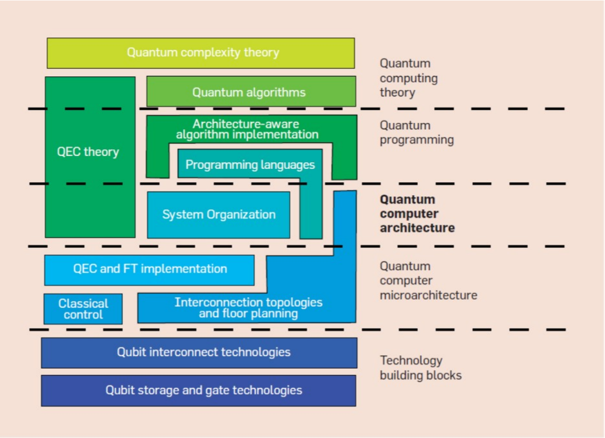
Building Blocks for Quantum Computation



At the bottom of the stack we have the technologies for storing, processing or transporting individual qubits.
Referenze [1, 5, 2, 3, 4]

DiVincenzo Criteria

The first significant attempt to characterize the technology needed to build a computer came in the mid-1990s, when Di Vincenzo listed criteria that a viable quantum computing technology must have:

1. two-level physical systems to function as a qubit;
2. means to initialize the qubits into a known state;
3. universal set of gates operating between qubits;
4. measurement;
5. long memory lifetime; These criteria were later augmented with two communication criteria:
6. ability to convert between stationary and “flying” qubits;
7. ability to transmit the latter between two locations.

DiVincenzo Criteria: 1

1. A scalable physical system with well characterized qubits is needed.

A qubit is simply a quantum two-level system like the two spin states of a spin 1/2 particle, like the ground and excited states of an atom, or like the vertical and horizontal polarization of a single photon. The generic notation for a qubit state denotes one state as $|0\rangle$ and the other as $|1\rangle$. The essential feature that distinguishes a qubit from a bit is that, according to the laws of quantum mechanics, the permitted states of a single qubit fills up a two-dimensional complex vector space; the general state is written $a|0\rangle + b|1\rangle$, where a and b are complex numbers, and a normalization convention $|a|^2 + |b|^2 = 1$ is normally adopted. The general state of two qubits, $a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$, is a four-dimensional vector, one dimension for each distinguishable state of the two systems. These states are generically entangled, meaning that they cannot be written as a product of the states of two individual qubits. The general state of n qubits is specified by a 2^n -dimensional complex vector

DiVincenzo Criteria: 2

2. The ability to initialize the state of the qubits so that:
-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).
If the time it takes to do this initialization is relatively long compared with gate-operation times (see requirement 4), then the quantum computer will have to equipped with some kind of "qubit conveyor belt", on which qubits in need of initialization are carried away from the region in which active computation is taking place, initialized while on the "belt", then brought back to the active place after the initialization is finished. (A similar parade of qubits will be envisioned in requirement 5 for the case of low quantum-efficiency measurements [28].)

DiVincenzo Criteria: 3

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. The simplified definition of this time is that it is the characteristic time for a generic qubit state $|\psi\rangle = a|0\rangle + b|1\rangle$ to be transformed into the mixture $\rho = |a|^2|0\rangle\langle 0| + |b|^2|1\rangle\langle 1|$.

A better characterization of decoherence would imply to specify that the decay can depend on the form of the initial state, in which the state amplitudes may change as well, and in which other quantum states of the qubit can play a role (in a special form of state decay called "leakage" in quantum computing).

Furthermore, the concept of decoherence should be extended to include the possibility that the decoherence of neighboring qubits is correlated. They will be neither completely correlated nor completely uncorrelated. Quantum error correction takes this into account.

DiVincenzo Criteria: 4

4. A "universal" set of quantum gates

This requirement is of course at the heart of quantum computing. 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 Hamiltonians which generate these unitary transformations, viz., $U_1 = e^{iH_1 t/\hbar}, U_2 = e^{iH_2 t/\hbar}, U_3 = e^{iH_3 t/\hbar}$, etc.; then, the physical apparatus should be designed so that H_1 can be turned on from time 0 to time t then turned off and H_2 turned on from time t to time $2t$, etc.

DiVincenzo Criteria: 5

5. A qubit-specific measurement capability

Finally, the result of a computation must be read out, and this requires the ability measure specific qubits. In an ideal measurement, if a qubit's density matrix is $\rho = p|0\rangle\langle 0| + (1-p)|1\rangle\langle 1| + \alpha|0\rangle\langle 1| + \alpha^*|1\rangle\langle 0|$, the measurement should give out- come "0" with probability p and "1" with probability $1-p$ independent of α and of any other parameters of the system, including the state of nearby qubits, and without changing the state of the rest of the quantum computer. If the measurement is "non-demolition", that is, if in addition to reporting outcome " 0" the measurement leaves the qubit in state $|0\rangle\langle 0|$ then it can also be used for the state preparation of requirement 2; but requirement 2 can be fulfilled in other ways.

