"Quantum Computing Course Overview" by Abbas (Omid) Hassasfar

- 0. Python Programming Language (Essentials)
- 1. Postulates of Quantum Mechanics
- 2. Linear algebra & Complex numbers & Multivariable calculus (Essentials)
  - Vectors & Matrices
  - Inner product & Outer product
  - Unitary & Hermitian matrices
  - Diagonalization and singular values
  - Tensor products
  - Trace of a matrix
  - The Pauli matrices
  - Dirac notation
  - orthogonality and orthonormality for sets of vectors
  - Eigenvalues and Eigenvectors
  - Gradient, Hessian, Jacobians
- 3. Classical Logic Gates & Truth tables (Essentials)
  - Boolean logic operations:
  - AND, NAND, OR, NOR, XOR (exclusive-OR), XNOR
- 4. Learn the fundamental concepts in quantum computing & Quantum circuit with single systems
  - The notion and mathematical representation of of qubit
    - Six important states { |0⟩, |1⟩ }, { |+⟩, |−⟩}, { |+i⟩, |−i⟩}
  - Superposition
  - Operations on qubit states (Unitary Matrix) Quantum Gates, Unitary evolution
    - I, H, X, Y, Z, S, T
    - Global and relative (local) phases
    - Rotations: Rx, Ry, Rz
    - Universal gate set for single-qubit operations
  - Bloch Sphere & Operation on bloch sphere
  - Measurement outcome probabilities concept of projective measurements.
    - Born rule
  - Bases
  - Visualizing quantum circuits (Initialization - Gates - Measurements)
  - Observables (Hermitian Operators / Matrix) & Expectation Value
- 5. Quantum Circuits with two and Multi-Qubit Systems (Multiple systems)
  - Separable vs Entangled states Quantum non-locality
    - Important states
      - Bell States
      - W States
      - GHZ States
    - Quantifying Quantum Entanglement & the level of entanglement
      - Concurrence (for two-qubit state)
        - C=0: separable. C=1: maximally entangled.
      - Von Neumann Entropy
      - Negativity & Logarithmic Negativity
      - Schmidt Decomposition (for pure states)
      - Relative Entropy of Entanglement
      - Tangle
  - Two or multi qubit gates
    - CNOT
    - CZ
    - CRz, CRx, CRy
    - CU — Controlled Unitaries
    - SWAP
    - CCZ
    - Multiqubit control gate
    - Toffoli (CCNOT)
    - Fredkin gate (Controlled-SWAP)
    - Universal gate sets
  - Multi-qubit bases
  - Partial measurements
  - Circuit depth
  - No-Cloning Theorem
  - Density matrices and the spectral theorem
    - Pure States vs Mixed States
    - Reduced states and the partial trace
    - Purifications and fidelity
- 6. Basics quantum protocols
  - Superdense Coding
  - Quantum Teleportation
  - Entanglement Swapping
    - Entanglement Swapping is a protocol that allows two particles that have never interacted to become entangled.
  - CHSH game
    - quantum nonlocality test protocol
  - BB84 Protocol
  - E91 Protocol (Ekert)
- 7. Quantum query algorithms
  - Oracle or black box
  - Phase Kickback
  - Deutsch
  - Deutsch–Jozsa
  - Bernstein–Vazirani
  - Simon's Algorithm
- 8. Grover's Algorithm
  - a quantum algorithm that provides a **quadratic speedup** for searching unsorted databases/ unstructured data
  - Grover's iteration & Amplitude Amplification
  - Grover diffusion operator
  - number of iterations
  - One matching entry vs Multiple matching entries
  - Grover's Algorithm for Max-Cut Problem
- 9. Fourier Transform
  - Classical Fourier Transforms
    - Discrete Fourier Transform (DFT)
    - Fast Fourier Transform (FFT)
    - for signal and image processing, Spectral analysis
  - Quantum Fourier Transform (QFT)
    - Inverse QFT (QFT†)
- 10. Quantum Phase Estimation (QPE)
  - Controlled unitaries
  - QPE is an application of Quantum Fourier Transform (QFT is a core subroutine inside QPE)
- 11. Shor's Algorithm
  - Basic number theory & Modular arithmetics
  - Order Finding/Period Finding Algorithm
  - Factoring by order-finding QPE for order finding
  - Impact on RSA and cryptography
- 12. HHL Algorithm
  - The Harrow–Hassidim–Lloyd (HHL) algorithm is a quantum algorithm for numerically solving a system of linear equations
- 13. Quantum state tomography
  - Reconstructs the quantum state ρ of a system from measurement outcomes.
