Model Curriculum for Minor Degree for UG Degree Course in

QUANTUM TECHNOLOGIES

2024
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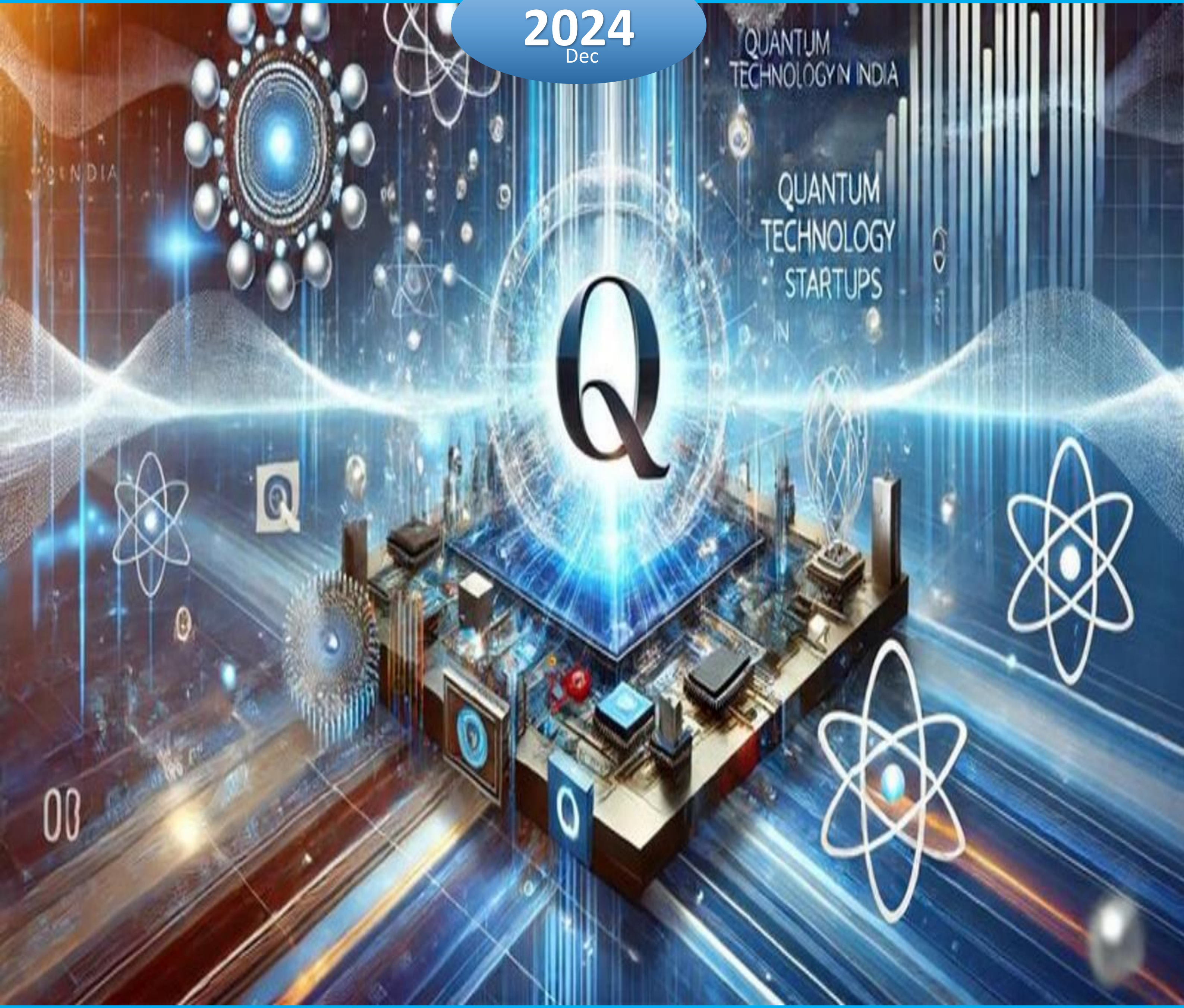

विज्ञान एवं प्रौद्योगिकी विभाग
DEPARTMENT OF
SCIENCE & TECHNOLOGY

All India Council for Technical Education
AICTE
योगः कर्मसु कौशलम्

National Quantum Mission

विज्ञान एवं प्रौद्योगिकी विभाग
DEPARTMENT OF
SCIENCE & TECHNOLOGY

MODEL CURRICULUM FOR MINOR DEGREE FOR UG DEGREE COURSE IN QUANTUM TECHNOLOGIES

ALL INDIA COUNCIL FOR TECHNICAL EDUCATION

NELSON MANDELA MARG, VASANT KUNJ, NEW DELHI 110070

www.aicte-india.org

प्रो. टी. जी. सीताराम
अध्यक्ष
Prof. T. G. Sitharam
FNAE, DGE, FASCE, FICE (UK)
Ph.D. (Univ of Waterloo, Canada), D.Sc
Post Doc (Univ of Texas, @Austin USA)
Chairman

