Computer Architectures, von Neumann & Quantum

Heraeus Seminar

5.2025 | DAVID DIVINCENZO

JÜLICH
Forschungszentrum

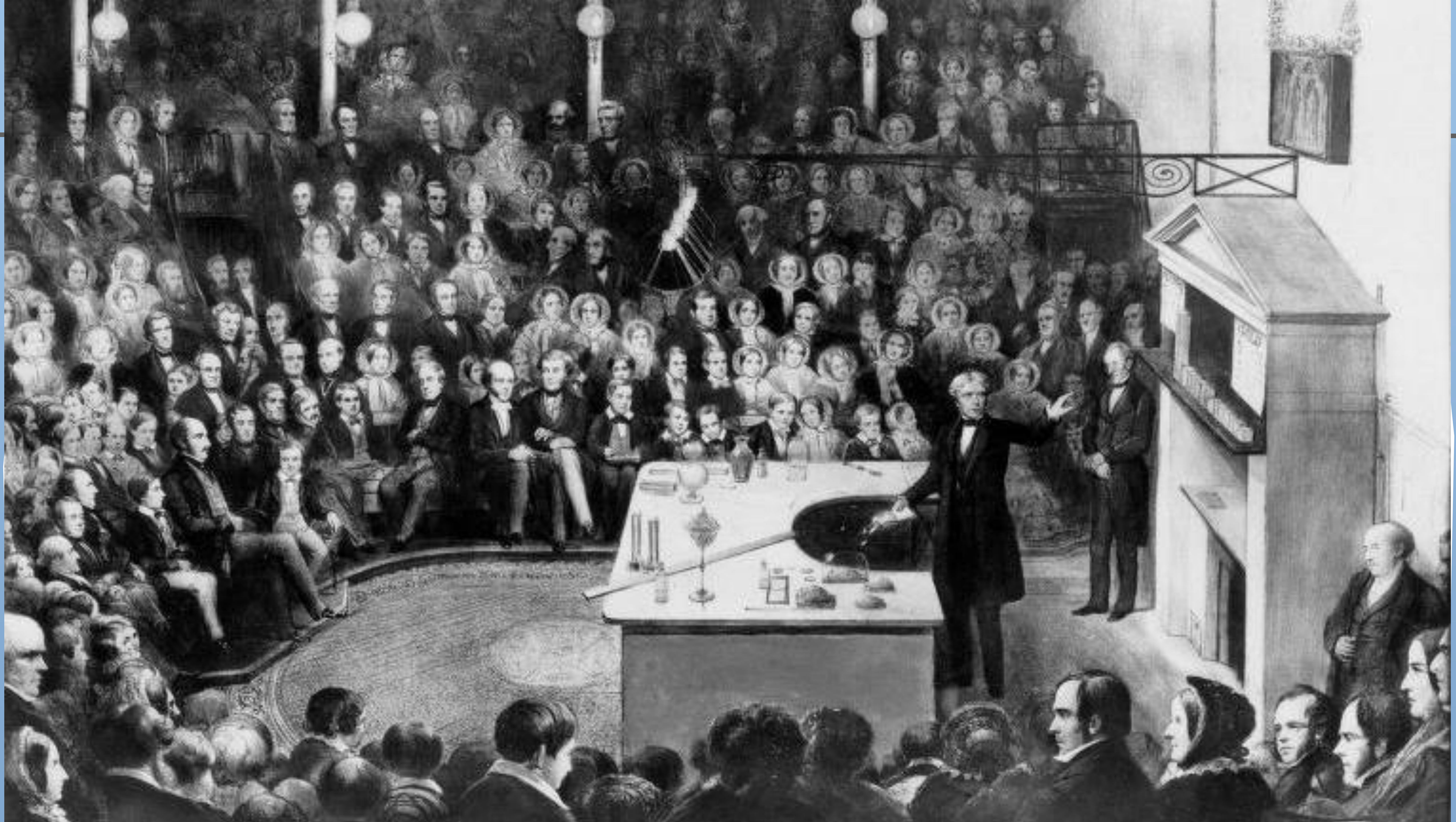
Outline

- Von Neumann’s prescriptions for computing machines: reliable vs. unreliable parts
- Situation at the University of Pennsylvania, 1946 & 1976
- “Computers will fill a big room” – classical & quantum!
- First quantum attempts: computers without architecture
- Realization: “architecture” can be all on classical side (von Neumann+)
  - Quantum part only there to provide non-classical correlations to classical computation
- Concepts and resources coming together for million-qubit machine

My life with computers: What a show!

