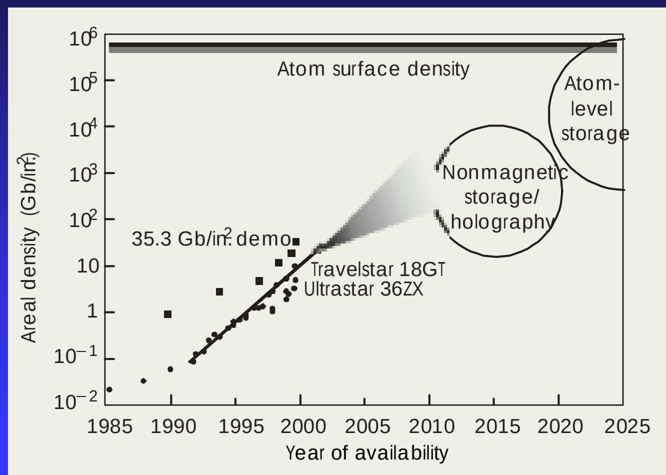
Лекция 2

Влияние физических идей на развитие новых компьютерных технологий

План лекции

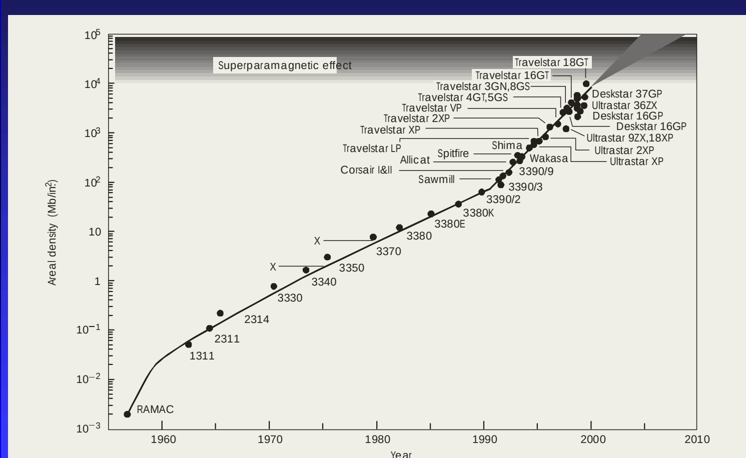
- Условное деление ЭВМ на классы и поколения
- Устройства хранения информации
  - Пределы магнитной памяти
  - Память на атомных структурах
  - Оптическая память
- Квантовые компьютеры и квантовые вычисления
- Самоорганизация, нейронные сети, обучающиеся системы, и др.

Перспективы устройств памяти



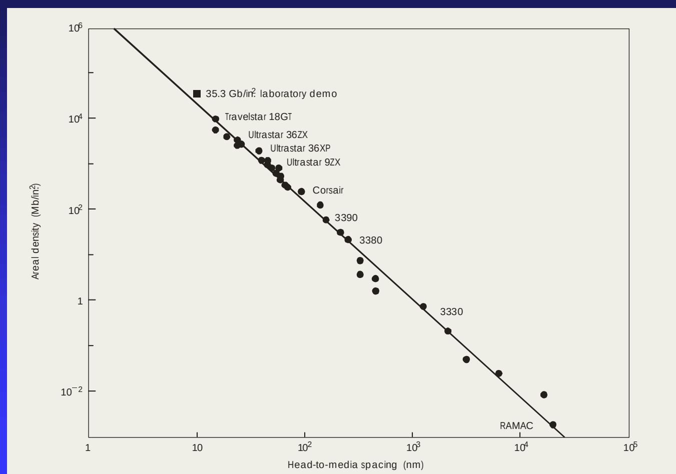
Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Магнитная память: Увеличение плотности записи