सत्यमेव जयते

अखिल भारतीय तकनीकी शिक्षा परिषद्
(भारत सरकार का एक सांविधिक निकाय)
(शिक्षा मंत्रालय, भारत सरकार)
नेल्सन मंडेला मार्ग, वसंत कुंज, नई दिल्ली–110070
दूरभाष : 011–26131498
ई–मेल : chairman@aicte-india.org
ALL INDIA COUNCIL FOR TECHNICAL EDUCATION
(A STATUTORY BODY OF THE GOVT. OF INDIA)
(Ministry of Education, Govt. of India)
Nelson Mandela Marg, Vasant Kunj, New Delhi-110070
Phone : 011-26131498
E-mail : chairman@aicte-india.org

MESSAGE

As India takes monumental strides towards becoming a global leader in innovation and self-reliance, it gives me immense pride to announce Undergraduate Minor Degree in Quantum Technologies. This initiative, crafted in collaboration with AICTE and Department of Science & Technology (DST) under the National Quantum Mission (NQM), reaffirms our commitment to fostering a future-ready generation equipped to tackle the challenges of emerging technologies.

Under the ambit of the National Quantum Mission (NQM), this programme aims to harness the transformative potential of quantum technologies. The NQM reflects the Government of India's visionary approach to establishing India as a global hub for research, innovation, and application of quantum technologies. From breakthroughs in quantum computing and secure communication to advancements in sensing and materials science, the quantum revolution promises to redefine industries and address some of the most complex challenges of our time.

At the All India Council for Technical Education (AICTE), we recognize the pivotal role of quantum technologies in shaping the future. This initiative will equip students with a strong foundation in quantum principles and hands-on experience in real-world applications. By nurturing talent in this cutting-edge field, we are preparing the next generation of leaders who will drive India's quantum ecosystem forward.

I encourage educational institutions across the nation to embrace this transformative initiative. Together, we can cultivate a vibrant ecosystem of learning, research, and innovation, strengthening India's position as a world leader in science and technology.

Let us join hands to create a future where India innovates, and the world celebrates.

T. G. Sitharam
Prof. T.G. Sitharam

सत्यमेव जयते
प्रो. अभय करंदीकर
Prof. Abhay Karandikar

आज़ादी का अमृत महोत्सव

सचिव
भारत सरकार
विज्ञान एवं प्रौद्योगिकी मंत्रालय
विज्ञान एवं प्रौद्योगिकी विभाग
Secretary
Government of India
Ministry of Science and Technology
Department of Science and Technolo

31st December, 2024

MESSAGE

It is with great pride and enthusiasm that we present the Undergraduate Minor Programme on Quantum Technologies, a collaborative initiative by the Department of Science & Technology (DST) and the All India Council for Technical Education (AICTE) under the National Quantum Mission (NQM).

Quantum Technologies represent a new frontier in science and innovation, holding the promise of transformative advancements in computing, communication, sensing, and materials. This programme is designed to provide undergraduate students with a strong foundation in quantum principles and their practical applications, empowering them to become active contributors to India's quantum ecosystem.

This initiative reflects our commitment to nurturing a future-ready workforce equipped to harness the potential of emerging technologies. The programme curriculum has been crafted by leading experts and integrates theoretical insights with practical training to ensure holistic learning.

I encourage academic institutions across the country to adopt this programme and join us in creating a robust talent pipeline for quantum technologies. Together, we can accelerate India's journey to becoming a global leader in this critical domain.

I extend my sincere appreciation to all contributors and stakeholders for their dedication and vision in developing this programme. I am confident it will inspire and equip students to shape the future of science and technology in India and beyond.

(Abhay Karandikar)

Technology Bhavan, New Mehrauli Road, New Delhi - 110016
Tel: +91 11 26511439 / 26510068 | Fax: + 91 11 26863847 | e-mail: dstsec@nic.in | website: www.dst.gov.in

Preamble

Quantum technology is an emerging new paradigm that promises to disrupt and revolutionize computing, communication and sensing in the coming decades. Keeping in mind the immense strategic potential, and possibilities for unforeseen breakthroughs in research, the global investment from Governments alone exceeds 40 B$. In the Indian context, the National Quantum Mission from the Government of India is a decisive step in accelerating the nation's research in this field. To fulfil the mandates of the mission, India needs to develop a highly skilled workforce through immediate initiatives in teaching and training. The training imparted to this workforce must enable them to reach global standards, and simultaneously address the multi-disciplinary needs of quantum technology development -- from core hardware and back-end engineering support to algorithms for cryptography and machine learning. To create a thriving quantum-trained ecosystem in India it is thus imperative to introduce a dedicated curriculum at the undergraduate level, as well as at the post graduate level, along with programmes for faculty members and teachers involved in undergraduate and post graduate education. While institutes of national importance have begun programs to this end, expanding such training to a larger pool of institutes across the country enables the nation to tap into the vast resource of students who can then participate in the mission to accelerate its progress towards its goals.