ML4Q Student & Postdoc Retreat

7.2025 | DAVID DIVINCENZO



Physical Realization of Qubits

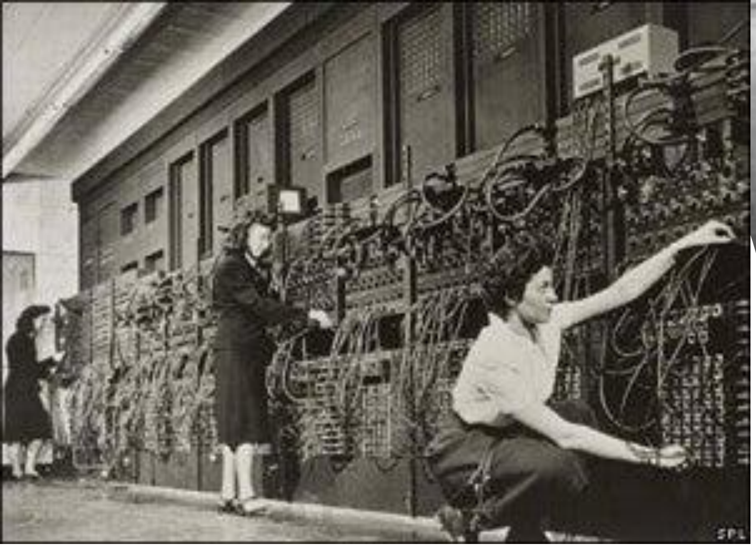
2025 Qiskit Global Summer School (Crowdcast)

7.2025 | DAVID DIVINCENZO

Outline

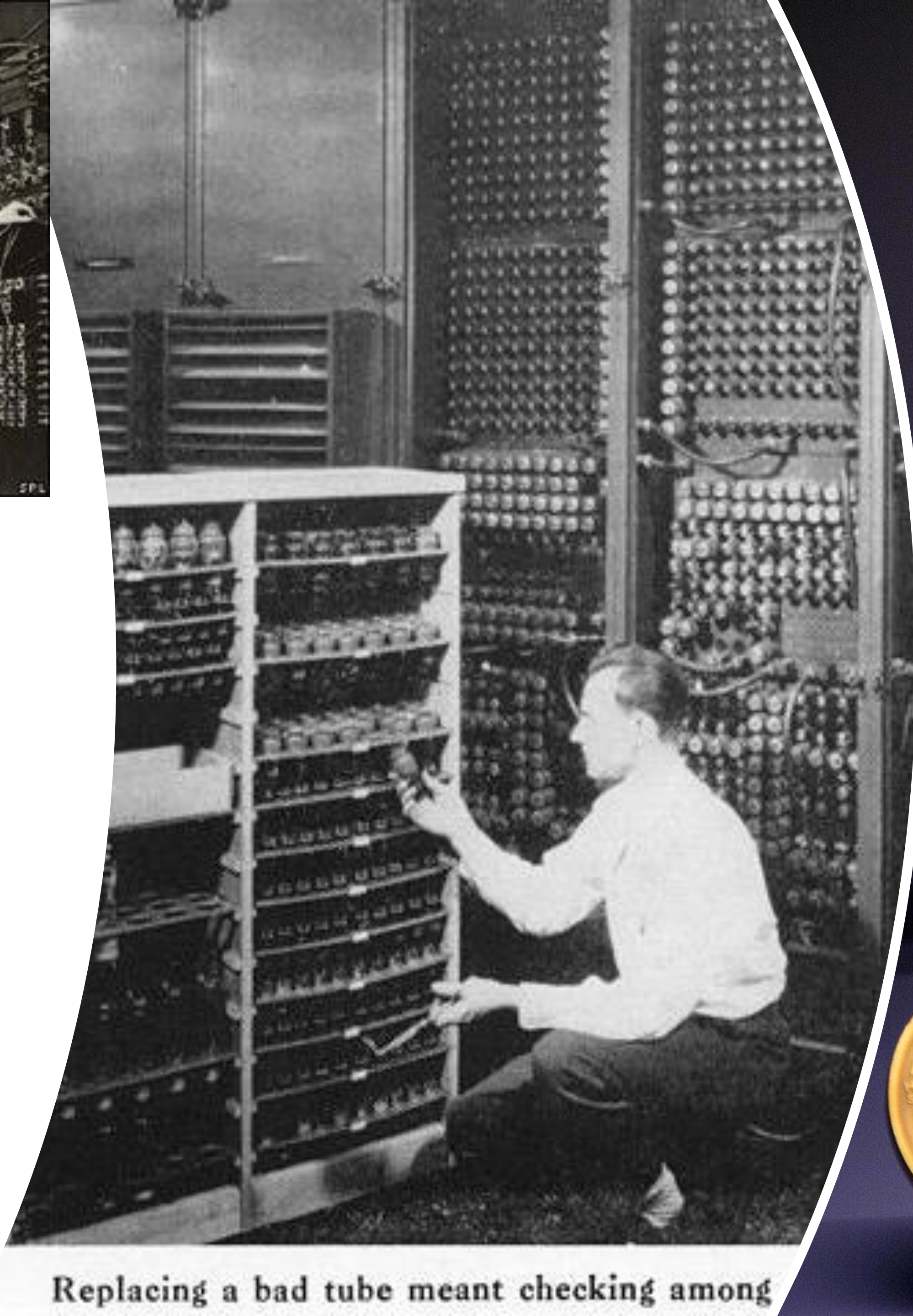
- My early life with computers --- the ENIAC
- Earliest understanding of quantum computers, and qubits
- Earliest IBM influences – Landauer, Bennett, and others
- First qubits, and some false starts
- 2000 and on:
  - Spin qubits
  - Superconducting qubits – first models
  - Dreams of an architecture