DiVincenzo Criteria: 6 e 7

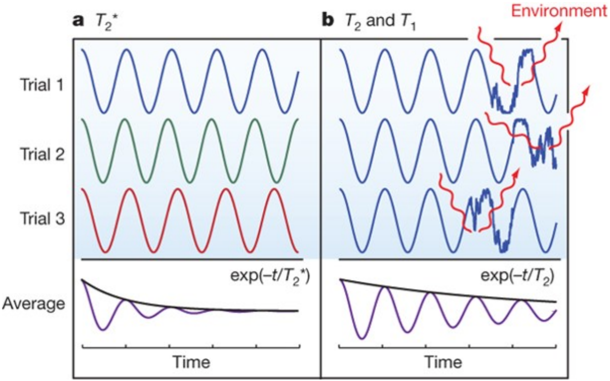
For computation alone, the five requirements above suffice.
6. The ability to interconvert stationary and flying qubits
7. The ability to faithfully transmit flying qubits between specified locations
There are many kinds of information-processing tasks that involve not only computation but also communication. The list of these tasks is fairly long and diverse: for example it includes secret key distribution, multiparty function evaluation as in appointment scheduling, secret sharing, and game playing.
When we say communication we mean quantum communication: the transmission of intact qubits from place to place.
The requirements 6 and 7 are obviously closely related, but it is worthwhile to consider them separately, because some tasks need one but not the other. For instance, quantum cryptography involves only requirement 7 it is sufficient to create and detect flying qubits directly.

Qubit Technologies

Type	Scaled CMOS (classical)	Ion trap	Quantum dot	Optical circuit	Gate-based superconducting circuit	Superconducting circuit (adiabatic computation)
State variable	Electrical charge	Ion spin	Electron spin, energy level, or position	Photon polarization, time, or position	Magnetic flux, charge, or current phase	Magnetic flux
Material	Doped silicon	Atoms in free-space electromagnetic field	Solid-state semi-conductor at cryogenic temperatures	Optical waveguides, for example, etched in silicon	Superconducting Josephson junction at cryogenic temperatures	Superconducting Josephson junction at cryogenic temperatures
Device gate	MOSFET	Laser- or vibrational-mediated interaction	Laser- or electrically-driven exchanges and rotations	Beam splitters and photon detectors	Electrically-driven exchanges and rotations	Electrically-controlled couplers
Maximum demonstrated variables	$> 10^9$ transistors per chip, $\approx 10^{16}$ per supercomputing system	14	3	8	2 full qubits + 2 special-purpose memories	8 coupled, 50 functional?

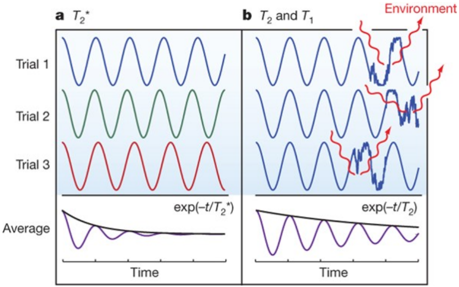
Different technologies rely on the same or different state variables to hold quantum data, implemented in different materials and devices. However it remains unclear which technology will ultimately prove successful.

Dephasing and Decoherence



Decoherence comes in several forms. Quantum mechanical waves such as light from a laser, or the oscillations of the constituents in quantum computers-show interference phenomena, but these phenomena vanish in repeated trial experiments because, owing to various processes, phases no longer 'cohere' after a certain time.

Dephasing and Decoherence



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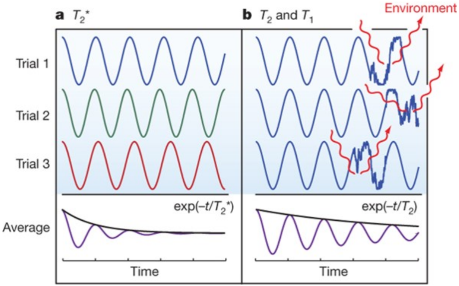
These interference phenomena vanish in repeated trial experiments because, owing to various processes, phases no longer 'cohere' after a certain time. In an ensemble measurement, trial-to-trial variations in oscillator frequency lead to an apparent damping of wave interference on a timescale called T_2^*. A single trial of a single quantum oscillator might retain its phase coherence for a much longer time than T_2^*.