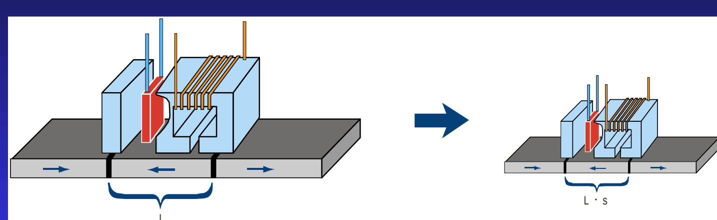
Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Магнитная память: расстояние от головки до магнитной среды



Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Магнитная память: Закон масштабирования



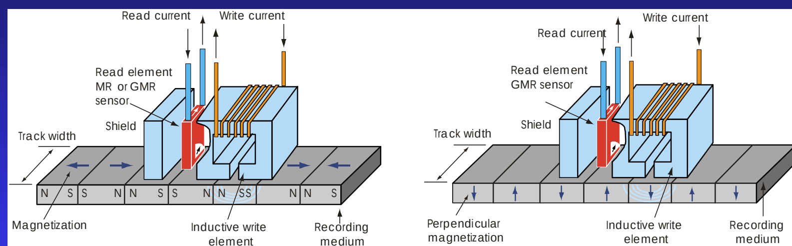
Уменьшение размера магнитной гранулы в 2 раза приводит к увеличению плотности записи в 4 раза и к уменьшению объема гранулы в 8 раз.

Физические пределы:

- Суперпарамагнитный предел – TB/in^2
- Расстояние от головки считывания до магнитного слоя – 2 nm
- Энергетические ограничения и др.

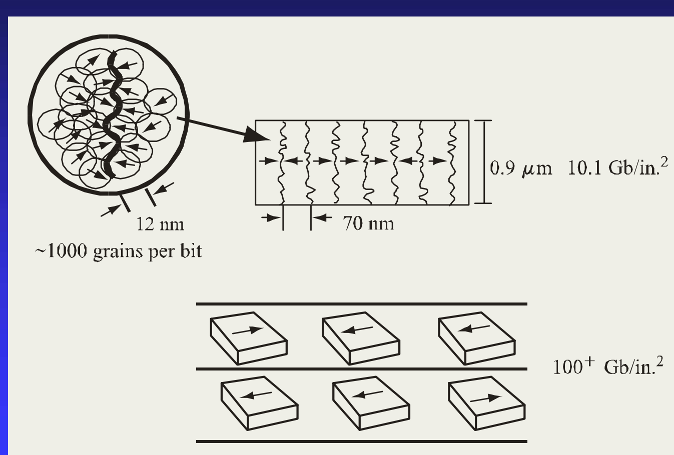
Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Магнитная память: продольная и вертикальная запись



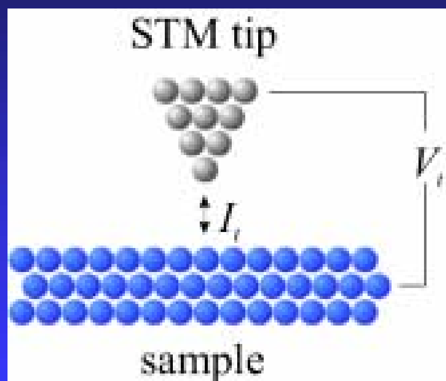
Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

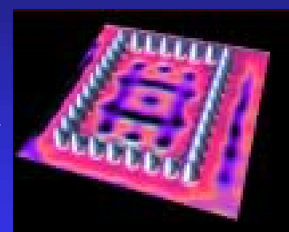
Магнитная память на базе макро- и одиночных гранул



Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

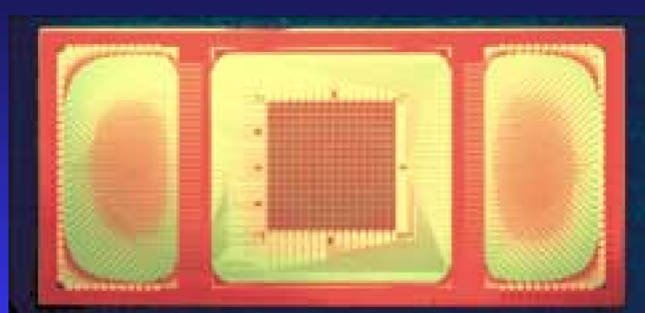
Сканирующая туннельная микроскопия (СТМ)