My early life with computers

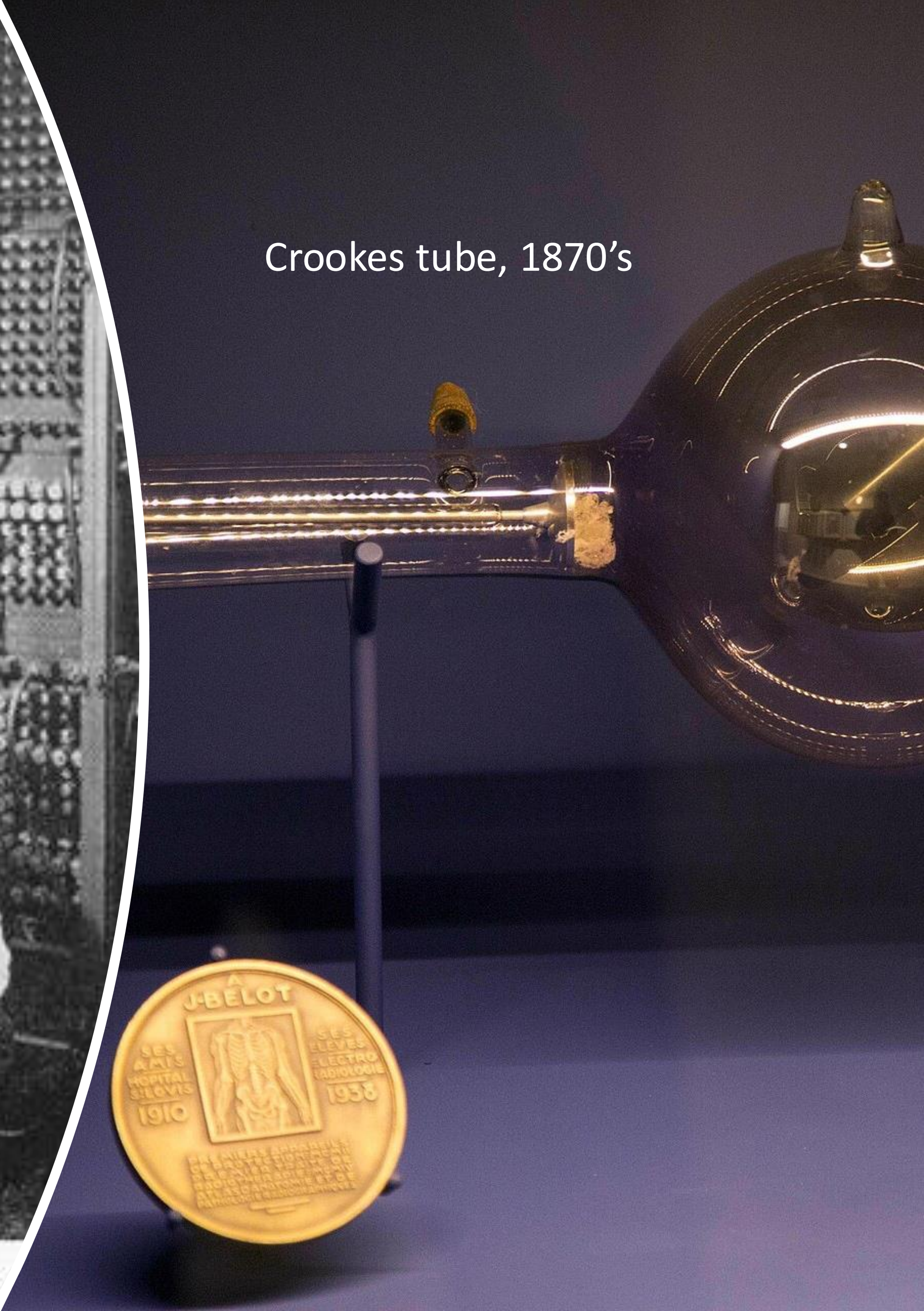


ENIAC electronic computer,
1944-1946

Standard computers, 1940s



Crookes tube, 1870’s



First Draft of a Report on the EDVAC

by

John von Neumann

Contract No. W–670–ORD–4926

Between the

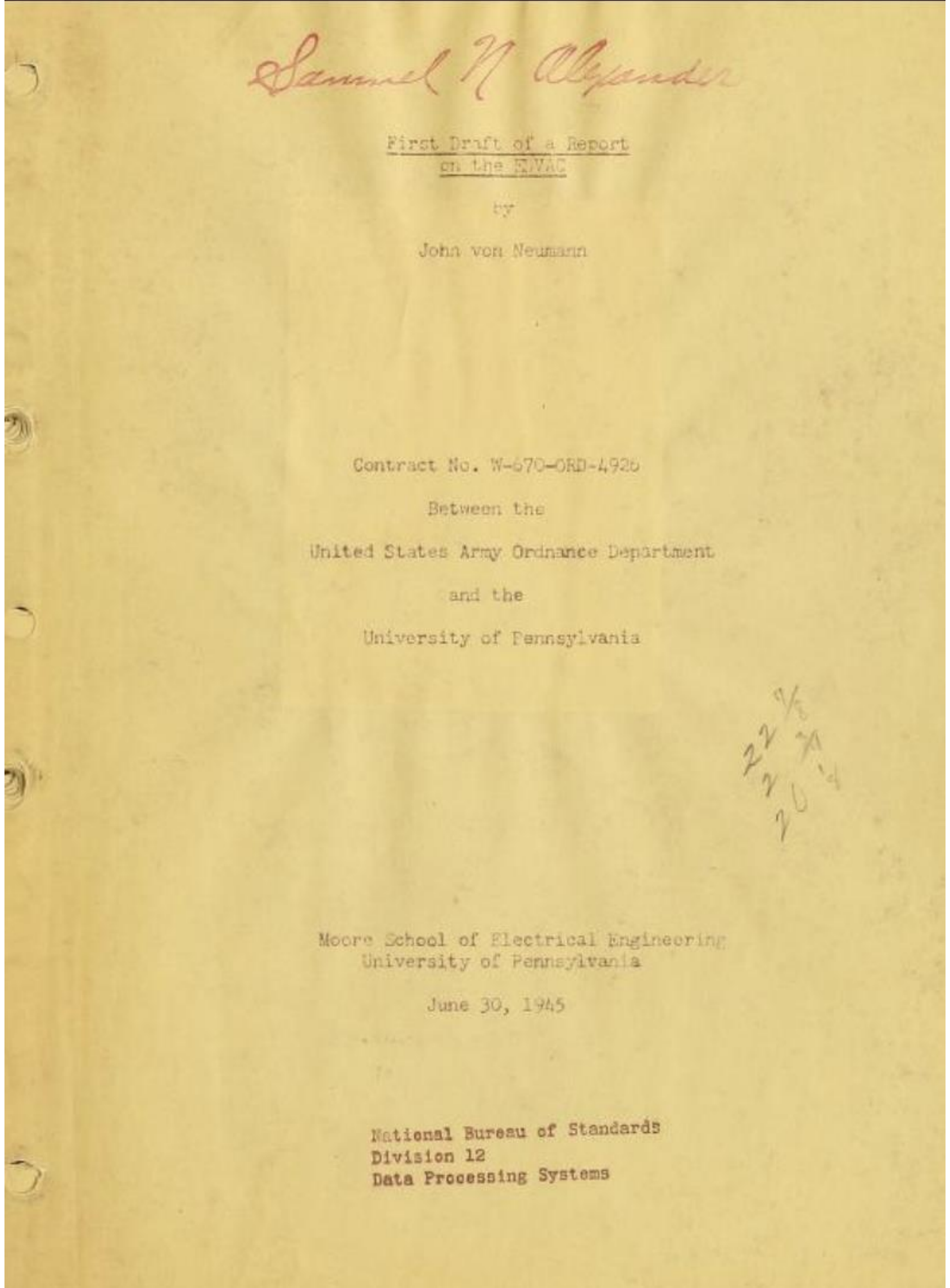
United States Army Ordnance Department

and the

University of Pennsylvania

Moore School of Electrical Engineering
University of Pennsylvania

June 30, 1945



Samuel N Alexander

First Draft of a Report
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June 30, 1945

National Bureau of Standards
Division 12
Data Processing Systems

Moore School of Electrical Engineering

33rd & Walnut

Moore School of Electrical Engineering

1976

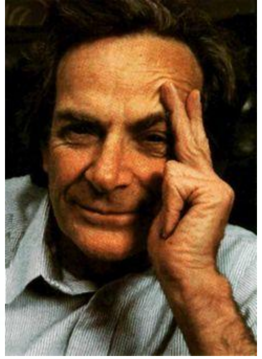
1978

First quantum inspirations, IBMers and others

