COURSE CONTENT FOR PH7021

Academic Year	2022/2023	**Semester**	2
School/Programme	SPMS		
Course Coordinator	Asst Prof Nelly Ng		
Course Code	PH7021		
Course Title	Quantum Information		
Pre-requisites	For graduate students: No pre-requisites For undergraduates: 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	52 contact hours		
Proposal Date ***i.e., date proposal was drafted***	9 February 2023		
Expected Implementation date of new/revised course	January 2023		
Suggested Class Size	30		
Any cross-listing? ***Is course opened to all Postgraduate students (including IGP) or specific program (please indicate)?***	Yes, SPMS Master by Research		

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

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**	**Weighting**	**Team/ Individual**	**Assessment Rubrics**
1. Continuous Assessment: Test 1	All	20%	Individual	Point-based marking
2. Continuous Assessment: Test 2	All	20%	Individual	Point-based marking
3. Continuous Assessment: Homework	All	25%	Individual	Point-based marking
4. Continuous Assessment: Project presentation	All	35%	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

If you are sick and unable to attend class, you must:
1. Inform the course instructor via email prior to the start of the class,
2. Submit the original Medical Certificate* or official letter of excuse to NTU portal,
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, Quantum channels	1g	
Week 5	Quantum communication protocols, Quantum channels, Experimental quantum information: cold atoms Quiz 1	1f, 2a, 2c	
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, 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 Quiz 2	N.A.	Student presentations, lecture notes
Week 13	Student presentations Concluding remarks	N.A.	

Other information(s)

Nil.

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 5%	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.
Report structure & organization 10%	Provides a complete and thorough presentation of the appropriate concepts, theories and principles of the subject.	Provides a good presentation of the appropriate concepts, theories and principles of the subject.	Provides an acceptable presentation of the appropriate concepts, theories and principles of the subject.	Provides an unsatisfactory presentation of the appropriate concepts, theories and principles of the subject.
Scientific communication 15%	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 5%	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

Instructions for Report structure & organization:

- **Presentation** of the appropriate **concepts, theories and principles** of the problem
- **Explanation** of the **observed phenomena**
- **Application** of **appropriate mathematics**
- Reasonable **experimental technique** to **gather** and **record data** (or to **demonstrate** the **phenomena** if appropriate)
- Linking of **theoretical** and **experimental findings** to draw **suitable conclusions**
- Attempt to communicate **difficult** or **complex** ideas in an **effective** and **understandable** manner

Duration: Presentation (20 min) + Q&A (5 min) = Total 25 min