In this context we propose the course structure for a minor program in Quantum Technologies at the undergraduate level. Here we consider Quantum Technologies to include all four verticals -- Quantum computation and simulation, Quantum communications and cryptography, Quantum sensing, Quantum materials and devices. We propose a curriculum spanning a minimum of 18 credits. We propose both theory and lab courses in this curriculum. We assume each course amounts to 3 credits (1 credit translating to 1 in-class contact hour per week for a theory course or 1 session of lab for 3 hours for a lab course), thereby making the minor program span a minimum of 6 courses. We propose a pool of courses amounting to 30+ credits, out of which any given institution may choose 18 credits depending on the availability of teachers in that institution. However, to retain the core mandate of the minor, we propose to make a couple courses mandatory. This flexibility in the curriculum, we believe, will allow institutions to readily start training students in one or more verticals of quantum technologies. We also believe that many of the listed courses may also be chosen as electives by students who do not opt for a minor in quantum technology. We also encourage institutions and students to incorporate project-based learning approaches wherever possible to enhance the impact of the curriculum.

We have designed the curriculum keeping in mind the diversity in the institutions, as well as the different engineering disciplines. We believe that this minor program can be taken up by students of ALL engineering disciplines from their third or fourth semester (assuming an 8 semester or 4-year undergraduate program as the standard format). The students undertaking this course need to be familiar with basic engineering mathematics (basic linear algebra, complex numbers, probability and statistics) and physics at high school level (newton's laws, optics, thermodynamics), along with the basics of programming (simple arithmetic operations, basic sorting and search algorithms). These basic prerequisites are easily met by most students after their first year of undergraduate engineering/science education. We designed the curriculum to contain a quick review of all the requisite basics to acknowledge the possibility that some students may not have them covered and still want to pursue this minor.

We believe that extensive training programs for teachers are necessary to enable them to do justice to the goals of the minor program. Such sustained teacher training efforts will also enhance the quality of the training imparted to students over the years leading to long-term benefits and enable India to become a world leader in this field. We also believe that a textbook writing exercise should be carried out, such that topics in quantum technologies

Committee for Model Curriculum

S.No	Name	Organisation	Designation
1	Prof. Arindam Ghosh	IISc	Chairman
2	Dr. Anindita Banerjee	C-DAC, Pune	Member
3	Prof. Rajendra Singh	IIT Delhi	Member
4	Prof. Kasturi Saha	IIT Bombay	Member
5	Prof. Baladitya Suri	IISc	Member
6	Prof. Sunil Nair	IISER Pune	Member
7	Dr. Swati Rawal	Scientist, DST	Member
8	Sh. Sridhar CV	Head Quantum Initiatives, TCS	Member
9	Sh. L Venkata Subramaniam	IBM,Quantum India	Member
10	Sh. Vijaya Koumar	Inlamobi	Member

Proposed structure of the program

Concept of Minor Degree:

• With a view to enhance the employability skills and impart deep knowledge in emerging areas which are usually not being covered in Undergraduate Degree credit framework, AICTE has come up with the concept of '**Minor Degree**' in emerging areas.

• AICTE approval is not required for offering Minor Degree/Hons. in any such area, however the criteria is "Minor Degree or Hons. will cumulatively require additional 18 to 20 credits in the specified area in addition to the credits essential for obtaining the Undergraduate Degree in Major Discipline (i.e. 160 credits)".

Definition of Credit:

1 Hr. Lecture (L) per week	1 Credit
1 Hr. Social (T) per week	1 Credit
1 Hr. Practical (P) per week	0.5 Credit
2 Hours Practical (P) per week	1 Credit

Minimum credits to fulfil – 18

- A 3:0 course amounts to at least 36 hours of lectures (considering holidays, exam days etc.) per semester, assuming an average length of 14 weeks for the semester.
- A **n:m** lab course has **n** hours of lectures and **m** sessions (2 hours each) of lab per week.
- The proposed course structure is only to provide a guideline. Based on the available teaching resources, an institute may choose to add more modules, having covered the ones mentioned here.
- Project Based Learning (PBL) is encouraged and institutes must try to incorporate projects related to the domain of the minor degree wherever possible.

Table of Courses

Course code	Title	Credits (Theory: Lab)
QT 01 and QT 02 are both Mandatory		
QT 01	Survey of Quantum technologies and Applications	3:0
QT 02	Foundations of Quantum Technologies	3:0
At least one of QT 03 and QT 04 is Mandatory		
QT 03	Basic Programming Lab	2:1
QT 04	Basic Laboratory Course for Quantum Technologies	2:1
At least one of QT 05, QT 06, QT 07, QT 08 is Mandatory		
QT 05	Introduction to Quantum Computation	3:0
QT 06	Introduction to Quantum Communication	3:0
QT 07	Introduction to Quantum Sensing	3:0
QT 08	Introduction to Quantum Materials	3:0
Optional / Additional Courses		
QT 09	Engineering Foundations of Quantum Technologies	3:0
QT 10	Solid State Physics for Quantum Technologies	3:0
QT 11	Quantum Optics	3:0

Prerequisites for all courses: Engineering Mathematics (Linear Algebra, Complex algebra, basics of 2nd of ODEs and initial value problems, 2nd order PDEs and boundary value problems, Probability and Statistics, Random variables). Maxwell's equations and EM theory at the level of the core physics syllabus from AICTE model curriculum.

QT 01: Survey of Quantum Technologies and Applications 3:0 (Mandatory)

This course is meant to give an overview of the field of quantum technologies and make the students familiar with the state-of-the-art in all four verticals. The emphasis is not on depth in this course, but on covering the exciting aspects of the field.