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman



There are two ways that we can go about it. We can give up on our rule about what the computer was, we can say: Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws. Or we can turn the other way and say: Let the computer still be the same kind that we thought of before—a logical, universal automaton; can we imitate this situation? And I'm going to separate my talk here, for it branches into two parts.

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

The first branch, one you might call a side-remark, is, Can you do it with a new kind of computer—a quantum computer? (I'll come back to the other branch in a moment.) Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind. If we disregard

Rolf Landauer, IBM, c. 1960
“Information is Physical”

Y. Manin, c. 1980
“Computable & Uncomputable”, mentions quantum computer

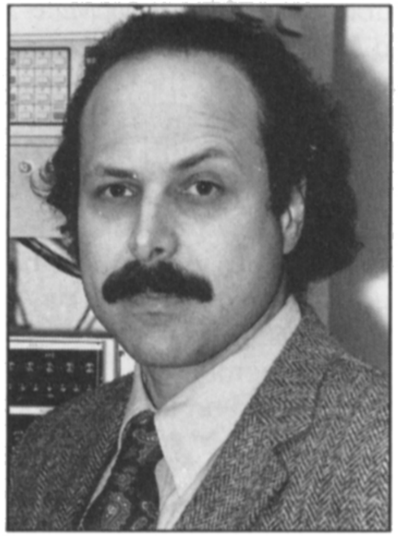
модели репликации, при разворачивании спирали часть хромосомы должна вращаться со скоростью, не меньшей 125 оборотов в секунду. Параллельно должна происходить сложная сеть безошибочных биохимических превращений.

Возможно, для прогресса в понимании таких явлений нам недостает математической теории квантовых автоматов. Такие объекты могли бы показать нам математические модели детерминированных процессов с совершенно непривычными свойствами. Одна из причин этого в том, что квантовое пространство состояний обладает гораздо большей емкостью, чем классическое: там, где в классике имеется N
дискретных состояний, в квантовой теори
зицию, имеется c^N планковских ячеек. П
систем их числа состояний N_1 и N_2 пе
варианте получается $c^{N_1 N_2}$.