STM/STS image

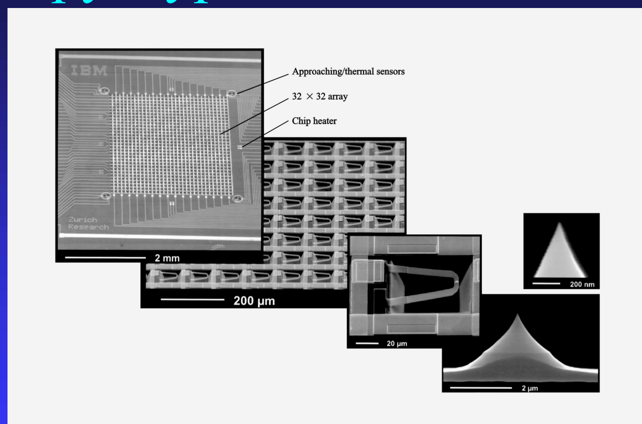
Память на атомных структурах



Фотография микросхемы (14x7 mm), содержащей массив 32x32 головок СТМ для записи/чтения информации на атомных структурах.

Source: P. Vettiger et. al, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

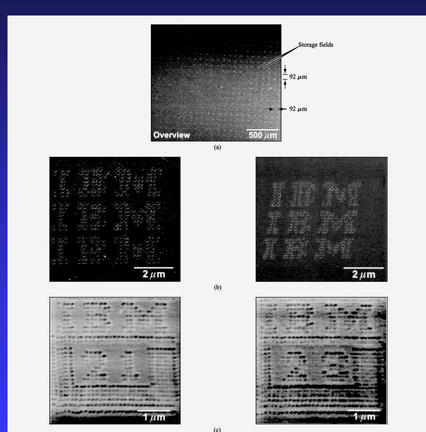
Память на атомных структурах



Детали предыдущей микросхемы, полученные с помощью сканирующей электронной микроскопии

Source: P. Vettiger et. al, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Память на атомных структурах

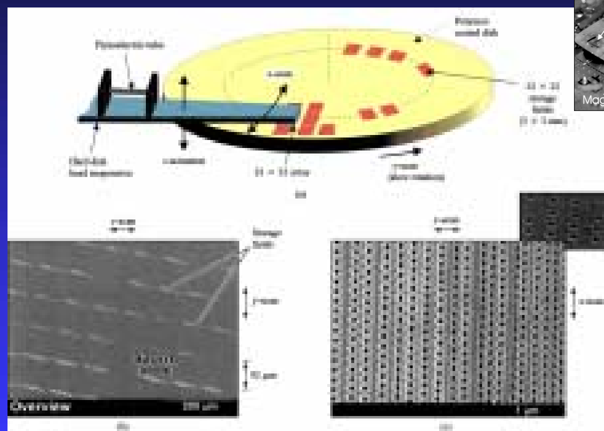


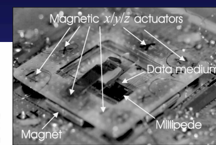
Демонстрация работы устройства записи/чтения на атомных структурах

Плотность: 100-200 Gb/in^2

Source: P. Vettiger et. al, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Память на атомных структурах

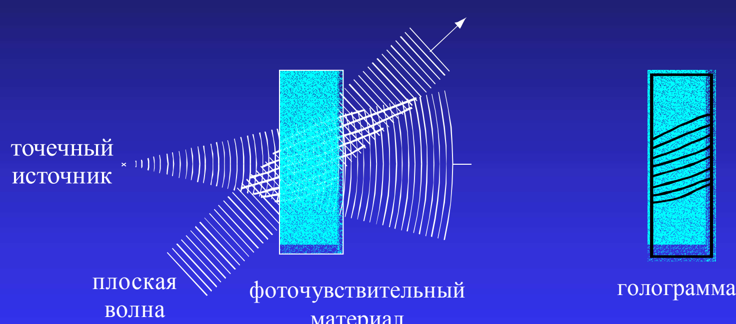




Прототип жесткого диска, базирующегося на технологии Millipede (IBM)

