Nanyang Technological University
Division of Physics and Applied Physics

COURSE CONTENT FOR PAP750 for Undergraduates

Academic Year	2021/2022	**Semester**	2
Course Coordinator	Asst. Prof. Nelly Ng		
Course Code	PAP750		
Course Title	Quantum Information		
Pre-requisites	(PH3404 Physics of Classical & Quantum Information or MH2500 Probability & Introduction to Statistics), and PHY (PPHY) or PHY (APHY) programme and CGPA 4.0 or higher		
No of AUs	4 AU		
Contact Hours	Face-to-face, physical classes Lecture: 39, Tutorial: 12 (3 hrs lecture each week; 1 hr tutorial each week)		
Proposal Date	4th Feb 2022		

Course Aims

This course aims to equip you with the central theoretical framework and tools which are paramount to understanding the advantage brought by quantum information processing and some experimental basics of realizing these technologies. You will learn a comprehensive overview of central topics of interest in active research areas.

These skills are critical for you who are aiming at a career in quantum information technologies.

Intended Learning Outcomes (ILO)

By the end of this course, you should be able to:

1. Demonstrate an understanding of the structure and properties of objects in quantum information (classical random variables and channels, density matrices, quantum processes) and interpret the physical meaning behind these objects.
2. Translate a preparation procedure into typical multipartite density matrices such as classical-quantum states.
3. Compute probabilities corresponding to the output of a quantum measurement after a series of entangling quantum gates.
4. Identify the techniques that allow for a proof of quantum advantage in quantum cryptography
5. Distinguish between problems in different computational complexity classes
6. Derive the speedup in basic quantum algorithms

Course Content

Syllabus:

1) Theory

a) Classical random variables, entropic quantities, and properties, basic overview of channel coding theorems
b) Quantum information formalism: states, unitaries and quantum circuit model
c) Entropic measures and uncertainty relations, no-go theorem
d) Computational and query complexity classes in quantum computing
e) Quantum cryptography: QKD
f) Unit quantum protocols: superdense coding & teleportation
g) Quantum states (density matrices) and channels (CPTPMs, CJ isomorphism, Kraus theorem, main studied examples)
h) Distance measures (distance norms, fidelity variants)

i) elementary quantum algorithms: Quantum Fourier Transform, Grover's algorithm, phase estimation, overview of modern algorithms
j) Classical and quantum typicality, quantum versions of coding theorems

2) Experiment
- a) Ultracold atoms: Atomic Qubits / Qubit realization / Rydberg Interaction / Optical lattices / Atom arrays / Ion Traps / trapping
- b) Superconducting Quantum Electronics:
  - a. Circuit realization of qubits (various flavours)
  - b. Characterization (T1 / T2)
  - c. Various physical realization single and two qubit gates / benchmarking
  - d. Readout strategies / State Tomography
  - e. Implementation of algorithms
- c) Noise and other challenges

3) Research seminars
- a) Quantum linear optics / continuous variable quantum information
- b) Quantum metrology and sensing
- c) Quantum simulators
- d) Quantum resource theories

Assessment (includes both continuous and summative assessment)

Component	ILO Tested	Related Programme LO or Graduate Attributes	Weighting	Team/Individual	Assessment Rubrics
1. Continuous Assessment: homework	All	Competency 1,2,4,5,6	60%	Individual	Point-based marking
2. Project presentation	All	Competency 1,2,4,5,6, Communication 1,2 Character 1,2	40%	Individual	See Appendix
Total			100%		

Formative feedback

Formative feedback is given weekly through assignments marking and tutorial classes. During the tutorial hours, the instructor discusses the progress, pace, and difficulty level of lectures.

Learning and Teaching approach

Approach	How does this approach support you in achieving the learning outcomes?
Lectures	Lectures provide the necessary content and practice of problem solving and discussion of conceptual understanding.
Tutorial	The students review and discuss main concepts learned in lectures by working through problems.

Homework	The homework comprises practice questions that are covered during tutorials, allowing for formative assessment and feedback.
Project	Students read a milestone paper in the field of quantum information and present it to their peers.

Reading and References

1. Quantum Computation and quantum information, M. Nielsen and I. Chuang, Cambridge University Press (2010). ISBN: 978-1107002173

2. Quantum Information Theory, Mark Wilde, Cambridge University Press (2017) ISBN: 978-1107176164

3. Learning quantum computation using Qiskit, online textbook, Qiskit (No ISBN Number, online resource)

Course Policies and Student Responsibilities

Absence Due to Medical or Other Reasons

If you are sick and unable to attend your class, you have to:

1. Send an email to the instructor regarding the absence,
2. Submit the original Medical Certificate* or official letter of excuse to administrator,
3. Attend the assigned replacement class (*subject to availability*).

