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

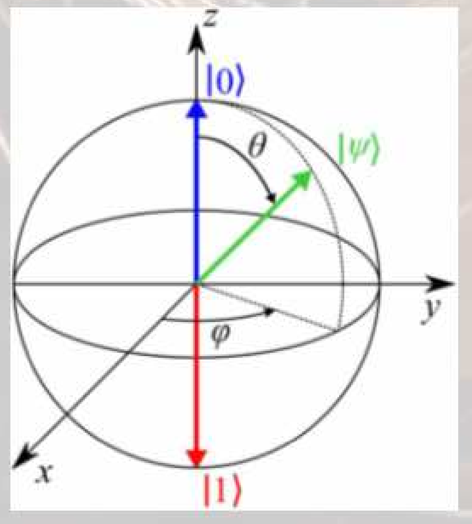

Figure 1. Bloch sphere representation of a qubit

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

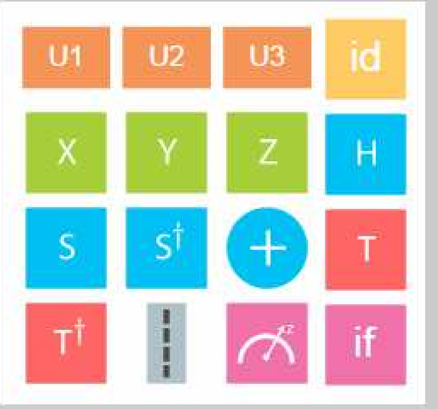

Figure 2. Quantum gates of IBM Q

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

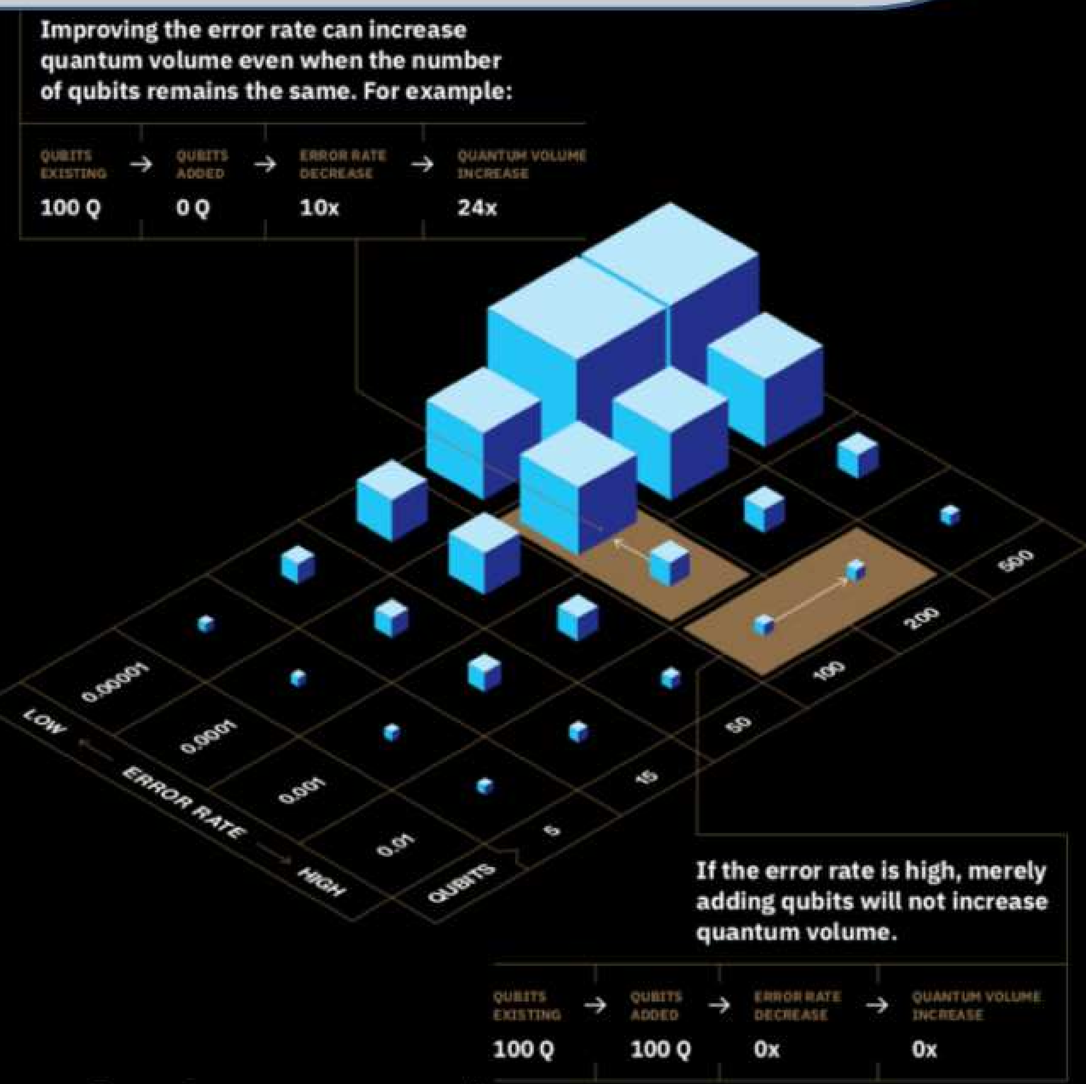

Figure 3. Quantum volume (*source*: IBM Research)

Technical Barriers

- operatability 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 superstition 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].

References

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