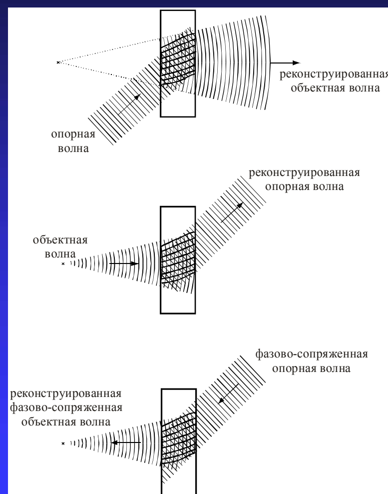
Source: P. Vettiger et. al,   IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Голографическая запись одного бита информации

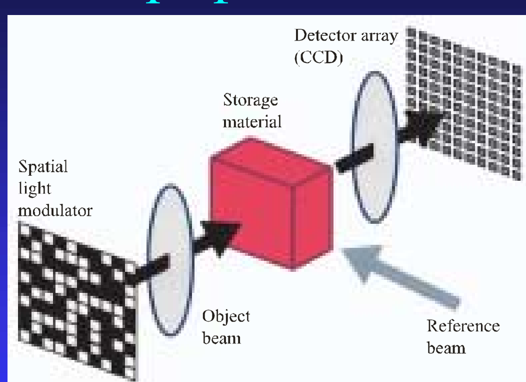


Теоретический предел: ~10^{14}-10^{15} бит/см^3

Чтение информации, записанной на голограмме



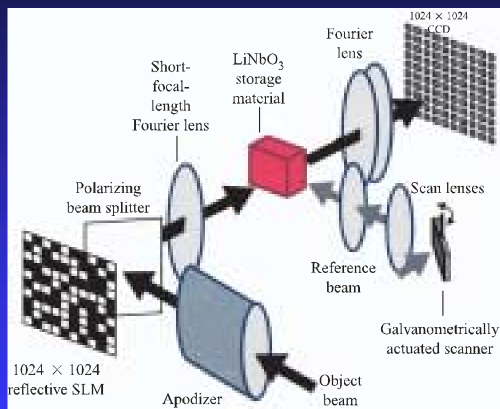
Принцип работы голографической памяти



Матричный ввод/вывод данных
Ассоциативный поиск информации!

Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

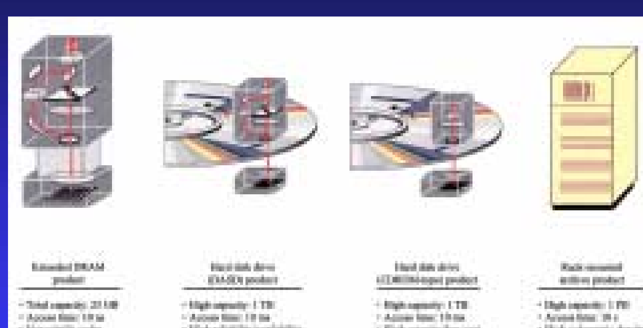
Видео на кристалле: IBM DEMON II



8 мм кристалл LiNbO$_3$:Fe
1200 голограмм
BER< $2x10^{-8}$

Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Возможные устройства голографической памяти



Source: D.A.Thompson, J.S.Best, IBM J. Res. Develop., Vol. 44, No. 3, May 2000

Компьютеры как физические системы

Our goal is to make computers faster

The fact that a real computer is a physical system prompts us to think about the *space*, *time*, and *energy* implications of trying to make computers faster

Due to the signal speed limit we have to squeeze components closer together. Therefore, components have to be *smaller* to be packed closer

Limit: Atomic size

We have to drive components at a *higher clock speed*

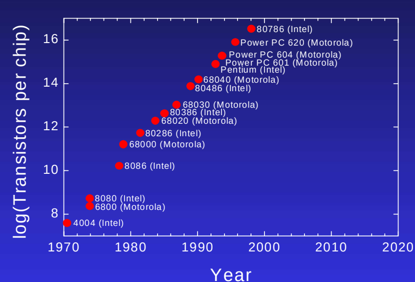
Limit: ~ 40 GHz

The components inside conventional computers give off a certain amount of heat as a side effect of their operation. Therefore, the components could not be packed closer with no improving their *energy efficiency*.