  - Qubit tomography using Pauli measurements
  - Quantum Process Tomography (QPT)
    - Reconstructs the quantum operation (channel) E, e.g., a quantum gate or noise process.
- 14. Error-Correction and Fault-Tolerance
  - Classical error-correction vs Quantum errors
  - Types of noise and decoherence
    - Detecting a bitflip-error
    - Detecting a phaseflip-error
  - The surface code
  - Stabilizers
  - Shor's 9-qubit code
  - Magic State & Magic State Distillation
  - Fault-tolerant quantum computing
- 15. Hamiltonian Simulation
  - Matrix Exponential
  - Lie-Suzuki-Trotter methods
  - Linear combination of unitaries (LCU)
  - Quantum signal processing
    - Qubitization
      - Quantum Singular Value Transform theorem
- 16. NISQ Era Noisy Intermediate-Scale Quantum
  - Error Detection
    - Recognize when an error happens.
  - Error Suppression
    - Physically reduce the likelihood of errors occurring.
  - Error Mitigation & Noise models
    - Zero Noise Extrapolation (ZNE)
    - Probabilistic Error Cancellation
- 17. Variational Quantum Algorithms (VQAs)
  - A hybrid quantum-classical algorithm.
  - Parameterized Quantum Circuit (PQC) Concept of Reference States and Ansatz
  - Cost Functions
  - Optimization Loops & Optimizer
  - Gradient Descent & Barren Plateaus Vanishing Gradients
    - Gradient-based optimizers
      - Adam, SGD
  - Variational Quantum Eigensolver (VQE)
    - Find minimum eigenvalue of a given observable
    - Quantum Chemistry
      - Electronic structure & Molecular Hamiltonian
      - Second quantization form of Hamiltonian
        - fermionic (bosonic) creation and annihilation operators
      - Mapping Fermionic (Bosonic) to the Qubit Space
        - Jordan–Wigner
        - Bravyi–Kitaev
        - Parity mapping
  - Variational Quantum Deflation (VQD)
  - Quantum Chemistry: Ground State and Excited Energy Solver
  - Quantum Approximate Optimization Algorithm (QAOA)
    - Cost Hamiltonian & Mixer Hamiltonian
    - Optimization: Max-Cut problem
    - QUBO: Quadratic Unconstrained Binary Optimization
      - QUBO ↔ Ising Model
  - Variational Quantum Linear Solver (VQLS)
  - Variational Quantum Classifier (VQC)
  - Quantum Neural Networks (QNN)
  - Variational QML
- 18. Quantum Machine Learning (QML)
  - Data Encoding
    - Basis Encoding
    - Amplitude Encoding
    - Angle Encoding
    - Higher-Order Encoding
  - Quantum Feature Maps & Quantum Kernel functions
  - Supervised QML Algorithms
    - Variational Quantum Classifiers (VQC)
    - Quantum Support Vector Machines (QSVM) Quantum Kernel Method
      - Quantum-enhanced support vector machine
    - Quantum k-Nearest Neighbors (qkNN)
    - Quantum Decision Trees
    - Quantum Regression Models
    - Quantum Neural Network (QNN)
      - Quantum feedforward neural networks (QFFNN)
      - Quantum convolutional neural networks (QCNN)
      - Recurrent Quantum Neural Network (RQNN)
      - Quantum Long Short-Term Memory (QLSTM)
      - Barren Plateaus in Quantum Neural Networks
      - Generative Quantum Machine Learning
        - Quantum Generative Adversarial Network (QGAN)
  - Unsupervised QML Algorithms
    - Quantum principal component analysis (QPCA) Quantum Kernel Methods
    - Quantum k-Means Clustering Quantum Kernel Methods
    - Quantum Autoencoders
    - Quantum Boltzmann machines
- 19. Adiabatic Quantum Computation (AQC) & Quantum Annealing (QA) vs Gate-Based Quantum Computing
  - QUBO optimization (Quadratic Unconstrained Binary Optimization)
    - Formulating QUBO Problems and Ising Hamiltonians
    - MAX-CUT can be directly translated into QUBO form
    - D-Wave quantum annealer
  - QA is a practical version of AQC
- 20. Overview of hardware platforms Quantum Processing Units (QPUs)
  - Different physical realization or modalities
    - Superconducting
    - Trapped Ion
    - Photonic
    - Neutral Atom
    - Spin Qubits in Semiconductors
    - Topological Qubits
    - ...
- 21. Assessing Quantum Capability
  - Quantum Supremacy
  - Quantum Advantage
  - Quantum Utility
  - Quantum Usefulness
  - Quantum Practicality
  - ...

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