Course Content and syllabus:

- Quantum Technologies – four verticals (1 lecture)
    - Motivation for Quantum Technologies
- A qualitative overview of salient aspects of quantum physics (4-5 lectures)
    - Quantum States, Wavefunctions, Probabilistic interpretation
    - Physical observables, Hermitian operators, expectation values
    - Heisenberg uncertainty principle
    - Schrodinger equation, Time evolution
    - distinction from classical physics
    - Heuristic description of Superposition, Tunnelling and entanglement
    - No cloning theorem
    - Simulating classical systems – Feynman's idea of a quantum simulator and the birth of the field
- Quantum Computation (10-12 lectures)
    - Basics of qubits -- what is a qubit?
    - How is it different from a classical bit? – Review of classical logic gates
    - Di Vincenzo criteria for realising qubits
    - Basics of qubit gates and quantum circuits
    - Physical implementation of qubits (very qualitative description)
        - Solid State Qubits
            - Semiconducting Qubits – quantum dots, spins
            - Superconducting Qubits – charge, flux and phase
            - Topological Qubits – proposals and advantages
        - Atoms and Ions
            - Trapped ions
            - Rydberg atoms
            - Neutral atoms
        - Photonic Qubits
            - Conventional linear optical setups
            - Integrated Photonics
        - NMR qubits
            - Conventional NMR qubits
            - NV centres
    - Overview of applications and recent achievements

            - RSA and Shor’s algorithm
            - Quantum Advantage
        - Long term goals and strategies being followed
            - Error correction
- Quantum Sensing (8-10 lectures)
    - Basics of quantum sensing
    - Basics of Photon (single and entangled) generation and detection
    - Gravimetry
    - Atomic clock
    - Magnetometry
    - State of the art in Quantum Sensing
- Quantum Communications (8-10 lectures)
    - Basics of digital communication
    - Quantifying classical information – Shannon entropy
    - Basic ideas of quantum communication, security, eavesdropping
    - Overview of quantum communication achievements
        - Terrestrial – fibre-based
        - Free space, Satellite-based
- **Topics on Quantum Materials are to be covered in the other portions of the course wherever required and are not listed separately here.**

Course Outcomes:

Students of this course learn:

1. The general physical principles of realising qubits for computation
2. The various hardware implementations of qubits for computation
3. The basic ideas of quantum sensing
4. The applications of quantum sensing
5. The implementations of quantum communications protocols in fibre-based and free-space

Course References:

1. Quantum Information Science – Manenti R., Motta M., 1st Edition, Oxford University Press (2023)
2. Quantum computation and quantum information – Nielsen M. A., and Chuang I. L., 10th Anniversary edition, Cambridge University Press (2010)
3. Elements of Quantum Computation and Quantum Communication, A. Pathak, Boca Raton, CRC Press (2015)
4. An Introduction to Quantum Computing, Phillip Kaye, Raymond Laflamme, and Michele Mosca, Oxford University Press (2006)
5. Quantum computing explained, David McMahon, Wiley (2008)

QT 02: Foundations of Quantum Technologies, 3:0 (Mandatory)

This course is meant for laying down the central theoretical aspects of quantum mechanics in a rigorous manner where students learn the techniques and develop a good intuition for quantum physics.

Course Content and syllabus:

- Quantum Mechanics **(16 - 18 lectures):**
    - Brief overview of classical physics (This segment is meant for the student to understand what a Hamiltonian is, which will feature later in quantum mechanics)
        - Hamiltonian function and Hamilton’s equations
        - Phase-space description of a system
        - Connection and Equivalence with Newton’s laws for simple systems – free particle, particle moving in a conservative potential, examples of Harmonic oscillator, hydrogen atom
    - Historical evolution of quantum mechanics
        - Planck’s quantum hypothesis
        - Photo electric effect
        - Atomic spectra
        - Bohr’s quantisation principle
        - De Broglie’s Wave particle duality
    - Postulates of Quantum Mechanics
        - State vectors and Hilbert Space
        - Dirac Bra-Ket notation
        - Measurables and Hermitian Operators
        - Unitary Transformations
        - Schrodinger Equation and Time evolution of quantum states
        - Measurement Postulate
        - Schrodinger, Heisenberg and Interaction pictures
        - Eigen values, Expectation values and Matrix elements
        - Heisenberg’s Uncertainty principle
    - Density operator formalism of quantum mechanics – pure and mixed states
    - Superposition and Entanglement in quantum mechanics
    - No cloning theorem
    - Applications of postulates –Particle in a box, Hydrogen atom, Harmonic Oscillator
    - Number states, ladder operators and Coherent states of a harmonic oscillator
    - Spin and Angular momentum – spin half particles
    - Rabi problem of a spin-half particle in a rotating magnetic field