Example: in a PC ~10^8 kT in DNA ~100 kT per bit

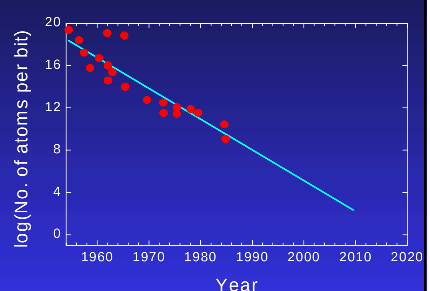
Limit: kTln2 per operation

Развитие технологий микроэлектроники



Logarithm of the number of transistors per chip as a function of calendar year and the processors that achieved these transistor densities.

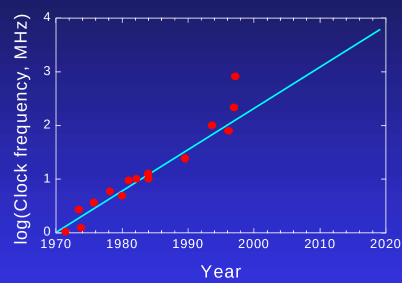
Adapted from: G.D.Hutcheson, J.D.Hutcheson, “Technology and economics in the semiconductor industry,” Scientific American, January, pp.54–62 (1996)



The number of atoms needed to represent one bit of information as a function of calendar year. Extrapolation of the trend suggests that the one-atom-per-bit level is reached in about the year 2020.

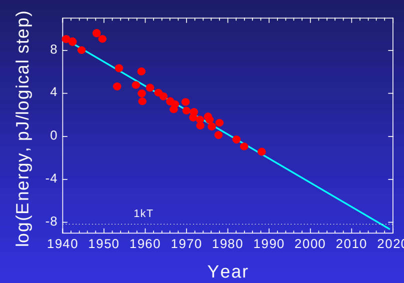
Adapted from: R.W.Keyes, “Miniaturization of electronics and its limits,” IBM Journal of Research and Development, vol. 32, January, pp. 24–28 (1988).

Развитие технологий микроэлектроники



Clock speed (MHz) versus calendar year. Note the exponential increase of clock speed with time.

Adapted from: Malone, "The microprocessor: A biography," TELOS, Santa Clara (1995).



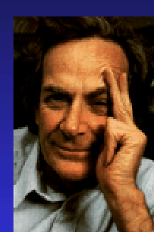
Energy (pico-Joules) dissipated per logical operation as a function of calendar year. The 1 kT level is indicated by a dashed line.

Adapted from: R.W.Keyes, "Miniaturization of electronics and its limits," IBM Journal of Research and Development, vol. 32, January, pp. 24–28 (1988).

Начало эры квантовых компьютеров

"There's plenty of room at the bottom."
— *Richard Feynman**)

"…it seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds dominant sway."
— *Richard Feynman***)



Richard P. Feynman

*) R.P.Feynman, "There's plenty of room at the bottom," *Engineering and Science*, vol. 23, pp.22-36 (1960).

**) R.P.Feynman, "Quantum mechanical computers," *Optics News*, vol. 11, pp. 11-20 (1985).

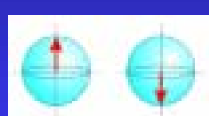
Быстрее ли квантовые компьютеры классических?

