EN2912C: Future Directions in Computing
Lecture 20: Quantum error correction / Quantum physical implementations

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Error correction

- General idea of error correction is always to encode states by adding enough redundancy such that the original state is recoverable after has acted on the noise. The amount of redundancy needed depends on the severity of noise in the channel.

- Fault-tolerance allow us to perform logical operations on encoded states in a manner that tolerates faults in the underlying gate operations.

- Challenges for quantum error correction:
  - No cloning
  - Errors are continuous
  - Measurement destroys quantum information
Quantum error correction (QEC)

- In quantum error correction, we do not need to know the error in order to correct the error. Instead, the logical qubit should be protected by entangling it with several ancilla, allow an error to occur among the entangles qubits, and then discover how to undo the error by measuring the ancilla qubits to reveal an error syndrome.

- For each possible error syndrome there is a particular operation to be performed on the remaining (unmeasured) logical qubit to its bug-free state.
Bit flip codes

\[ |ψ⟩ = α₀|0⟩ + α₁|1⟩ \]

Encoder

\[ |ψ_{enc}⟩ = α₀|000⟩ + α₁|111⟩ \]

Error detection + correction

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Phase flip codes

If we work in the Hadamard basis, phase flip errors are just like bit flip errors.
Shor code

Encodes 1 qubit in 9 qubits

Code can protect against the effect of an arbitrary error on a single qubit!
Physical realizations of quantum systems

- Physical quantity
- Challenges
  - Qubits must be prepared and isolated from environment to prevent/reduce decoherence.
  - Fundamental inability to copy a quantum state (no FANOUT)
  - Need to perform logic operations and measurements on qubits.
    Ease of qubit movement and ease of operation implementation are contradicting
Requirements for a quantum computer (DiVincenzo rules)

• A quantum register described as a collection of well-defined single-qubit states must be initialized to a well-known starting state (i.e., $|00 ... 0\rangle$).
• A “universal” set of quantum logic must be available, where the gate time cycle must be much shorter than the relevant decoherence time cycle of the quantum register.
• Reliable measurements must be performed on any single-qubit state.
• The ability to transmit quantum information between specified locations, either through the direct physical movement of the qubit, or by passing the information to “flying” qubits which can then pass it back to “stationary” qubits for gate manipulation.
Potential quantum computing technologies

• Optical quantum computing
• Ion trap
• Nuclear magnetic resonance devices
• Cavity quantum electro-dynamic computation
• Solid state spin-based devices
• Quantum dots
1. Optical quantum computers

Main components of the computer:
1. Photons are used as the physical implementation of qubits. State is stored in the polarization of a photon
2. Phase shifters and phase splitters are used for gates
3. Photo detectors are used for measurement

State of the art:
- Single-qubit operations are virtually noiseless
- Two-qubit operations (e.g. CNOT) exhibit high amount of noise so quite unsuccessful
- Most advanced technology for performing entanglement and transfer

See a video of the optical-based quantum computing experiment on lecture 2 of David Deutsch lectures on quantum computers
2. Trapped-ion quantum computers

- Qubits are stored in the stable electronic states (energy levels) of each ion (e.g., beryllium)

- Ions, or charged atomic particles, are confined or trapped and suspended in free space using electromagnetic fields. Laser cooling is used to cool the ions to reduce the thermal noise

- Quantum information can be processed and transferred through the collective quantized motion of the ions in the trap.

- One of the most promising architectures for a scalable, universal quantum computer
Architecture of a scalable Ion-trap quantum computer

By changing the operating voltages on the electrodes, ions can be trapped or shuttled from trap to trap

Memory regions: hold trapped ions storing quantum information

To perform logic, trapped ions are moved to an interaction region. In the interaction regions:

- Ions are held together, enabling the Coulomb coupling necessary for entangling gates
- Lasers are focused through the interaction region to drive gates

Monroe and Wineland Nature 2002