        - Bosons and Fermions
- Statistical Physics (8-10 lectures)
    - Quick review of first and second laws of thermodynamics
    - Thermal Equilibrium and Gibbs principle
    - Applying Gibbs principle to Classical and Quantum harmonic oscillators
    - Bosons and Fermions and Quantum statistics – Fermi-Dirac and Bose-Einstein distributions
- Information Science (3-4 lectures)
    - Digital communication and information
        - Quantifying information in terms of Shannon entropy
    - Basic ideas of quantum information
    - Decoherence and noise
    - Introductory ideas of Kraus operators
- Brief overview of Computational Complexity (5-6 lectures)
    - Qualitative ideas of a Turing machine
        - Types of Turing machines
    - Time and Space complexity – P vs NP, PSPACE
    - Quantum complexity classes – Q, EQP, BQP, BPP, QMA
    - Post Quantum Cryptography (PQC)

Course Outcomes:

Students of this course learn

1. The most relevant mathematical techniques
2. Basic postulates of quantum mechanics and applications
3. Basics of Statistical Physics
4. Basics of Information Science
5. Basics of computational complexity

Course References:

1. Introduction to Quantum Mechanics, Griffiths D. J., 3rd Edition, Cambridge University Press (2024)
2. Introduction to Electrodynamics, Griffiths D. J., 4th edition, Cambridge University Press (2020)
3. Principles of Quantum Mechanics, Shankar, R., 2nd edition, Springer (2014)
4. Quantum Information Science – Manenti R., Motta M., 1st Edition, Oxford University Press (2023)
5. Quantum computation and quantum information – Nielsen M. A., and Chuang I. L., 10th Anniversary edition, Cambridge University Press (2010)
6. A Pathak, Elements of Quantum Computation and Quantum Communication, Boca Raton, CRC Press (2015)
7. Information Theory, Robert B. Ash, Dover Publications (2003)
8. Introduction to the Theory of Computation, Michael Sipser, 3rd edition, Cengage India Pvt. Ltd. (2014)
9. Statistical Mechanics, Pathria R. K., Paul D. Beale, 4th edition, Academic Press, (2021)

QT 03: Basic Programming Lab (2:1)
(Out of QT 03 and QT 04, at least ONE is mandatory)

This course is meant to provide students a quick hands-on experience in scientific computing and its applications to areas within Quantum Technologies.

Course Content and syllabus:

- Basics of programming
    - Data structures, classes, Object-oriented programming
    - Data storage and retrieval, Memory allocation
    - Scientific plotting, documentation of codes
- Simple algorithms and benchmarking run time
    - Sorting
    - Searching
    - Arithmetic algorithms like GCD, Prime factorisation
- Numerical Integration and differential equations
    - Linear 2nd Order ODEs with constant coefficients
    - Linear 2nd order ODEs with variable coefficients
    - Boundary value problems
        - Poisson equation
        - Laplace equation
        - Wave equation
        - Diffusion Equation
- Numerical techniques in linear algebra
    - Matrix inverse
    - Eigenvalue problem
    - Diagonalisation of matrices
    - Singular value decomposition
- Numerical techniques in Probability and Statistics
    - (Pseudo) Random number generation
    - Computing statistical moments for data samples
    - Least Squares fitting
    - Error Analysis
    - Hypothesis Testing
    - Monte Carlo sampling
- Applications to Quantum Mechanics (can be done using openly available modules in languages like Python, Julia etc.)
    - Eigen energies of coupled two level systems
    - Eigen energies of two-level system coupled to oscillator (Jaynes-Cummings Model)
    - Driven two-level system – Rabi Problem
    - Driven damped oscillator — coherent states

- Applications to EM theory (e.g. magnetic field simulation)
    - Electrostatic charge distributions
    - Magnetostatic current distributions
    - Finite Element techniques for electromagnetic simulations

Course outcomes:

Students of this course learn

1. Basics of programming
2. To write programs to solve scientific problems
3. Techniques for scientific computing
4. Applications to quantum mechanics and electromagnetism

Course References:

- Computational Physics, Nicholas Giordano, Hisao Nakanishi, 2nd edition, Pearson-Addison Wesley (2005)

QT 04: Basic Laboratory Course for Quantum Technologies (2:1)
(Out of QT 03 and QT 04, at least ONE is mandatory)

Course Content and syllabus:

- Optics
    - Interferometry – wavelength measurements, intensity measurements
    - Diffraction – single slit, grating
    - Microscopy – magnification, aberration
    - Polarization optics – PBS, HWP, QWP
- RLC circuits
    - Series and parallel RLC circuits – Verifying the quality factor formulae
    - Extracting intrinsic losses
- Digital circuits
    - Adder, Multiplier
    - Encoder, Decoder
    - D flipflop, shift registers
    - How to use common Integrated Circuit chips
- Radio Frequency Technology:
    - Using Oscilloscope
        - Ring-up and ring-down time measurements of RLC circuits
        - Measurements of different pulse-shapes generated by a function generator
    - Using Vector Network Analyser
        - Transmission and reflection measurements of coaxial cable in open, short and matched termination
        - Voltage standing wave ratio measurement
        - Amplitude and Phase quadrature, In-phase and Out-of-phase quadrature plots and Quality factor measurement of RLC circuits
        - Characterising S-parameters, ABCD and Z matrices of common 2 port networks – coaxial cable, attenuator, low pass high pass bandpass filters etc.
        - Characterising 3 port networks – directional couplers, circulators, isolators
    - Using a spectrum analyser
        - Noise from a resistor at different temperatures