APPLICATIONS	QUANTUM COMPUTERS	CLASSICAL COMPUTERS
Cryptographic applications	*Shor's algorithm (1994)* finds prime factors of an N-digit number in a time of order N^3.	Any factoring algorithm that runs on a classical computer require a time that increases with N faster than any power.
Searching an unsorted database	In a database containing N items, the one item that meets a specific criterion can be found with the help of *Grover's algorithm (1996)* in a time of order $N^{1/2}$.	The database search would take a time of order N.
Simulation behavior of quantum systems (material science, chemistry, etc.)	Quantum device can store quantum information far more efficiently than any classical device (Feynman, 1982). N qubits live in a Hilbert space of dimension 2^N and operations on them are massively parallel.	A classical device would record 2^N–1 complex numbers to describe N qubits. Operations on them also require exponential resources.

Биты и кубиты

Classical bit

Has only two states "0" and "1"



Quantum bit (qubit*)

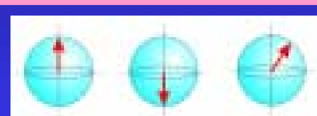
$|\Psi\rangle = a|0\rangle + b|1\rangle$

has two "classical" states:

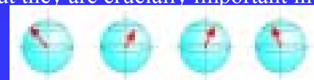
"0": $|\Psi\rangle_0 = 1|0\rangle + 0|1\rangle = |0\rangle$

"1": $|\Psi\rangle_1 = 0|0\rangle + 1|1\rangle = |1\rangle$

and all the states "in between"



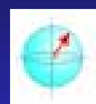
The phase factors do not affect the relative contributions of the eigenstates to the whole state, but they are crucially important in quantum interference effects



*) This term was coined by Schumacher (Phys. Rev. A51, 2738 (1995)

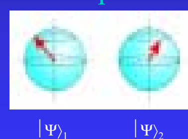
Квантовые запутанные (перепутанные) состояния

One qubit



$|\Psi\rangle = a|0\rangle + b|1\rangle$

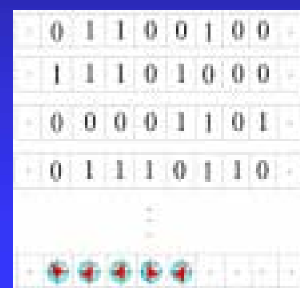
Two qubits



$|\Psi\rangle_{12} = |\Psi\rangle_1 \otimes |\Psi\rangle_2$

$|\Psi\rangle_{12} = c_{00}|00\rangle + c_{01}|01\rangle + c_{10}|10\rangle + c_{11}|11\rangle$

A quantum memory register can store multiple sequences of classical bits in superposition. An *exponential number* of inputs can be stored in a *polynomial number* of qubits.



Классические логические элементы

NOT

a	NOT a
0	1
1	0

AND

a b	a AND b
0 0	0
0 1	0
1 0	0
1 1	1

OR

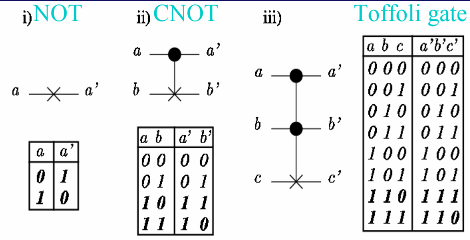
a b	a OR b
0 0	0
0 1	1
1 0	1
1 1	1

Reversible OR

a b	a	a OR b
0 0	0	0
0 1	0	1
1 0	1	1
1 1	1	1

- Fundamental set of gates (NOT, AND, and OR)
- These gates (except NOT) are logically irreversible
- Irreversible gates generate energy as they run
- Irreversible gates can be converted into reversible ones

Квантовые логические элементы



a	a'
0	1
1	0

a b	a' b'
0 0	0 0
0 1	0 1
1 0	1 1
1 1	1 0

a b c	a'b'c'
0 0 0	0 0 0
0 0 1	0 0 1
0 1 0	0 1 0
0 1 1	0 1 1
1 0 0	1 0 0
1 0 1	1 0 1
1 1 0	1 1 1
1 1 1	1 1 0

FIG. 5. Truth tables and graphical representations of the elementary quantum gates used for the construction of more complicated quantum networks. The control qubits are graphically represented by a dot, the target qubits by a cross. i) NOT operation. ii) Control–NOT. This gate can be seen as a "copy operation" in the sense that a target qubit (b) initially in the state 0 will be after the action of the gate in the same state as the control qubit. iii) Toffoli gate. This gate can also be seen as a Control–control–NOT: the target bit (c) undergoes a NOT operation only when the two controls (a and b) are in state 1.