Эти грубые подсчеты показывают гора
сложность квантового поведения системы
ческой имитацией. В частности, из-за
деления системы на элементы состояние
рассматриваться многими способами ка
ных виртуальных классических автомато
тельным подсчетом в конце работы [17].
расчета молекулы метана требуется про
сеток в 10^{42} точках. Если считать, что в
нить всего 10 элементарных операций,
числения производятся при сверхнизкой
то и при этом расчет молекулы метана п
гию, производимую на Земле примерно

Первая трудность при проведении этой программы состоит в выборе правильного баланса между математическими и физическими принципами. Квантовый автомат должен быть абстрактным: его математическая модель должна использовать лишь самые общие квантовые принципы, не предрешая физических реализаций. Тогда модель эволюции есть унитарное вращение в конечномерном гильбертовом пространстве, а модель виртуального разделения на подсистемы отвечает разложению пространства в тензорное произведение. Где-то в этой картине должно найти место взаимодействие, описываемое по традиции эрмитовыми операторами и вероятностями.

A. Holevo, c. 1975:
quantum channels



David D. Awschalom

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David D. Awschalom, a professor in the Department of Physics at the University of California, Santa Barbara, is the 1992 recipient of the Materials Research Society's Outstanding Young Investigator Award.

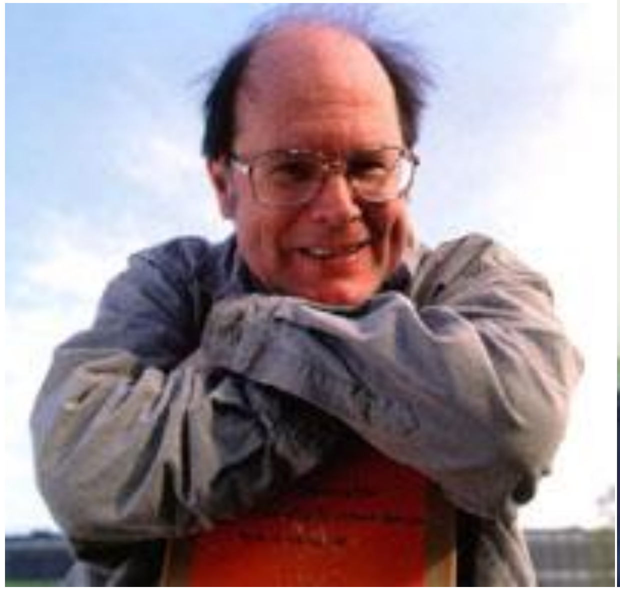
Awschalom was nominated for his contributions to the physics of manmade materials. Among these contributions are the study and explanation of thermodynamic properties of molecular systems in confined geometries, the first direct observations of the dynamic and static magnetic properties in magnetic superlattices, and the first observation of macroscopic spin phenomena in nanometer-scale magnets.

Awschalom, who has been described by one of his nominators as "a popular speaker in various national and international meetings," will talk on "Spin Dynamics and Tunneling in Quantum Magnetic Systems" during Symposium X

My personal first "qubit":

