ECE 498SB Fall 2022

University of Illinois at Urbana-Champaign

ELECTRICAL AND COMPUTER ENGINEERING 498SB

Manipulation of Elementary Quantum Systems

(course will be later offered as ECE 405 "Quantum Systems II")

The course director 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 final presentation and participation throughout the class lectures.

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

Prerequisites are either of the following:

- credit or concurrent registration for ECE 305 or PHYS 486,
- credit or concurrent registration for a basic QM class equivalent to above
- 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 computers, 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 4 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:

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

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

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

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

- ECE 406 "*Quantum Optics & Devices*" (former ECE 498KF),
- ECE 404 "*Quantum Information Processing*" (former ECE 498EC),
- 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 difficulties in realizing 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: **(temporary website)**
Canvas space

Room 2120 ECEB is the office for registration, lost & found.

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

[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 containing 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%)	20%

Students will be assigned eight homeworks between the modules. The homeworks will count for 5% of the grade each. The homeworks will consist of a series of simple problems sometimes followed by more complex "asterisk" problems for additional credit.

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

The final project counts as 40% of the final grade, with 25% allocated to the evaluation of the final presentation and 15% - 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 classmates. The presentation will be further assessed based on 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, try another book, find a review article, and attend office hours. Be resourceful!

Final project

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 **is not** allowed, but reproduction and adaptation of published figures **are** 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.

Recommended timeline for the final project:

Date	Action
09/26 - 10/10	Read candidate papers and conduct preliminary literature research
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
12/05 and **12/07**	Presentations
12/15	Final reports due by 11:59 PM

Fall 2022 ECE 498SB COURSE SCHEDULE AND OUTLINE

#		DATE	TOPIC	LECTURE CONTENT	READ
1	PART I	M 08/22	**Introduction**	Applications of quantum technology, platforms, and building blocks. Quantum supremacy.	Slides
2		W 08/24	**Quantum Formalism**	Hilbert spaces, wave functions. Operators.	IQC 1 IQC 4.1-9
3		F 08/26		Uncertainty principle, product, and entangled states.	FLP 1 IQC 4.10-13 IQC 5.1-5.4
4		M 08/29		Schrodinger equation and time evolution.	FLP 6,7
5		W 08/31		Position and momentum spaces.	IQC 2.1–6 FLP 8
		HOMEWORK 1 due on Friday 09/02			
6		F 09/02	**Quantum levels and hybridization**	Quantum wells, optical waveguides, atomic levels.	IQC 2.7-14 FLP 16,19
		M 09/05		LABOR DAY – NO CLASS	
7		W 09/07		Classical and quantum harmonic oscillators.	TMQM 10
8		F 09/09		Energy gaps. Semiconductors and photonic crystals.	FLP 8,13,14
	PART II	**HOMEWORK 2 due on Friday 09/09**			
9		M 09/12	**Two-level quantum systems**	Classical dipole interaction with driving fields. Bloch plane.	Slides
10		W 09/14		Classical dipole spontaneous emission and dephasing.	Slides
11		F 09/16		Two-level systems, **d**.**E** interaction Hamiltonian and Bloch sphere	IQC 16.1-2
12		M 09/19		Coherent manipulation of two-level systems	IQC 16.4-6
13		W 09/21		Relaxation and dephasing. T_1 and T_2.	IQC 25.1-4
		HOMEWORK 3 due on Friday 09/23			
14		F 09/23	**Interactions of quantum systems**	Strong dipolar interaction of two-level systems.	IQC 17
15		M 09/26		Adiabatic elimination.	IQO 2C.5
16		W 09/28		Lambda systems and electromagnetically induced transparency.	IQO 2D.2
17		F 09/30		Introduction to nonlinear optics: second-order nonlinear processes.	IQO 7.1-7.3
18		M 10/03		Spontaneous parametric down-conversion.	IQO 7.4
		HOMEWORK 4 due on Friday 10/07			
19		W 10/05	**Quantum Information**	Introduction to quantum computation. Qubits.	IQC 7
20		F 10/07		Grover search.	IQC 12
21		M 10/10		Introduction to quantum error correction.	IQC 25
22		W 10/12		Introduction to quantum communication.	IQC 6 IQC 5.7 – 11
23		F 10/14		Introduction to quantum metrology	Slides
24		M 10/17	**Review and problem solving**		
		MITDERM (tentative date: Tuesday 10/18, 6 – 8 PM, ECEB 3081)			

25		W 10/19	**Photons**	Producing, detecting and encoding single photons	IQC 24.1-3
26		F 10/21		Deterministic and linear quantum gates	IQC 24.4-8
27		M 10/24		Spin-photon interfaces. Quantum memories.	Slides
28		W 10/26		Teleportation. Repeaters. State-of-the-art quantum networks	Slides
29		F 10/28	**Trapped neutral atoms**	Magneto-optical traps. Atomic qubits.	IQO 8.1-3
30		M 10/31		Preparation and readout of atomic states;	Slides
31		W 11/02		Rydberg blockade and atomic quantum gates	Slides
32		F 11/04		Neutral atom quantum simulators.	Slides
33		M 11/07	**Trapped ions**	Quadrupole traps; hyperfine and optical qubits;	IQC 21.1-3
34		W 11/09		Cooling of the phonon modes. Optical state preparation and readout	IQC 21.4-9
35		F 11/11		Entangling ionic gates: a qualitative overview	Slides
36		M 11/14		Ion-based quantum computers	Slides
37		W 11/16	**Super-conducting qubits**	Resonators. Transmission lines. Introduction to superconductivity.	IQC 22.1-4
				FALL BREAK NOV 19 – NOV 27	
38		F 11/28		Josephson effect. Transmon qubits.	IQC 22.5-22.15
39		W 11/30		Interaction between qubits in the fixed coupling regime Decoherence mechanisms	IQC 22.16-18
40		F 12/02		Superconducting quantum computers	Slides
41		M 12/05	**FINAL PRESENTATIONS 1**		
42		W 12/07	**FINAL PRESENTATIONS 2**		
		W 12/15	Final reports due at 11:59 pm		