A quantum network is a quantum computing device consisting of quantum logical gates whose computational steps are synchronized in time

Source: V.Vedral, M.B.Plenio, Progr. Quant. Electron., vol. 22, pp. 1–40 (1998)

Простое квантовое вычислительное устройство

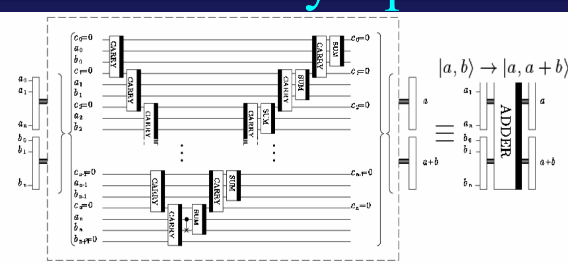
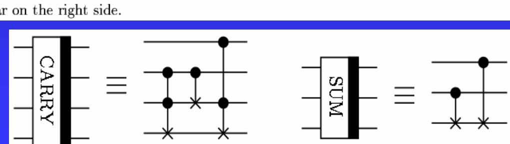


FIG. 6. Plain adder network. In a first step, all the carries are calculated until the last carry gives the most significant digit of the result. Then all these operations apart from the last one are undone in reverse order, and the sum of the digits is performed correspondingly. Note the position of a thick black bar on the right or left hand side of basic carry and sum networks. A network with a bar on the left side represents the reversed sequence of elementary gates embedded in the same network with the bar on the right side.



Source: V.Vedral, M.B.Plenio, Progr. Quant. Electron., vol. 22, pp. 1–40 (1998)

Время факторизации на классическом компьютере

Size of modulus (bits)	1,024	2,048	4,096
Factoring time in 1997	10^7 years	$3x10^{17}$ years	$2x10^{31}$ years
Factoring time in 2006	10^5 years	$5x10^{15}$ years	$3x10^{29}$ years
Factoring time in 2015	2,500 years	$7x10^{13}$ years	$4x10^{27}$ years
Factoring time in 2024	38 years	10^{12} years	$7x10^{25}$ years
Factoring time in 2033	7 months	$2x10^{10}$ years	10^{24} years
Factoring time in 2042	3 days	$3x10^8$ years	$2x10^{22}$ years

Table 2: Projected future factoring times using the GNFS for various moduli using 1,000 workstations.

(We assume that each workstation in 1997 is rated at 200 MIPS and there are no algorithmic developments beyond the General Number Field Sieve (GNFS) algorithm.)

Source: R.J.Hnughes, e-print, quant-ph/9801006

Время факторизации на квантовом компьютере

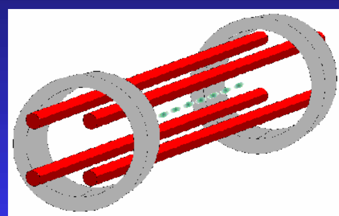
Алгоритм Шора (Shor)

Size of modulus (bits)	512	1,024	2,048	4,096
Quantum memory (qubits)	2,564	5,124	10,244	20,484
Number of quantum gates	$3x10^9$	$3x10^{10}$	$2x10^{11}$	$2x10^{12}$
Quantum factoring time	33 seconds	4.5 minutes	36 minutes	4.8 hours

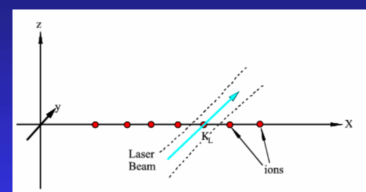
Table 3: Quantum factoring times of various moduli on a hypothetical 100-MHz QC.

