Nanyang Technological University
Division of Physics and Applied Physics

| | | | |
|---|---|---|---|
| **Academic Year** | 20/21 | **Semester** | 1 |
| **Course Coordinator** | Asst Prof Gu Mile | | |
| **Course Code** | PH3404 | | |
| **Course Title** | Physics of Classical and Quantum Information | | |
| **Pre-requisites** | (PH2101 Quantum Mechanics I & MH1402 Algorithms and Computing II)<br>OR<br>(PH2101 Quantum Mechanics I & MH2802 Linear Algebra for Scientists)<br>OR<br>(CZ1016 Introduction to Data Science & MH2802 Linear Algebra for Scientists)<br>OR<br>(CY1602 Mathematics II & CY1307 Relativity and Quantum Physics) | | |
| **No of AUs** | 3 | | |
| **Contact Hours** | Lectures: 26 hours (2 hours per week)<br>Tutorial: 12 hours (1 hour per week) | | |
| **Proposal Date** | 29 April 2020 | | |

**Course Aims**

This interdisciplinary course aims to arm you with the knowledge required to appreciate rapidly growing cross-disciplinary research frontiers that interface physics, information science and computation. You will be introduced to the fundamentals of classical and quantum information science and their underlying physical principles, which will give you the necessary expertise to follow and initiate research in the blossoming fields of information physics, quantum information, and quantum computation.

**Intended Learning Outcomes (ILO)**

By the end of this course, you (as a student) would be able to:

1. Describe uncertainty and correlations in terms information entropy, and apply these tools analytically to related problems in thermodynamics and computation.

2. Describe the fundamental conceptual differences between classical and quantum information (e.g. quantum non-realism), and show how these can lead to new technologies (e.g. quantum bomb detection).

**Course Content**

The 21st Century has seen a string of profound discoveries that interface physics, information theory and computer science. This course will introduce undergraduate students these exciting ideas. On completion of the course, students will appreciate how information theory has led to new understanding in physics, and how the discovery of new physics – such as quantum mechanics - has led to complete new ways of processing and transferring information.

Topics include

- *Computation and its physical consequences*: Turing machines, the physical Church-Turing thesis, Halting problem, computational complexity, emergence.

- *Introduction to information theory:* Quantifying information, Shannon entropy, correlations and mutual information.

- *Thermodynamics of information*: Maxwell's Demons, Szilard Engines, Landaur's Erasure, energetic limits of computation.

- *Introduction to quantum Information:* Quantum bits, quantum gates, quantum non-locality, quantum entanglement

- *Quantum technologies (time permitting):* A sampling of iconic quantum technologies, e.g. Quantum bomb detection, quantum teleportation.

**Course Outline**

| S/N | Topic | Lecture Hours | Tutorial Hours |
|---|---|---|---|
| 1 | Course introduction and Overview | 2 | 0 |
| 2 | Computation and its physical consequences | 4 | 2 |
| 3 | Introduction to information theory | 4 | 2 |
| 4 | Thermodynamics of information | 4 | 2 |
| 5 | Introduction to quantum Information | 6 | 3 |
| 6 | Quantum technologies | 6 | 3 |

**Assessment (includes both continuous and summative assessment)**

| **Component** | **Course LO Tested** | **Related Programme LO or Graduate Attributes** | **Weighting** | **Team/Individual** | **Assessment Rubrics** |
|---|---|---|---|---|---|
| 1. Final Examination | LO 1-2 | Competency: 1, 2, 4, 5<br><br>Creativity: 1 | 60% | Individual | Appendix 1:<br><br>2 hours closed book examination with formula sheet provided for students.<br>Structured questions |
| 2. Mid-term Test | LO 1-2 | Competency: 1, 2, 4, 5<br><br>Creativity: 1 | 20% | Individual | A 1 hour mid-term test, similar to the format of the final exam. |
| 3. Continuous Assessment 1 (CA1): Assignments | LO 1-2 | Competency: 1, 2, 3, 4, 5<br>Creativity: 1, 2<br>Character 2: | 20% | Individual | Four assignments, each worth 5%. |
| Total | | | 100% | | |

**Formative feedback**

The assignments/tests are aimed to give students a constant, continuing feedback on their understanding. The questions in the assignments are designed to extend what is described in classes – testing your capability of integrating what you have learnt and applying it to situations not been explicitly covered. Though, you will get feedback on your capacity to think in ways that cross traditional disciplinary boundaries.

Meanwhile the classes will be designed to have plenty of opportunity to discussion and dialogue. You will be encouraged in the class to describe your views and perspectives on the open questions in this field. This allows you the capacity to get real-tie feedback and how well they are following concepts being introduced.

