

Quantum Computation, Quantum Algorithms & Implications on Data Science

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Quantum Computing

- a new *revolutionary* computing paradigm
 - quantum Turing machine theorized at ANL in 1981
 - post Moore's Law beyond silicon-based computer
- quantum bit (**qubit**): basic building block [7]
 - inherent randomness and uncertainty due to fundamental *stochastics*
- quantum physics & quantum mechanics based on
 - pure state of a quantum system given by a unit vector $|\psi\rangle$ in a complex Hilbert space
 - time evolution of state generated by Hamiltonian H according to the Schrödinger equation

$$i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = H |\psi(t)\rangle \quad \leftrightarrow \quad |\psi(t)\rangle = e^{-iH/\hbar} |\psi(0)\rangle$$

with Planck constant \hbar and $i = \sqrt{-1}$

- structure of composite systems given by tensor product
- projective measurements (*observables*) according to non-degenerate Hermitian operators
 - * measurement process changes the observed system from state $|\psi\rangle$ to eigenstate $|\phi(t)\rangle$ w/ probability $p(\phi) = |\langle\psi|\phi\rangle|^2$ by the Born rule [5].

3 Aspects of QC

- Superposition**
 - state $|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$
w/ $|\alpha_0|^2 + |\alpha_1|^2 = 1$, $\alpha_i \in \mathbb{C}$
 - enables natural *parallelism*
- Entanglement**
 - enables *indirect measurement* preserving system's integrity
- Interference**
 - constructive or destructive
 - enables speedy processing of Big Data

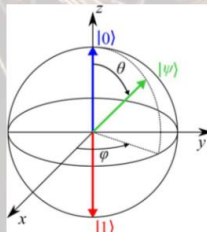


Figure 1.
Bloch sphere
representation
of a qubit

Quantum Algorithms

- described by quantum *circuits*
 - genuine* random number generation
 - quantum random walks to speed up stochastic diffusion process
 - quantum Fourier transform, quantum phase estimation
 - Shor's factoring algorithm [6]
 - Grover's search/sort algorithm [4]
 - quantum state tomography (density matrix) [3]
 - quantum Monte Carlo integration, Monte Carlo simulation, quantum MCMC [8]
- quantum algorithms speed up solving decision problems, functional problems, *oracular* problems, sampling tasks and optimization problems [8].
- quantum algorithms speed up **Machine Learning (ML)** w/ **Big Data**.
 - often rely on quantum annealers for learning-type problems.
 - quantum *Simulated Annealing* (SA) for NP-hard problems
 - * Ising model to minimize (Hamiltonian) energy, given coupling and local field [8]
 - quantum *Principal Component Analysis* (qPCA)
 - quantum *Support Vector Machines* (qSVM)
- quantum algorithms speed up **Artificial Intelligence (AI)**.
 - can search all possible solutions at the same time, and then collapse output to most probable solution
 - faster training and update of *neural networks* by estimating weights instantly [2]
 - quantum *Reinforcement Learning* (qRL) based on PO-MDP
 - design/evaluation of agents + environments interaction [2]

→ **Quantum Computation + Data Science**
= *super-duper-exponential learning!!*

Quantum Information

- aim to design target quantum evolutions, including quantum gate design
 - need to find the optimal control functions or extended system parameters
 - non-convex and very difficult to do; could utilize online learning and RL

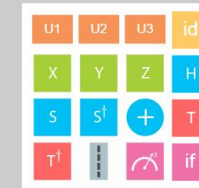


Figure 2.
Quantum gates
of IBM Q

Current Development

- quantum computers w/ more qubits
 - quantum volume* increase >2x/yr
 - Google 72 qubit processor: chip w/ most qubits
 - D-Wave 2,000 qubits (\$15M): computer w/ most qubits
- library of functions (*circuits*) [1]
 - IBM cloud service for quantum computing

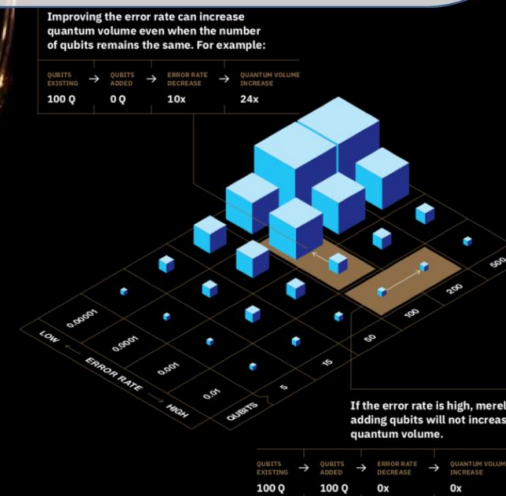


Figure 3. Quantum volume (source: IBM Research)

Technical Barriers

- operability at temperatures far above 0 K
 - current operation requires near 0 K w/ liquid nitrogen or helium.
- better error correction to put more qubits in superposition
 - currently high error rate (millions of errors/hr)
 - most qubits are used for error correction than actual computing.
- better stability to hold superposition states longer for more sophisticated algorithms
 - currently held only for fractions of a second
- better techniques for setting/holding quantum states
 - currently controlled by ion traps using *magnetic fields*, optical traps by light waves, quantum dots, semiconductor impurities, or superconducting circuits

Concluding Remark

- advancements in ML/AI could help w/ critical steps in building quantum computers [2].
- ML/AI applications can benefit tremendously by quantum computers.
- quantum computing will accelerate science and technology w/ transformative impact on our society (e.g., computation, communication, cryptography) [7].

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