- Interfacing instruments with a computer

- Data acquisition
    - Signal demodulation – heterodyne vs Homodyne, Mixing of signals
    - Sampling, digitisation using ADCs – under-sampling and aliasing, oversampling and noise

    - Averaging and interpolation techniques
- Quantum Simulators
    - Running quantum protocols in a quantum simulator
    - Implementing simple quantum algorithms on cloud-based quantum computers (depending on availability of time on such machines)
- Running simple algorithms on cloud-based quantum processors (optional)

Course outcomes:

Students of this course learn

1. Basic experimental techniques in optics
2. Basic experimental techniques in characterising resonators and RLC circuits
3. Basic digital circuits
4. Fundamental techniques in RF engineering
5. Interfacing instruments with computers and carry out data acquisition

Course References:

1. Optics, Eugene Hecht, A. R. Ganesan, 5th edition, Pearson (2019)
2. Art of Electronics, Paul Horowitz and Winfield Hill, 3rd edition, Cambridge University Press (2015)
3. Digital Design, Morris Mano, Michael D. Cilletti, 6th edition, Pearson Education (2018)
4. Microwave Engineering, David Pozar, 4th edition, Wiley (2013)
5. Discrete-time signal processing, Alan V. Oppenheim and Ronald W. Shaffer, 4th edition, Pearson (2009)
6. Optical quantum information and quantum communication, A. Pathak and A. Banerjee, SPIE Spotlight Series, SPIE Press (2016)

QT 05: Introduction to Quantum Computation 3:0
(Out of QT 05, QT 06, QT 07 and QT 08, at least ONE is mandatory)

Course Content and syllabus:

- Qubits versus classical bits
    - Spin-half systems and photon polarizations
    - Trapped atoms and ions
    - Artificial atoms using circuits
    - Semiconducting quantum dots
    - Single and Two qubit gates – Solovay - Kitaev Theorem
- Quantum correlations
    - Entanglement and Bell’s theorems
- Review of Turing machines and classical computational complexity
    - Time and space complexity (P, NP, PSPACE)
- Reversible computation
- Universal quantum logic gates and circuits
- Quantum algorithms
    - Deutsch algorithm
    - Deutsch Josza algorithm
    - Bernstein - Vazirani algorithm
    - Simon’s algorithm
- Database search
    - Grover’s algorithm
- Quantum Fourier Transform and prime factorization
    - Shor’s Algorithm.
- Quantum complexity classes – Q, EQP, BQP, BPP, QMA
- Additional Topics in Quantum Algorithms
    - Variational Quantum Eigensolver (VQE)
    - HHL
    - QAOA
- Introduction to Error correction
    - Fault-tolerance
    - Simple error correcting codes
- Survey of current status
    - NISQ era processors
    - Quantum advantage claims
    - Roadmap for future

Course outcomes:

Students of this course learn

1. To review the basic postulates of quantum mechanics
2. The theoretical basics of qubits and their physical realisations

3. To work with density operators and time evolution for mixed states
4. The basic ideas of quantum gates
5. The working of important quantum algorithms
6. The basics of quantum error correction

Course References:

1. Quantum Information Science – Manenti R., Motta M., 1st Edition, Oxford University Press (2023)
2. Quantum computation and quantum information – Nielsen M. A., and Chuang I. L., 10th Anniversary edition, Cambridge University Press (2010)
3. A Pathak, Elements of Quantum Computation and Quantum Communication, Boca Raton, CRC Press (2015)
4. Quantum error correction and Fault tolerant computing, Frank Gaitan, 1st edition, CRC Press (2008)
5. Quantum computing explained, David McMahon, Wiley (2008)
6. Introduction to Quantum Computing: From a lay person to a programmer in 30 steps, Hui Yung Wong, 1st edition, Springer-Nature Switzerland AG (2022)

QT 06: Introduction to Quantum Communication
(Out of QT 05, QT 06, QT 07 and QT 08, at least ONE is mandatory)

Course Content and syllabus:

- Basics of Polarization optics
    - Quarter and half-wave plates
    - Polarizing beam splitters
- Basics of linear and square-law detectors
    - Quadrature amplitude modulation
    - Heterodyne and Homodyne demodulation and linear detectors
    - Intensity measurements and square law detectors
    - Photomultipliers, Avalanche Photo diodes
- Digital communication – information theory (basics)
    - Information entropy
    - Noiseless channel encoding
    - Noisy channel encoding
- No cloning theorem
- Quantum Memories
- Quantum repeaters
- Entanglement and Bell Theorems
- Bell Measurements and Tests
- Quantum Teleportation protocol
- Quantum Dense coding
- Quantum Key Distribution protocols
    - BB84
    - E91
    - BBM92.
    - B92
    - COW
    - DPS
- Quantum Networks and Quantum Internet
- Survey of Hardware implementations
    - Free space communications
    - Satellite based communications
    - Fibre optics-based communications

Course Outcomes:

Students of this course learn

1. The basics of EM theory
2. The basics of photodetection
3. The basics of information theory
4. The central ideas in quantum communications

Course References:

