The Physical Implementation of Quantum Computation

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Overview

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David DiVincenzo

- He received his doctorate at the University of Pennsylvania in 1983
- Postdoc at Cornell University
- Research Staff Member at IBM Watson Research Center (1985-2011).
- Professor at the Institute of Theoretical Quantum Information at RWTH Aachen University
- Director of the Peter Grünberg Institute, where he serves to the present.
- Has a secondary appointment as professor at the EEMCS Department at the TU Delft and a staff member at QuTech since 2017.

David DiVincenzo

- One of the first physicists to engage in quantum information research
- Considered an authority on quantum information processing.
- In particular, his name is associated with the development of criteria for the quantum computer, known as the DiVincenzo Criteria, and also with the Loss-DiVincenzo approach to solid-state spin-based qubits.

Introduction

- Why Quantum Information Processing?
- Requirements for the physical implementation of quantum computation

DiVincenzo criteria

1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits
3. Long relevant decoherence times, much longer than the gate operation time
4. A universal set of quantum gates
5. A qubit-specific measurement capability
6. The ability to interconvert stationary and flying qubits
7. The ability to faithfully transmit flying qubits between specified locations

1. A scalable physical system with well characterized qubits

- A physical system containing a collection of qubits is needed
- A quantum bit (qubit) is a 2-level quantum system, described by a 2-dimensional complex Hilbert space.
- Example: Electron spin
- The states $|0\rangle$ and $|1\rangle$ form a computational basis.

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

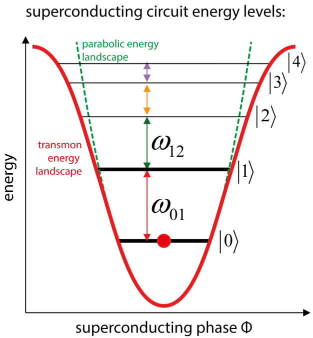
The absolute squares of the amplitudes are the probabilities: $|\alpha|^2 + |\beta|^2 = 1$

1. A scalable physical system with well characterized qubits

A qubit being well characterized means we should accurately known:

- Its physical parameters including the internal Hamiltonian of the qubit
- The presence of and couplings to other states of the qubit
- The interactions with other qubits
- The couplings to external fields that might be used to manipulate the state of the qubit

1. A scalable physical system with well characterized qubits



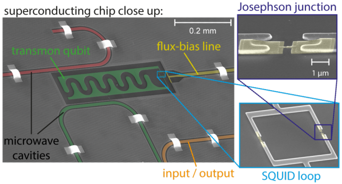


Image from [Dickel, 2017].

2. The ability to initialize the state of the qubits $|000...\rangle$

- Registers should be initialized to a known value before the start of computation
- Quantum error correction requires a continuous, fresh supply of qubits in a low-entropy state (like the $|0\rangle$ state)
- The system can be naturally cooled when the ground state of its Hamiltonian is the state of interest.
- The standard state can be achieved by a measurement which projects the system either into the state desired or another state which can be rotated into it.

3. Long relevant decoherence times, much longer than the gate operation time

- Decoherence times characterize the dynamics of a qubit (or any quantum system) in contact with its environment.
- A way of representing quantum system is using the Density Matrix or Density Operator

$$|\psi\rangle = p_0 |0\rangle + p_1 |1\rangle \qquad \rho = |\psi\rangle \langle\psi|$$

$$\rho = \begin{array}{c c} & \begin{array}{cc} |0\rangle & |1\rangle \end{array} \\ \begin{array}{c} |0\rangle \\ |1\rangle \end{array} & \begin{pmatrix} p_0 & c_{01} \\ c_{10} & p_1 \end{pmatrix} \end{array} \quad \text{Decoherence} \rightarrow \rho = \begin{array}{c c} & \begin{array}{cc} |0\rangle & |1\rangle \end{array} \\ \begin{array}{c} |0\rangle \\ |1\rangle \end{array} & \begin{pmatrix} p_0 & 0 \\ 0 & p_1 \end{pmatrix} \end{array} \tag{1}$$

where p_i are the probabilities of being in the state $|i\rangle$ and $c_{01} = c_{10}^*$ quantifies the coherence $|0\rangle \langle 1|$ between the two states.

