/community-of-care/resources/students/religious-observances/ to request appropriate accommodations. This should be done in the first two weeks of classes.

Class Attendance and Absence Policy: Part 5, 1-501 of the Student Code provides background on class attendance and provides useful information for students. The code stipulates the conditions under which an absence letter from the Office of the Dean of Students may be requested. A brief illness - less than 3 days - would not qualify for an absence letter.

Academic Integrity: Academic dishonesty may result in a failing grade, ignorance is not an excuse for any academic dishonesty. Every student is expected to review and abide by the Academic Integrity Policy described in Part 4, 1-401 of the Student Code --- it is your responsibility to read this to avoid any misunderstanding. Do not hesitate to ask the instructor(s) if you are in doubt about what constitutes plagiarism, cheating, or any other breach of academic integrity.