1. Quantum computation and quantum information – Nielsen and Chuang Cambridge University Press, Cambridge (2010)
2. A Pathak, Elements of Quantum Computation and Quantum Communication, Boca Raton, CRC Press (2015)

QT 07: Introduction to Quantum Sensing 3:0
(Out of QT 05, QT 06, QT 07 and QT 08, at least ONE is mandatory)

Course Content and syllabus:

- Classical sensing
  - Photo detection
- Classical noise
  - Johnson Noise, Telegraph noise, flicker or 1/f noise
- Sensitivity of classical measurements
  - Classical Fisher information
  - Cramer - Rao bounds (information theory basics may be required here).
- Quantum measurements
  - projective/orthogonal measurements
  - Approximate/non-orthogonal measurements
  - Weak continuous measurements
  - Error-disturbance relations
  - Standard quantum limits
  - Quantum non-demolition measurements
- States of light
  - Fock states
  - Coherent states
  - Squeezed states
  - Tomography
  - Wigner quasi-probability distribution
  - P-distribution
  - Husimi Q function
- Quantum photo detection
  - Square-law detectors, Intensity measurements and Photo-detection
  - Linear Detectors and Quadrature Measurements
- Quantum Cramer-Rao bounds
- Single photon-based sensing applications
- Entanglement based sensing applications
- Atomic state-based sensing, solid-state spin-based sensing applications (gravimetry, magnetometry)

Course Outcomes:

Students of this course learn

1. The basics of classical sensing
2. Aspects of quantum measurement
3. Ways to quantify quantum sensing
4. About measurements of quantum states of light
5. About the applications of quantum sensing

Course References:

1. Quantum Measurement and Control, Howard Wiseman and David Milburn, Cambridge University Press (2014)
2. Quantum Measurement, Vladimir Braginsky and Farid Ya Khalili, Cambridge University Press (1995)
3. Quantum Information Science – Manenti R., Motta M., 1st Edition, Oxford University Press (2023)

QT 08: Introduction to Quantum Materials 3:0
(Out of QT 05, QT 06, QT 07 and QT 08, at least ONE is mandatory)

Course Content and syllabus:

- Band theory basics
  - Metals, Semiconductors and Insulators
  - Band structure of solids
  - Survey of semiconducting devices for quantum technologies (electronic, quantum optical devices and principle of operation)
- Correlated systems
- Magnetism
  - Para, ferro magnetism basics
  - Magnetic measurements, hall effect, magnetoresistance
  - Faraday and Kerr effects
- Superconductivity
  - BCS theory
  - Ginzburg Landau
  - Josephson Effect – AC and DC Josephson effects
  - Survey of superconducting devices for quantum technologies
- 2D materials
  - Graphene and its properties – single and few layers
  - Transition Metal Dichalcogenides – Electronic and Optical Properties
- Topological Phases of matter
  - Basics of Topology
  - Geometric phases - Berry Phase
  - Aharonov Bohm effect
  - Topological phases of matter
- Survey of material growth techniques
  - Molecular beam epitaxy
  - Chemical vapor deposition, MOVPE
  - Pulsed laser deposition, etc.
  - Crystal growth techniques

Course Outcomes:

Students of this course learn

1. The basic idea of quantum materials
2. The basics of band theory of solids
3. The basics of magnetism
4. The basics of superconductivity
5. About new 2D materials like graphene, TMDCs
6. About topology and topological phases of matter

Course References:

1. Condensed Matter Physics, M P Marder, 2nd Edition, John Wiley and Sons, 2010
2. Introduction to Superconductivity, Michael Tinkham, standard ed., Medtech (2017)

QT 09: Engineering Foundations of Quantum Technologies 3:0 (optional / additional)

This course is meant to cover topics in electrical, electronics and communication engineering, as well as in computer science that are relevant to Quantum computation, Communications and Sensing. This is a survey course and not meant for a rigorous treatment of each topic.

Course Content and syllabus:

- Electrical Networks (4 hours)
  - Analog RLC circuits – resonances, impedances, quality factors
  - Transmission line basics (2 hours)
    - Telegrapher equations, wave impedance, impedance matching, transmission line resonators
- Computer Science (15 hours)
  - Basics of computer architecture (1 hour)
    - Arithmetic Logic Unit
    - Memory
  - Abstract models of computation (12 hours)
    - Finite State Machine
    - Turing Machines
    - Overview of Hierarchy of languages – Regular, Context-Free, Turing Decidable and Turing Recognisable
  - Complexity Theory (2 hours)
    - Time and Space complexity
    - P vs NP, NP-completeness
- Electrical Communications (1 hour)
  - Analog Communications (1 hour)
    - Quadrature amplitude modulation
    - Heterodyne and Homodyne demodulation
- Noise and Signals (6 hours)
  - Characterising Noise
  - Types of Noise
    - Shot Noise
    - Johnson-Nyquist Noise
    - Telegraphic noise or flicker or 1/f noise
  - Signal conditioning and noise mitigation
  - Amplification and Added Noise
    - Linear Amplifier theory
    - Signal-Noise Ratio, Added Noise, Noise Figure of amplification
    - Dynamic Range
    - Noise temperature
    - Quantum limits on noise in linear amplifiers