- A quantum algorithm is typically specified as a sequence of unitary transformations $U_1, U_2, U_3 \ldots ;$, each acting on a small number of qubits, typically no more than three.
- The most straightforward transcription of this into a physical specification is to identify Hamiltonian which generate these unitary transformations, $U_1 = e^{iH_1 t/\hbar}$, $U_2 = e^{iH_2 t/\hbar}$, $U_3 = e^{iH_3 t/\hbar}$

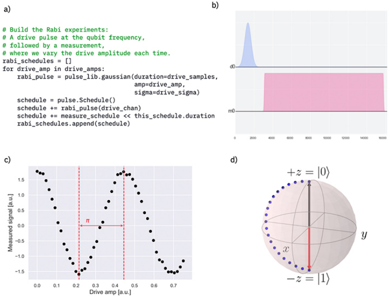


Image from [Asfaw, et al., 2019].

5. A qubit-specific measurement capability

In an ideal measurement,

$$\rho = p\,|0\rangle\,\langle 0| + (1-p)\,|1\rangle\,\langle 1| + \alpha\,|0\rangle\,\langle 1|\,\alpha^*\,|1\rangle\,|0\rangle$$

the measurement should give outcome 0 with probability p and 1 with probability $(1-p)$ independent of α and of any other parameters of the system.

- While quantum efficiency of 100 % is desirable, much less is needed for quantum computation; there is, in fact, a tradeoff possible between quantum efficiency and other resources which results in reliable computation.

6. The ability to interconvert stationary and flying qubits

- When we say communication we mean quantum communication: the transmission of intact qubits (Flying qubit) from place to place.
- The information encoded in a qubit within the quantum computer (often referred to as the stationary qubit in this context) should be reliably transferred to a flying qubit. Additionally, an obtained flying qubit's information needs to be reliably transferred back to a stationary qubit as well [JSdJ , 2019].

7. The ability to faithfully transmit flying qubits between specified locations

- A flying qubit should be reliably send from one node to another. This is a daunting task if you consider that the nodes might be very far apart. The coherence of the flying qubit needs to be preserved over this scale, possibly with the use of error correction [JSdJ , 2019] .

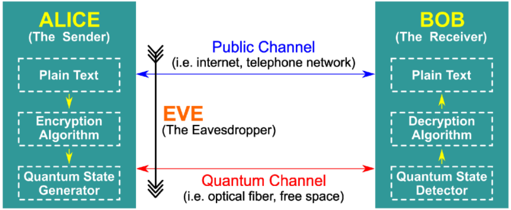


Fig. 1. Basic Block Diagram of QKD System

Image from [Nurhadi and Rachmana, 2018].

Looking back at the DiVincenzo criteria (2018)

Quotes from [DiVincenzo, 2018] :

- "Where are we today with "criteria"? I have heard various statements, first from the ion-trap community, and from the most advanced solid state techniques, that "all criteria are now satisfied". And still, we don't seem to have a scalable quantum computer yet. Were "criteria" then a failure? Partially, yes..".
- "The guides for these steps [the making of the system] are quite well laid out in the seven "complexity steps" of Devoret and Schoelkopf, and I think that these will be the more pertinent guiding principles for our upcoming future"

Looking back at the DiVincenzo criteria (2018)

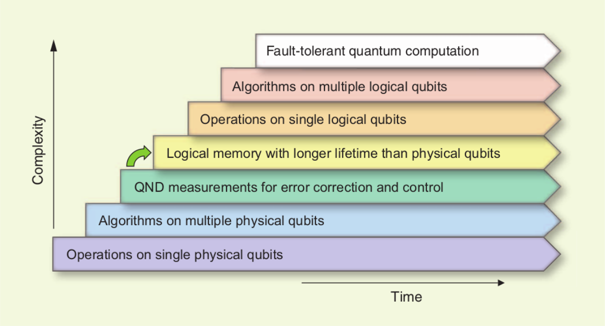


Fig. 1. Seven stages in the development of quantum information processing. Each advancement requires mastery of the preceding stages, but each also represents a continuing task that must be perfected in parallel with the others. Superconducting qubits are the only solid-state implementation at the third stage, and they now aim at reaching the fourth stage (green arrow). In the domain of atomic physics and quantum optics, the third stage had been previously attained by trapped ions and by Rydberg atoms. No implementation has yet reached the fourth stage, where a logical qubit can be stored, via error correction, for a time substantially longer than the decoherence time of its physical qubit components.

Image from [Devoret and Schoelkopf , 2013]

Questions

- How much is gained by computing with quantum physics over computing with classical physics?
- Which requirement is the more important?
- Can trade off one requirement for another?
- What is the winning technology going to be?

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Thank you for your attention