Quantum Computing Fundamentals

How quantum goes beyond classic computing

Meetup of Quantum Computing Vienna

Classic Information

- The fundamental unit of information is the "bit".
- Its value space is 0 and 1.
- All information is encoded in sequences of bits.
  - 01000001_b Latin capital letter A encoded in UTF-8
  - 01000001_b Decimal number 65 encoded as binary integer
  - 100001001111_b Color purple encoded in 12-bit RGB
  - 1001000100001110_b Instruction "add" encoded in RISC-V C

Classic Computing

- All computation is modifying bit sequences.
- 1-bit operations like "set", "clear", and "not"
- 2-bit operations like "and", "or", "xor", and "nand"
- Processor instructions like "add", "compare", and "load"
- Programming languages like Python, Java, and Rust
- Memory load/store and device input/output
- Sensors, emitters, and actuators interact physically.

Classic Computers

- Modern (but classic) computers contain
  - processors based on MOSFETs with doped silicon
  - cache based on static RAM (transistors)
  - memory based on dynamic RAM (capacitators)
  - storage (disk) on floating-gate MOSFETs (flash) or magnetic disk
  - communication (net) over electric (copper) or optic (glass) cable, or radio waves (wireless)

Enter Quantum Computing ...

Quantum Information

- The fundamental unit of information is the "qubit".
- Its value space is $a|0> + b|1>$ where
  - $|0>$ and $|1>$ are the classic 0 and 1
  - a and b are complex numbers
  - and $|a|^2 + |b|^2 = 1$.
- Observing (measuring) a qubit turns it into 0 or 1.
- $|a|^2$ is the probability to measure 0, $|b|^2$ to measure 1.

Quantum Computing

- is probabilistic instead of deterministic.
- You need an efficient classic algorithm to decide whether the outcome is a solution to your problem.
- It utilizes the quantum effects of superposition, entanglement, and phase shift.
- Quantum operations are unitary matrices with 2^n rows and 2^n columns operating on n qubits.

Superposition

- enables n qubits to be in 2^n states at the same time.
- One frequent method is to initialize all qubits to 0 and then use the Hadamard gate to reach a uniform probability distribution over all possible states.
- $H|0\rangle = 2^{-1/2} (|0\rangle + |1\rangle)$
- $P(0) = P(1) = |2^{-1/2}|^2 = 2^{-1} = 50\ \%$
- This enables 2^n concurrent computations.

Entanglement

- Non-entangled qubits do not interact and their probabilities are entirely independent.
- Entanglement makes qubits and their probabilities depend on each other.
- A Bell state like $2^{-1/2}(|00\rangle + |11\rangle)$ or $2^{-1/2}(|01\rangle + |10\rangle)$ ensures that measuring one qubit provides information on the other qubit, and vice versa.
- This is one way to program quantum computers.

Phase Shift

- You can shift the phases of qubit states, such that constructive (amplifying) and destructive (dampening) interference can occur.
- This interference can increase the probability of measuring the relevant information.
- The complex numbers in the quantum states describe these phase differences.
- That is another way to program quantum computers.

Measurement

- Reading a quantum state requires interacting with it.
- This causes it to adopt a classic state based on its probability distribution.
- Programming this probability distribution significantly increases the probability of measuring a relevant result.
- Quantum algorithms were found that are significantly faster than the best know classic algorithms for certain classes of problems.

Quantum Computers

- differ by computational model
  - gate array, measurement-based, adiabatic, and topological
- by technology
  - superconducting, trapped ion, photonic, nuclear magnetic resonance (NMR), and many more
- and by processing capacity (aka quantum volume)
  - qubit count, connectivity (topology), coherence time, error rate, fidelity, and frequency (computing speed)

Onward from here

- Quantum Computing in a Nutshell
  - https://qiskit.org/documentation/qc_intro.html
- Quantum Computing Field Guide
  - https://quantum-computing.ibm.com/composer/docs/iqx/guide/
- Quantum Computing Qiskit Textbook
  - https://qiskit.org/learn/

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Comments, feedback, or questions?