**Learning and Teaching approach**

| **Approach** | **How does this approach support students in achieving the learning outcomes?** |
| --- | --- |
| Lectures | The lectures will help communicate the big ideas in of their 4 learning outcomes. This presents you with the conceptual knowledge necessary to achieve LO 1-2. |
| Tutorials | Tutorials will reinforce what is taught in the lectures by going into detail on how the big ideas introduced can be applied to specific problems. |

**Reading and References**

1. Nielsen, Michael A and Isaac L. Chuang. *Quantum computation and quantuminformation*. Cambridge university press, 2010, ISBN: 0-521-63503-9

2. Leff, Harvey, and Andrew F. Rex, eds. *Maxwell's Demon 2 Entropy, Classical and Quantum Information, Computing*. CRC Press, 2010, Chapter 1, ISBN: 9780750307598

**Course Policies and Student Responsibilities**

**(1) General**

You are expected to complete all assigned pre-class and post-class readings, attend all classes punctually and take all scheduled assignments and tests by due dates. Problems and solutions discussed in tutorials and lecturers may not necessarily be made available outside contact hours. You are expected to take responsibility for course notes, tutorials, assignments and course related announcements for classes you have missed. You are expected to participate in all class discussions and activities.

**(2) Compulsory Assignments**

You are required to submit compulsory assignments on their specified due dates. Late assignments will field a deduction of 10% per day without exceptions. Assignments are meant to rflect individual work, and plagiarism is taken very seriously. In the event of detection, plagiarized assignments will be given a mark of zero.

**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/P Gu Mile | SPMS-MAS-05-42 | +65 65137175 | gumile@ntu.edu.sg |
| | | | |
| | | | |
| | | | |

**Planned Weekly Schedule**

| Week | Topic | Course LO | Readings/ Activities |
|---|---|---|---|
| 1 | Course introduction and Overview | 1 | The Big ideas. Universe as Simulation |
| 2 | Links Between Physics Computation | 1 | Physical Church-Turing Thesis, Non-computability |
| 3 | Physical Models of Computation | 1 | Circuit Models, Unconventional Models, Cellular Automata |
| 4 | Computability and Physics | 1 | Halting Problem, Rice's Theorem and what they mean for Physics |
| 5 | Information Thermodynamics - Motivations | 1 | Maxwell's Demon, Information Engines |
| 6 | Introduction to Information Theory | 1 | Bits, Entropy and the Physical Meaning |

| | | | |
|---|---|---|---|
| 7 | Introduction to Information Theory | 1 | Correlations, Mutual Information |
| 8 | Information Thermodynamics – Conclusions | 1 | Minimal Energetic Costs of Computation |
| 9 | Introduction to Quantum Information | 2 | Review of Quantum Mechanics, what makes it different? |
| 10 | Introduction to Quantum Information | 2 | Quantum Bomb Detection |
| 11 | Introduction to Quantum Information | 2 | Qubits, Quantum Gates, |
| 12 | Quantum Technologies | 2 | Bell Inequalities and Applications |
| 13 | Quantum Technologies | 2 | Big Open Questions and Outlook |
| | | | |

**Appendix 1: Assessment Criteria for Final Exam**

By mark range

| Marks | Criteria |
|---|---|
| >= 85% | Demonstrate complete understanding of classical and quantum information, and their physical consequences as covered in lectures. Capable of applying this knowledge to analyze situations covered in class and to entirely new situations (e.g. Entirely new phenomena that was *not* covered in lectures). |
| 70% to 85% | Demonstrates excellent understanding of classical and quantum information, and their physical consequences as covered in lectures. Capable of applying this knowledge to analyze situations covered in class. Has partial success in applying these ideas to entirely new situations. |
| 60% to 69% | Demonstrates reasonable understanding of classical and quantum information and their physical consequences as covered in lectures. Exhibits some difficulty in applying this knowledge to analyze situations covered in lectures. Has great trouble in applying these ideas to entirely new situations. |
| 40% to 59% | Demonstrates basic understanding of classical and quantum information and their physical consequences as covered in lectures. Exhibits significant difficulty in applying this knowledge to analyze situations covered in lectures. Unable to apply these ideas to situations they have not already seen in lectures. |
| < 40% | Do not possess sufficient understanding of course content to answer basic questions that they have seen during lectures and tutorials. |

**Appendix 2: Assessment Criteria for Assignments**

By mark range

| Marks | Criteria |
|---|---|
| >= 85% | Able to solve basic questions that test basic course knowledge. Able to extend these to study an entirely new research problem, and deliver the solution to a problem they have not seen before. Capable of interpreting this solution and it describe its physical meaning in a creative manner. |
| 70% to 85% | Able to solve basic questions that test basic course knowledge. Able to extend these to study an entirely new research problem with partial success, and deliver partial solutions to a problem they have not seen before. Exhibits some success in describing the full physical consequences of their solution. |
| 60% to 69% | Able to solve most basic questions that test course knowledge. Exhibits some difficulty in applying these tools to new research problems, and solving problems they have not previous seen. Has trouble describing the physical consequences of their results. |
| 40% to 59% | Able to solve most basic questions that test course knowledge. Exhibits significant difficulty in applying these tools to new research problems, or solving problems they have not previous seen. Unable to satisfactorily interpret the physical consequences of their results. |
| < 40% | Unable to solve most of the basic questions that test course knowledge. Makes little or no attempt to extend these ideas to unfamiliar settings. Unable to interpret the physical meaning of their results at all. |

# 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 and PHMA 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<br><br>[PHMA 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. |