Quantum Science with Superconducting Circuits

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1) Introduction to Quantum Information Processing

QIP $\hat{=}$ "The study of information processing tasks using quantum physical systems."

Challenge: Need complete control over individual quantum degrees of freedom.

1920's : Theoretical foundation of Quantum Physics to explain phenomena like photo effect, emission of atoms, Stern-Gerlach exp., ...

1970's : Gain experimental control over single trapped atoms. Theory of QIP developed.

since 2000 : Significant progress in developing quantum hardware in various physical systems (trapped ions, Rydberg atoms, Q dots, SC circuits, ...)

1.1 Quantum Computing: Why interesting?

- Scientifically rich: Turn longstanding theoretical predictions into reality.
- End of Moore's law approaching?! → Explore alternative paradigms for computing.
- No known classical algorithm can efficiently simulate a quantum computer.
- Theory for quantum error correction (QEC) exists.
  ⇒ Noise may be dealt with!
- Known quantum algorithms (Shor), which offer exponential advantage compared to best known classical algorithm.

1.2 Quantum bit: One, two, many

Classical bit "0" or "1"

Quantum bit $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, with basis states $\{|0\rangle, |1\rangle\}$

Linear combination $\hat{=}$ Superposition possible

complex valued amplitudes α, β with $|\alpha|^2 + |\beta|^2 = 1$.

Measurement projects into either one of the two states $|0\rangle$ or $|1\rangle$.

Consider two qubits with $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$ basis states.

$$|\psi\rangle = \sum_{i,j=0}^{1} \alpha_{ij} |ij\rangle$$

Example: $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$ $\hat{=}$ Entangled Bell states

Measurement outcomes are perfectly correlated.

Distinguish product state $|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$.

Generalize to n qubits

$$|\psi\rangle = \sum_{i_1,\dots,i_n=0}^{1} \alpha_{i_1,\dots,i_n} |i_1,\dots,i_n\rangle$$

2^n different amplitudes

For comparison: $2^{500} > \sim$ # of atoms in universe

A quantum system, in principle, processes all these amplitudes.

$\Rightarrow$ Exploit for computation.

1.3 Circuit model of quantum computation

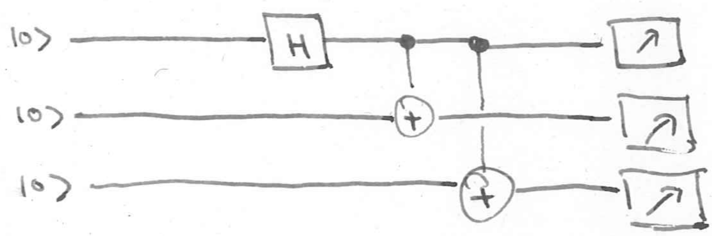
$$|\psi_{out}\rangle = U \, |\psi_{in}\rangle$$

output of algorithm — unitary operator — register of qubits e.g. $|00\ldots0\rangle$

Decomposition of any U into single-qubit gates and controlled NOT gate possible. (Nielsen & Chuang)

Example of a universal gate set.

Quantum circuit representation (an example)



-[H]- Hadamard gate $\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$

controlled NOT $\begin{pmatrix} 1 & & & 0 \\ & 1 & & \\ & & 0 & 1 \\ 0 & & 1 & 0 \end{pmatrix}$

- Each horizontal line represents one qubit
- Execute from left to right
- Vertical lines used to represent multi-qubit gates

1.4 Requirements for Physical implementation

Compare DiVincenzo's criteria (2000):

1) Scalable, physical realization of a qubit
2) Ability to initialize state of qubits
3) Coherence time $\gg$ gate operation time
4) Universal gate set
5) High-fidelity measurement

Two more criteria related to Q communication

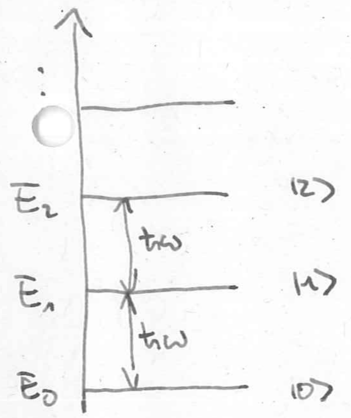
1.5 Physical realization of qubits

QM systems characterized by energy level diagram, i.e. eigen~~states~~ of Hamiltonian $E_i|i\rangle = \hat{H}|i\rangle$

Most physical systems have more than 2 states.

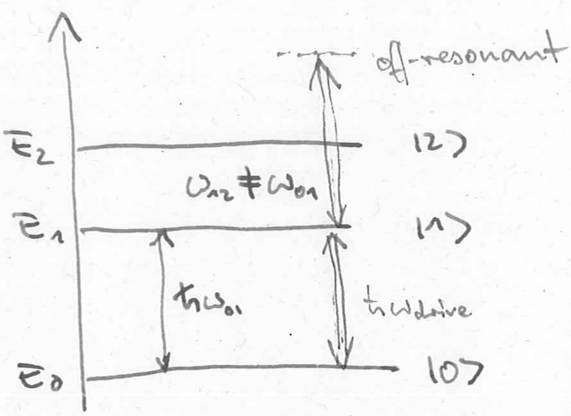
Distinguish between ... systems:

Harmonic (linear)



e.g. modes of radiation field, mechanical oscillators

Anharmonic (nonlinear)



e.g. (hydrogen) atom, SC qubits, spin systems, e^- confined in quantum dots, ...

- Anharmonic (multi-level) systems can be operated as qubits by selectively addressing transition in 2-level subspace
- Harmonic system useful to build auxiliary elements for control, coupling & readout.