- Digital Communications (4 hours)
    - Information entropy
    - Noiseless channel encoding
    - Noisy channel encoding
- Basics of cryptography (6 hours)
    - Basics of Number Theory
    - Random Number Generation
    - One time pad, Private key, public key, symmetric and asymmetric cryptography protocols
    - RSA and DH
    - Post Quantum Cryptography (PQC)

Course Outcomes:

Students of this course learn

1. Relevant topics from Electrical Networks to design and analyse analog circuits
2. Relevant topics from RF and Microwave Engineering to design systems
3. Relevant topics in Theory of computation to benchmark algorithms
4. Relevant topics in analog and digital communications
5. Basics of cryptography

Course References:

1. Art of Electronics, Paul Horowitz and Winfield Hill, 3rd edition, Cambridge University Press (2015)
2. Digital Design, Morris Mano, Michael D. Cilletti, 6th edition, Pearson Education (2018)
3. Microwave Engineering, David Pozar, 4th edition, Wiley (2013)
4. Information Theory, Robert B. Ash, Dover Publications (2003)
5. Introduction to the Theory of Computation, Michael Sipser, 3rd edition, Cengage India Pvt. Ltd. (2014)
6. Protecting Information – From Classical error correction to quantum cryptography, Susan Loepp and William K. Wootters, Cambridge University Press (2006)

QT 10: Solid State Physics for Quantum Technologies 3:0 (optional / additional)

Course Content and syllabus:

- Structure of solids –
  - Symmetry, Bravais lattices
  - Laue equations and Bragg's law,
  - Brillouin Zones
  - Atomic scattering and structure factors.
- Characterisation of crystal structures – XRD etc.
- Bonding in solids –
  - van der Waals and Repulsive interactions,
  - Lennard Jones potential,
  - Madelung constant
- The Drude theory of metals –
  - DC & AC electrical conductivity of a metal;
  - Hall effect & magnetoresistance,
  - Density of states, Fermi-Dirac distribution, Specific heat of degenerate electron gases
  - Free electron model
- Beyond the Free electron model
  - Kronig-Penney Model
  - Periodic potential – Bloch Theorem
  - Band theory
  - Tight binding model
- Phonons in Solids
  - One dimensional monoatomic and diatomic chains
  - Normal modes and Phonons
  - Phonon spectrum
  - Long wavelength acoustic phonons and elastic constants
  - Vibrational Properties- normal modes, acoustic and optical phonons.
- Magnetism
  - Dia-, Para-, and Ferromagnetism
  - Langevin's theory of paramagnetism
  - Weiss Molecular theory
- Superconductivity:
  - Phenomenological description – Zero resistance, Meissner effect
  - London Theory
  - BCS theory
  - Ginzburg-Landau Theory
  - Type-I and type-II superconductors
  - Flux quantization

  - ○ Josephson effect.
  - ○ High Tc superconductivity

Course Outcomes:

Students of this course learn

1. Basics of solid states physics
2. Various approximations for electronic states in matter
3. The theory of phonons in solids
4. The theory of magnetism
5. The theory of superconductivity

Course References:

1. Introduction to Solid State Physics, Charles Kittel, Wiley India Edition (2019)
2. Condensed Matter Physics, M P Marder, 2nd Edition, John Wiley and Sons (2010)
3. Introduction to Superconductivity, Michael Tinkham, standard edition, Medtech (2017)

QT 11: Quantum Optics 3:0
(optional / additional)

Course Content and syllabus:

- Quantization of the electromagnetic field
    - Number states, coherent states, squeezed states
    - Hanbury-Brown and Twiss experiments – Photon bunching, Photon anti bunching
    - Hong-Ou-Mandel interference
- Theory of Optical coherence
    - Young's double slit experiment and first order coherence
    - Coherence functions of arbitrary order
    - Normal ordering, symmetric ordering and ani-normal ordering of operators
    - Interferometry
- Phase-space representations of states of light
    - Wigner distribution
    - P-function and the notion of non-classicality with some examples of nonclassical states like squeezed states and their applications
    - Husimi Q function
- Light-matter interaction
    - Classical model of light-matter interaction
    - Semi-classical model of light-matter interaction-
    - Quantum light-matter interaction
    - Rabi Model
    - Jayne's-cummings model
- Open quantum systems
    - Fermi golden rule
    - Born-Markov Lindblad Master Equation

Course Outcomes:

Students of this course learn

1. To quantise the electromagnetic field
2. The various experimental techniques in photonics
3. The various representations of states of light
4. Classical, semi-classical and fully quantum models of light-matter interaction
5. Modelling decoherence through Master equation

Course References:

1. Introductory Quantum Optics, Christopher Gerry and Peter Knight, Cambridge University Press (2004)
2. Quantum Optics, D. F. Walls, Gerard J. Milburn, 2nd Edition, Springer (2008)
3. Quantum Optics: An introduction, Mark Fox, Oxford University Publishers (2006)
4. Quantum Optics for Beginners, Z. Ficek and M. R. Wahiddin, 1st edition, Jenny Stanford Publishing (2014)

ALL INDIA COUNCIL FOR TECHNICAL EDUCATION
NELSON MANDELA MARG, VASANT KUNJ, NEW DELHI 110070
www.aicte-india.org