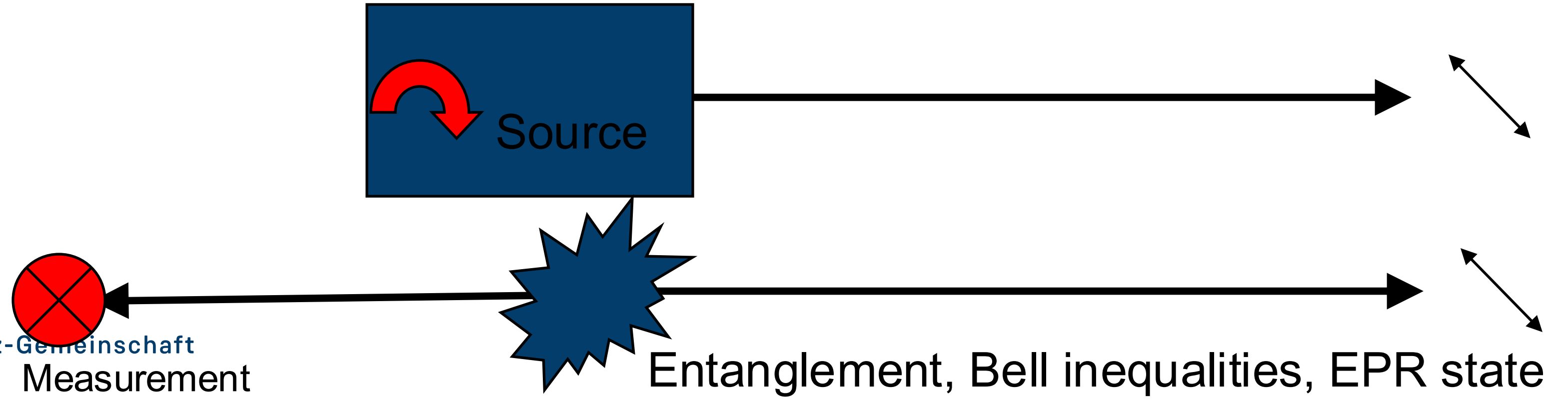
D. D. Awschalom, J. F. Smyth, G. Grinstein, D. P. DiVincenzo, and D. Loss, "Macroscopic quantum tunneling in magnetic proteins," Phys. Rev. Lett. **68**, 3092 (1992); 71, 4276(E) (1993).

The central ideas of a quantum cryptography and quantum communication



1984: Bennett and Brassard,
quantum key distribution

1992: Bennett and Wiesner,
superdense coding



Entanglement, Bell inequalities, EPR state, etc.

==

!NM! 4 S BENNETC - paper 5/02/94 15:20:27
Date: 2 May 1994, 15:20:27 EDT
From: DIVINCE at YKTVMV
To: BENNETC
Subject: paper

Charles--Thanks, I left a message [...] I found two copies of the
new version of the Shor paper, one of which left in the Bennetc folder,
in which I say your 8-cutps output.--David

==

First, my personal recollections of the interesting events after March, 1994 (FOCS submission) and November, 1994 (FOCS publication)

==

!NM! 87 S BENNETC -WATSON Peter Shor visit June 9 5/12/94 Ra 08:53:35
Date: 12 May 1994, 08:53:35 EDT
From: DIVINCE at YKTVMV
To: BENNETC at WATSON
Subject: Peter Shor visit June 9

Re: Note from you attached below

Charlie--My suggestion is to reserve the Aud. but keep the talk in 20-043,
with the planning of moving over if the overflow is too big.--David
------------------------------ Referenced Note ---------------------------
Received: from YKTVMV by watson.vnet.ibm.com with "VAGENT.V1.0"
id 1963; Wed, 11 May 1994 11:31:49 EDT
Received: from yktpub1.watson.ibm.com by yktvmv.watson.ibm.com
(IBM VM SMTP V2R3) with TCP; Wed, 11 May 94 11:31:49 EDT
Received: by yktpub1.watson.ibm.com (AIX 3.2/UCB 5.64/930311)
id AA72783; Wed, 11 May 1994 11:32:16 -0400
From: bennetc@yktpub1.watson.ibm.com (Charles H. Bennett)
Message-Id: <9405111532.AA72783@yktpub1.watson.ibm.com>
To: nabil@yktpub1.watson.ibm.com
Cc: divince@yktvmv.vnet.ibm.com, linsker@yktvmv.vnet.ibm.com,
neilg@media.mit.edu, ggrin@yktvmv.vnet.ibm.com
Subject: Peter Shor visit June 9
Date: Wed, 11 May 94 11:32:16 -0500

Peter Shor couldn't come Thursday June 2 when we'd hoped,
for our first "Physics but Computation" seminar, so I invited
him June 9th. I reserved room 20-043, with a capacity of 50,
from 11:00 to 12:30, but perhaps we should make a bigger
production of it, and reserve the auditorium. I figured people
would be more awake in the morning, but we could change the time
also (I have not mentioned a specific time to Shor yet). Also,
to give our series the appearance of being real and important,
we should probably print a nice flyer when we get Shor's
abstract. What other preparations do you think we should make?