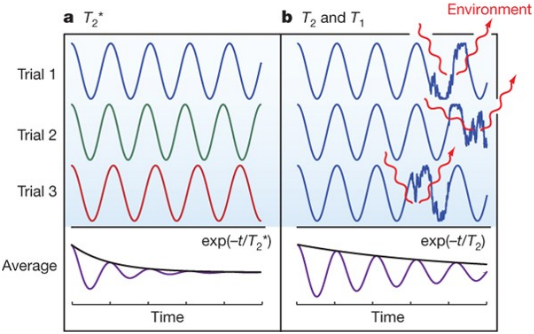
Dephasing and Decoherence



Eventually, random processes add or subtract energy from the oscillator, bringing the system to thermal equilibrium on a timescale called T_1.

Processes may also only 'borrow' energy from the environment, thus changing the oscillator's phase, causing oscillations to damp on a timescale called T_2. Fundamentally $T_2 \leq 2T_1$, and for most systems $T_1 \gg T_2$, which means that T_2 is more important for quantum computation.

Dephasing and Decoherence



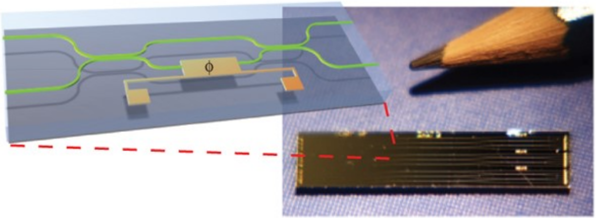
'Closed box' requirement: a quantum computer's internal operation, while under the programmer's control, must otherwise be isolated from the rest of the Universe. Small amounts of information leakage from the box can disturb the fragile quantum mechanical waves on which the quantum computer depends, causing the quantum mechanically destructive process known as decoherence.

T2 Performance of quantum technologies

Type of qubit	T_2	Benchmarking (%)		Referen
		One qubit	Two qubits	
Infrared photon	0.1 ms	0.016	1	20
Trapped ion	15 s	0.48†	0.7*	104–1
Trapped neutral atom	3 s	5		107
Liquid molecule nuclear spins	2 s	0.01†	0.47†	108
e^- spin in GaAs quantum dot	3 µs	5		43, 57
e^- spins bound to ^{31}P:^{28}Si	0.6 s	5		49
^{29}Si nuclear spins in ^{28}Si	25 s	5		50
NV centre in diamond	2 ms	2	5	60, 61,
Superconducting circuit	4 µs	0.7†	10*	73, 79,

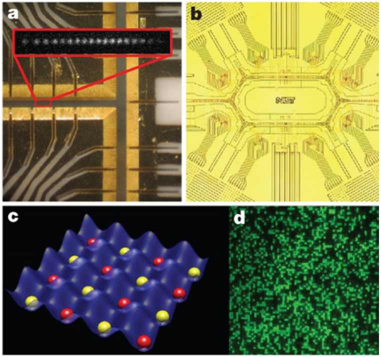
Measured T_2 times are shown, except for photons where T_2 is replaced by twice the (comparable to T_1) of a telecommunication-wavelength photon in fibre. Benchmark show approximate error rates for single or multi-qubit gates. Values marked with as found by quantum process or state tomography, and give the departure of the fide 100%. Values marked with daggers are found with randomized benchmarking[110]. Ot are rough experimental gate error estimates. In the case of photons, two-qubit gat frequently but success is heralded; error rates shown are conditional on a heraldec

Photonic quantum computer



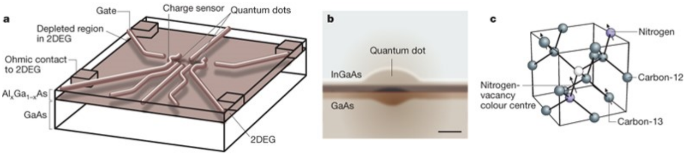
A microchip containing several silica-based waveguide interferometers with thermo-optic controlled phase shifts for photonic quantum gates. Green lines show optical waveguides; yellow components are metallic contacts. Pencil tip shown for scale.