Source: R.J.Hnughes, e-print, quant-ph/9801006

Квантовый компьютер на ионах в ловушке



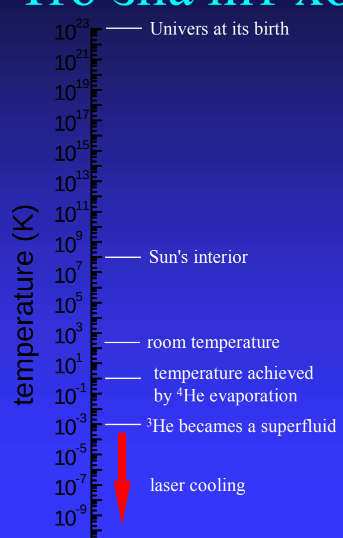
Source: V.Vedral, M.B.Plenio, Progr. Quant. Electron., vol. 22, pp. 1–40 (1998)



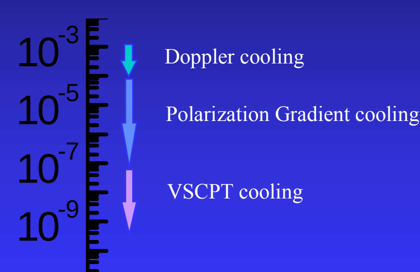
Source: D.F.V.James, et. Al. Proc. NASA-QCQC'98 (1998)

Proposal: J.I.Cirac, P.Zoller, Phys. Rev. Lett., vol. 74, p.4091 (1995)

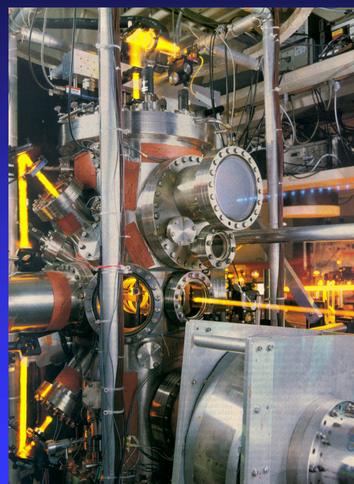
Температурная шкала: Что значит холодные атомы?



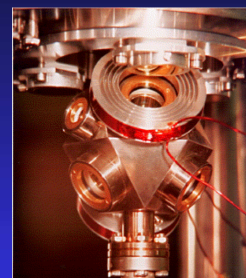
Laser Cooling



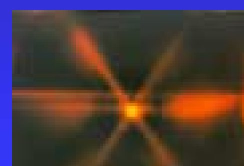
Ловушки для атомов/ионов



Source: *S.Chu, Scientific American, February 1992, p.48*



Source: *H.Bachor et al., Australian National University*



Source: *C.Cohen-Tannoudji, W.Phillips, Physics Today, October 1990, p. 35*

Прототипы твердотельных квантовых компьютеров

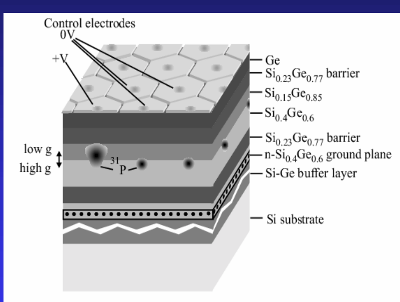


FIG. 13. In the future, we can expect arrays of Si-Ge SRT transistors. The center-to-center spacing would be ≈ 2000 Å. The gate electrodes on top will perform both single and 2-qubit operations, and can be used for data and instruction read-in.

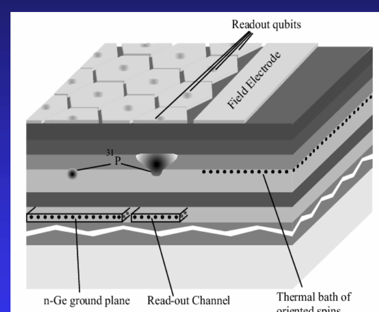


FIG. 15. A perspective view of Figure 14, gives more details of the readout architecture for the peripheral qubits. The field electrode allows the Readout Qubits to interact with the heat bath of oriented electron spins

Устройство компьютера на “бытовом уровне”