* The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

Academic Integrity

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Course Instructors

Instructor	Office Location	Phone	Email
Asst. Prof. Nelly Ng	SPMS PAP-03-05	89095913	nelly.ng@ntu.edu.sg

Planned Weekly Schedule

Week	Topic	ILO	Readings/ Activities
Week 1	Classical information theory	1a	Textbook, lecture notes, videos
Week 2	Pure quantum states and properties	1b	
Week 3	Limits of quantum information	1c,1d,1e	
Week 4	Density matrices and quantum channels	1g	
Week 5	Quantum communication protocols, more on quantum channels Experimental quantum information: cold atoms	2a,2c,1f	
Week 6	Quantum Fourier Transform Experimental quantum information: superconducting qubits	2b,2c	Guest lecture, textbook, lecture notes
Week 7	Phase estimation, application in Shor's algorithm	1i	Textbook, lecture notes, videos
Week 8	Grover's algorithm, closeness measures	1i, 1h	
Week 9	Classical and quantum typicality, quantum versions of data compression and channel capacity theorems	1j	
Week 10	Continuous variable quantum information, quantum metrology and sensing	3a, 3b	Guest lecture/ research seminar given by instructor
Week 11	Quantum simulation, resource theories	3c, 3d	
Week 12	Student presentations	N/A	Student presentations, lecture notes
Week 13	Student presentations, concluding remarks	N/A	

Appendix 1: Assessment Criteria for Project Presentation

Criteria	**Exceeds Standard (10 – 9)**	**Meets Standard (8.5 – 6)**	**Almost Meets Standard (5.5 – 3.5)**	**Does not meet standard (3 – 0)**
Use of pace, tone and style	Effective and creative use of pace, tone and style to emphasize key points and engage audience.	Effective use of pace, tone and style.	Somewhat effective use of pace, tone and style.	Ineffective use of pace, tone and style.
Engagement	Arouses interest and engages attention of audience throughout the presentation.	Arouses interest and engages attention of audience through most of the presentation.	Maintains attention of audience through part of the presentation.	Loses attention of audience through most of the presentation.
Scientific communication	Communicates difficult or complex ideas in an effective and understandable manner	Communicates ideas in an effective and understandable manner	Communicates ideas somewhat effectively, which are mostly understandable.	Does not communicate ideas effectively.
Q&A	Addresses all questions posed clearly, showing in-depth understanding	Addresses most questions posed clearly, showing satisfactory understanding	Addresses some questions posed, demonstrates partial understanding	Not able to address the posed questions clearly, showing lack of understanding

The main presentation should include:

- a ***presentation*** of the appropriate ***concepts, theories and principles*** of the problem
- an ***explanation*** of the ***observed phenomena***
- an ***application*** of ***appropriate mathematics***
- reasonable **experimental technique** to ***gather*** and ***record data*** (or ***demonstrate*** the ***phenomena*** if appropriate)
- linking of ***theoretical*** and ***experimental findings*** to draw ***suitable conclusions***
- an attempt to communicate ***difficult*** or ***complex*** ideas in an ***effective*** and ***understandable*** manner

Duration: Presentation (15 min) + Q&A (5 min) = Total of 20 min.

Graduate Attributes

What we want our graduates from Physics and Applied Physics to be able to do:

Upon the successful completion of the PHY, APHY, PHME and PHMS programs, graduates should be able to:

Competency	1	demonstrate a rigorous understanding of the core theories and principles of physics involving (but not limited to) areas such as classical mechanics, electromagnetism, thermal physics and quantum mechanics [PHMS only] demonstrate a rigorous understanding of the core theories and principles of mathematical sciences involving (but not limited to) areas such as analysis, algebra and statistical analysis
	2	read and understand undergraduate level physics content independently;
	3	make educated guesses / estimations of physical quantities in general;
	4	apply fundamental physics knowledge, logical reasoning, mathematical and computational skills to analyse, model and solve problems;
	5	develop theoretical descriptions of physical phenomena with an understanding of the underlying assumptions and limitations;
	6	critically evaluate and distinguish sources of scientific/non-scientific information and to recommend appropriate decisions and choices when needed;
	7	demonstrate the ability to design and conduct experiments in a Physics laboratory, to make measurements, analyse and interpret data to draw valid conclusions.

Creativity	1	propose valid approaches to tackle open-ended problems in unexplored domains;
	2	offer valid alternative perspectives/approaches to a given situation or problem.

Communication	1	

		describe physical phenomena with scientifically sound principles;
	2	communicate (in writing and speaking) scientific and non-scientific ideas effectively to professional scientists and to the general public;
	3	communicate effectively with team members when working in a group.

Character	1	uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results;
	2	readily pick up new skills, particularly technology related ones, to tackle new problems;
	3	contribute as a valued team member when working in a group.

Civic Mindedness	1	put together the skills and knowledge into their work in an effective, responsible and ethical manner for the benefits of society.