Quantum Engineering and Technology (QET)

Developed by Luca Dal Negro

Course Syllabus

Shall I refuse my dinner because I do not fully understand the process of digestion?
No, not if I am satisfied with the result. (O. Heaviside, Electromagnetic Theory, vol. 2, 1899)

1. **General introduction to the course** (2 lectures)
    - 1.1.1. The quantum manifesto
    - 1.1.2. Quantum technology in industry
    - 1.1.3. Quantum engineers
    - 1.2. *Thinking and questioning in quantum mechanics*
        - 1.2.1. The logic of quantum mechanics through examples
            - 1.2.1.1. Stern-Gerlach (SG) and double slit experiments
            - 1.2.1.2. Sequential choice experiments
            - 1.2.1.3. Wheeler's delayed-choice experiment
        - 1.2.2. Excerpts from the Bohr–Einstein debate

2. **A toolbox for quantum engineers** (8 lectures)
    - 2.1. *Description of physical systems in quantum mechanics*
        - 2.1.1. Classical versus quantum systems
        - 2.1.2. Dynamical variables
        - 2.1.3. State description approach
    - 2.2. *The algebra of quantum mechanics*
        - 2.2.1. Linear algebra in Dirac notation
        - 2.2.2. Hilbert Space and function spaces
        - 2.2.3. Linear operators and spectral decompositions
    - 2.3. *Operator representations: discrete and continuous bases*
        - 2.3.1. Quantum dynamics
        - 2.3.2. Commutators and general uncertainty relations
    - 2.4. *Measurements in quantum mechanics*
        - 2.4.1. Noise and decoherence
        - 2.4.2. Detector back-action and Rabi spectroscopy
        - 2.4.3. Quantum non-demolition (QND) measurements
        - 2.4.4. Weak measurements and the quantum Zeno effect

3. **Quantum principles in action** (4 lectures)
    - 3.1. *Interfering probabilities*
        - 3.1.1. Superposition of quantum amplitudes
        - 3.1.2. Uncertainty description and the density operator
    - 3.2. *Quantum oscillations*
        - 3.2.1. Harmonic oscillators
        - 3.2.2. General two-level systems
        - 3.2.3. Examples using quantum spin and polarization
    - 3.3. Light matter interaction
        - 3.3.1. The Fermi golden rule
        - 3.3.2. Strong coupling
    - 3.4. *Composite systems*
        - 3.4.1. Entangled states
        - 3.4.2. Quantum correlations
        - 3.4.3. Bell's theorem

4. **Quantum technology** (5 lectures)
    4.1. *Quantum metrology and sensing*
        4.1.1. Interferometry with matter waves
        4.1.2. Quantum imaging and lithography
        4.1.3. Remote sensing
        4.1.4. Quantum radars
    4.2. *Quantum communication and cryptography*
        4.2.1. Classical logic and computation
        4.2.2. Qubits in quantum computation
    4.3. *Quantum gates and circuits*
        4.3.1. Universal quantum gates
        4.3.2. The no- theorems
        4.3.3. Quantum key distribution
    4.4. Quantum programming
        4.4.1. The IBM Quantum Experience
    4.5. A survey of quantum technology in industry
        4.5.1. Google AI Sycamore quantum processor
        4.5.2. The IBM Q System One
        4.5.3. The Quantum Artificial Intelligence Lab
        4.5.4. D-Wave Systems

5. **Photons and atoms as quantum information carriers** (4 lectures)
    5.1. *Photons and single-photon sources*
        5.1.1. Entangled photon sources
        5.1.2. Quantum communication with single photons
    5.2. *Solid-state quantum qubits*
        5.2.1. Quantum memories
        5.2.2. Quantum networks
    5.3. *Physical implementations of quantum devices*
        5.3.1. Photons and spin systems
        5.3.2. High Q optical cavities and photon circuits
        5.3.3. Quantum transport in low dimensional structures
        5.3.4. Quantum noise and decoherence
    5.4. Emerging directions for quantum supremacy
        5.4.1. Quantum metamaterials and transmission lines
        5.4.2. Adiabatic quantum computing (AQC)
        5.4.3. Quantum engines
        5.4.4. Quantum learning

Topics for final projects

- 1.1. EPR and non-locality
  - 1.1.1. Local realism
  - 1.1.2. Testing non-locality
- 1.2. Superconducting quantum circuits
- 1.3. Quantum neural networks
- 1.4. Industry and quantum technology
  - 1.4.1. Rigetti Computing
  - 1.4.2. The Quantum Artificial Intelligence Lab
- 1.5. The quantum internet
- 1.6. Quantum imaging
- 1.7. Low-dimensional quantum devices
- 1.8. Quantum algorithms
  - 1.8.1. The BB84 protocol
  - 1.8.2. Deutsch's algorithm
  - 1.8.3. Shor's algorithm
  - 1.8.4. Grover's searches
  - 1.8.5. Super-dense coding

Textbook

Quantum Engineering: Theory and Design of Quantum Coherent Structures, by A. M. Zagoskin, Cambridge University Press. 2011

<u>Notes prepared by the instructor will be distributed.</u>

Additional references

- *Introduction to Optical Quantum Information Processing*, by Pieter Kok and Brendon W. Lovett, Cambridge University Press, 2010
- *Quantum Mechanics: Fundamentals and applications to technology*, by J. Singh, John Wiley and Sons, 1997
- *Quantum computation and information*, by Michael A. Nielsen and Isaak L. Chuang, Cambridge University Press, 2011
- *Quantum computing for everyone,* by Chris Bernhardt, MIT Press, 2019
- *Quantum Mechanics: The theoretical minimum* by L. Susskind and A Friedman, Basic Books 2014 (<u>attention:</u> strongly advised to read this book independently before the beginning of the course)

Prerequisites: CAS MA 225 (Multivariate Calculus), Linear Algebra, **ENG EK 127/128** (Engineering Computation), **ENG EK 102/CAS MA 142** (Intro linear algebra), **CAS PY 313 / 314** (Waves and Modern Physics). Background knowledge in classical electrodynamics, semiconductors physics, and quantum mechanics. Talk to the instructor before registering if unsure.