Trapped Atom qubit



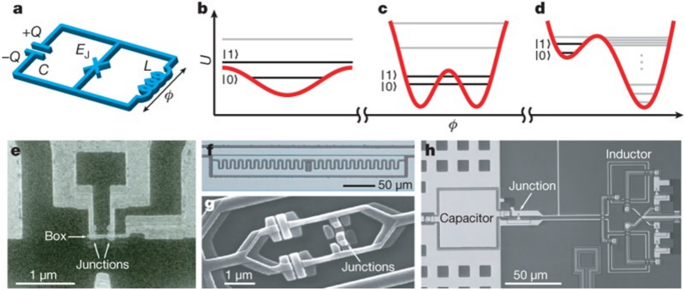
Trapped atom qubits. (a) Multi-level linear ion trap chip; the inset displays a linear crystal of several $^{171}\mathrm{Yb}^{+}$ ions fluorescing when resonant laser light is applied (the ion-ion spacing is $4\mu\mathrm{m}$ in the figure). Other lasers can provide qubit-state-dependent forces that can entangle the ions through their Coulomb interaction. (b) Surface ion trap chip with 200 zones distributed above the central hexagonal racetrack of width $2.5\mathrm{mm}$ (photograph courtesy of J. Amini and D. J. Wineland).
(c) Schematic of optical lattice of cold atoms formed by multi-dimensional optical standing wave potentials (graphic courtesy of J. V. Porto). (d) Image of individual Rb atoms from a Bose condensate confined in a two-dimensional optical lattice, with atom-atom spacing of $0.64\mu\mathrm{m}$ (photograph courtesy of M. Greiner).

Quantum Dots qubits



Quantum dot and solid-state dopant qubits. (a) An electrostatically confined quantum dot; the structure shown is several $\mu\mathrm{m}$ across. $\mathrm{2DEG}$, two-dimensional electron gas. (b) A self-assembled quantum dot. Scale bar, $\sim 5\mathrm{nm}$. (c) The atomic structure of a nitrogen-vacancy centre in the diamond lattice, with lattice constant 3.6 A.

Superconducting qubits



In superconductors at low temperature, electrons bind into Cooper pairs that condense into a state with zero-resistance current and a well-defined phase. In superconducting circuits, the potential for the quantum variables of that Cooper-pair condensate may be changed by controlling macroscopically defined inductances (L), capacitances (C) and so on, allowing the construction of qubits.

Nuclear Magnetic Resonance qubits

Nuclear spins in molecules in liquid solutions make excellent gyroscopes; rapid molecular motion actually helps nuclei maintain their spin orientation for T_2 times of many seconds, comparable to coherence times for trapped atoms. In 1996 methods were proposed for building small quantum computers using these nuclear spins in conjunction with 50 years' worth of existing magnetic resonance technology.

Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

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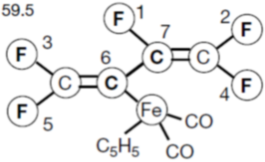
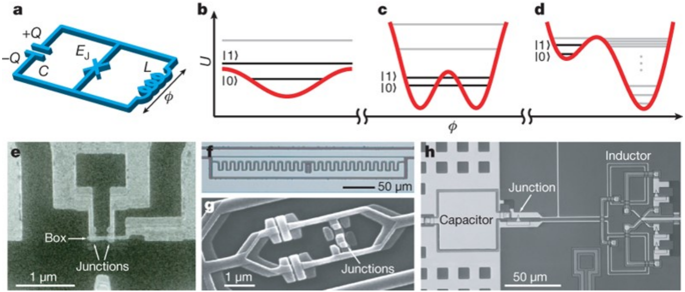
Nuclear Magnetic Resonance qubits

i	$\omega_i/2$	$T_{1,i}$	$T_{2,i}$	J_{7i}	J_{6i}	J_{5i}	J_{4i}	J_{3i}	J_{2i}
1	−22052.0	5.0	1.3	−221.0	37.7	6.6	−114.3	14.5	25.16
2	489.5	13.7	1.8	18.6	−3.9	2.5	79.9	3.9	
3	25088.3	3.0	2.5	1.0	−13.5	41.6	12.9		
4	−4918.7	10.0	1.7	54.1	−5.7	2.1			
5	15186.6	2.8	1.8	19.4	59.5				
6	−4519.1	45.4	2.0	68.9					
7	4244.3	31.6	2.0						



Structure and properties of the quantum computer molecule used in the Shor experiment, a perfluorobutadienyl iron complex.

Superconducting qubits



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Referenze

David P DiVincenzo.
The physical implementation of quantum computation.
Progress of Physics, 48(9-11):771–783, 2000.

Thaddeus D Ladd, Fedor Jelezko, Raymond Laflamme, Yasunobu Nakamura, Christopher Monroe, and Jeremy Lloyd O'Brien.
Quantum computers.
Nature, 464(7285):45–53, 2010.

Matthias Steffen, David P DiVincenzo, Jerry M Chow, Thomas N Theis, and Mark B Ketchen.
Quantum computing: An ibm perspective.
IBM Journal of Research and Development, 55(5):13–1, 2011.

Rodney Van Meter and Clare Horsman.
A blueprint for building a quantum computer.
Communications of the ACM, 56(10):84–93, 2013.

Lieven MK Vandersypen, Matthias Steffen, Gregory Breyta, Costantino S Yannoni, Mark H Sherwood, and Isaac L Chuang.
Experimental realization of shor's quantum factoring algorithm using nuclear magnetic resonance.