# Quantum Computing Fundamentals

CL-QCF | Virtual classroom | 3 days

**Audience:** Professionals
**Preparedness:** Matrix multiplication, vectors, complex numbers
**Exercises:** Hands-on

As the field of quantum computing continues to evolve and advance, there is a growing need for professionals with the knowledge and skills to tackle the complex challenges and opportunities it presents.
This comprehensive course is designed to provide participants with a thorough understanding of the fundamental principles and practical applications of quantum computing. Through a blend of theoretical and hands-on learning, participants will gain a deep appreciation for the potential of this cutting-edge technology and be equipped with the skills needed to make a real impact in the field.
Whether you are a researcher, engineer, or simply interested in this exciting and rapidly evolving field, this course offers a unique and valuable opportunity to gain the knowledge and skills needed to succeed in the quantum era.

## Outline:

- Introduction to quantum computing
- Postulates of Quantum Mechanics
- Bloch sphere
- IBM Quantum
- Entanglement
- Quantum Gates
- No Cloning Theorem
- Quantum algorithms
- Programming in Qiskit

## Participants attending this course will:

Gain the skills to accurately calculate the probabilities of quantum states
Obtain the knowledge and tools necessary to effectively illustrate quantum bits
Have the ability to write quantum circuits using the Qiskit language
Become proficient in utilizing the Quantum Computer of IBM

## Related courses:

- CL-QCI – Quantum Communication

# Detailed table of contents

## Day 1

### Introduction to Quantum Computing

- Introduction of the course
- Motivations behind quantum computing
  - What is it?
  - Quantum history - Classical physics is not enough!
  - Quantum Manifesto (EU)
  - Quantum Flagship (EU)
  - '2019: Quantum supremacy using a programmable superconducting processor'
  - IBM Quantum Experience
  - Motivation
  - But there are limitations
- Description of a Quantum Phenomenon
  - Mach-Zehnder interferometer
  - Double-slit experiment
  - Elitzur–Vaidman bomb tester experiment
  - Elitzur–Vaidman bomb tester experiment - ingredients
    - Elitzur–Vaidman bomb tester experiment - outcomes
    - Elitzur–Vaidman bomb tester experiment – lessons learned

### The Postulates of Quantum Mechanics

- Four postulates
- Quantum bits (qubits)
  - 1st postulate in details - qubit
  - Quantum bit (qubit)
  - Quantum bit with real probability amplitudes
  - Important qubits
  - Quantum bit with complex probability amplitudes
  - Qubits in practice
  - Bloch Sphere Simulator
- Quantum registers (quregisters)
  - 4th postulate in details - quantum register
  - What is a tensor product?
  - Matrix Multiplication
  - Matrix Exponentiation
  - How to calculate square of matrix A
  - Transponent of a matrix

  - Tensor product in practice - example
  - Quantum registers
- Quantum gates
  - 2nd postulate in details
  - Unitary transformation
  - 'Sidenote: mathematical background'
  - 'Sidenote: mathematical beckground - inner and outer product'
  - How does a quantum gate look like?
- Extracting information from quantum registers (Measurements)
  - 3rd postulate in details
  - 3rd postulate using ket notations
  - Projective measurement
    - How to calculate measurement operators?
    - How to write the measurement operators?
    - Completeness relation
    - Projective measurement - practical notation
    - 3rd postulate in case of projective measurement
    - How measurement works?
    - Measurement using computational basis states
    - Repeated projective measurement
    - What is randomness?
    - How to create projective measurement?

## IBM Quantum

## Entanglement

- Decomposition exercise
- Entangled states
- Difference between product and entangled states
- How does it work?
- What does entanglement mean?
- Famous entanglement pairs
- How to produce entangled pairs?
- Changing the bases of an entangled pair

## Implementation examples for qubits

- Physical qubits
- Di Vincenzo criteria
- Superconducting qubits
  - Pros and cons

- Trapped ions
  - Pros and cons
- Photonic qubits
  - Pros and cons

## Elements of classical digital technology

- Logical gates and circuits
  - Classical digital system
  - Inverter (NOT gate)
  - Classical gates
  - Boolean circuit
  - Circuits
- Synchronous Sequential circuits
  - Flip-flop
  - Why is the clock important?
  - Synchronous logic
  - Classical register vs quantum register
  - CPU, GPU, QPU

# Day 2

## Quantum Gates

- One Qubit Gates
  - Identity gate
  - Pauli X gate, or bit-flip gate
  - Pauli Z gate, or phase-flip gate
  - Pauli Y gate
  - Pauli gates and the Bloch sphere
  - Phase rotator gate
  - Hadamard gate
- Two (or more) Qubits Gates
  - n-qubit Hadamard gate
  - Controlled NOT gate (CNOT gate)
  - Controlled Z gate (CZ gate)
  - SWAP gate
  - Toffoli gate ("controlled-controlled-not" gate)
  - Toffoli gate and Hadamard gate
  - Fredkin gate

- CNOT gate
    - Bell state generator
    - Generalized quantum entangler
    - Remarks
    - How to create entangled qubits physically? - An example

## Quantum Circuit Model

- 'Quantum Circuit: Overview'
    - The beam-splitter experiment
    - The experiment with gates

## How to prepare a superposition?

- Preparing an arbitrary quantum state

## No cloning theorem

- No Cloning Theorem - Proof

## Quantum Algorithms

- Receipt of quantum algorithm design
- Initialization
- Quantum parallelism
- Amplitude amplification
- Measurement
- Classical post-processing
- Algorithms with polynomial speedup
    - Polynomial time vs exponential time
    - Polynomials with multiple exponents
    - Properties of quantum algorithms with polynomial speedup
- Grover's algorithm
    - Problem formulation
    - Receipt of quantum algorithm design
    - Quantum algorithm/circuit
    - Amplitude amplification
    - Measurement
    - Geometrical interpretation

- Error probability
- Post-processing
- Computational complexity

# Day 3

## Quantum Algorithms

- Algorithms with superpolynomial speedup
  - Polynomial time vs exponential time
- The Deutsch-Jozsa algorithm
  - Problem formulation
  - Quantum algorithm/circuit
  - Initialization
  - Quantum parallelism
  - Amplitude amplification
  - Measurement
  - Post-processing
  - Computational complexity
- Quantum Fourier Transform
  - Classical Fourier Transform
  - Quantum Fourier Transform
- Phase estimation
  - Problem formulation
  - Quantum algorithm/circuit
  - Initialization
  - Quantum parallelism
  - Amplitude amplification
  - Measurement
  - Post-processing
  - Computational complexity
  - Non-idealistic case
- Deutsch-Jozsa algorithm and phase estimation
  - Connection between H and QFT
- Quantum Counting
  - Problem formulation

    - Application of phase estimation
- Shor's algorithm
    - Problem formulation
    - Problem formulation – Symmetric key systems
    - Problem formulation – Asymmetric key systems
    - Problem formulation – the RSA algorithm
    - Shor algorithm – breaking RSA classically
    - Shor algorithm – order finding
    - Shor algorithm – breaking RSA by quantum computing
- Quantum optimization
    - Quantum optimization – existence testing
    - Quantum optimization – relation testing
    - Quantum optimization

## Programming Quantum Computers

- The main approaches
- Qiskit
    - Quiskit–Deutsch–Jozsa algorithm
    - Quiskit - interactive quantum demos
- Q#
    - Q# – Grover algorithm
- IBM Quantum
- Xanadu Quantum Computer

## Summary and outlook

- Post quantum cryptography
- Quantum communications