-Charles

==

Polynomial-Time Algorithms for Factoring and Discrete Logarithms on a Quantum Computer

Peter Shor

AT&T Bell Labs

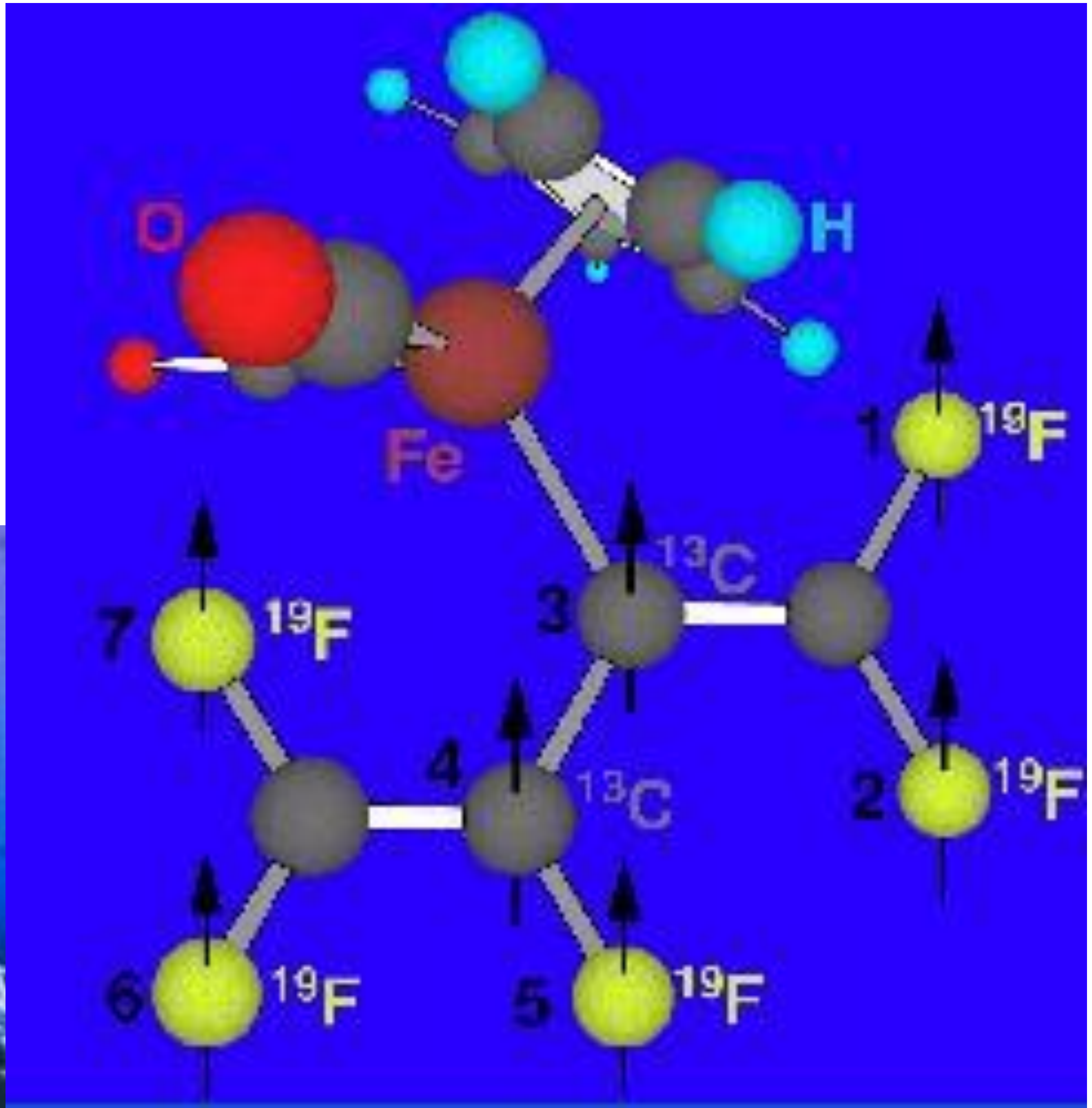
Seminar, 6/9/94.

First qubits and some false starts

NMR quantum computer –
7 qubit operation in y. 2000 CE

Nuclear spin
=1/2 for
F-19 and C-13

- "Factored 15."
- (Can't factor 221.)
- I.e., not scalable.
- Taught us the value of precision instruments
- Taught us a lot about control techniques



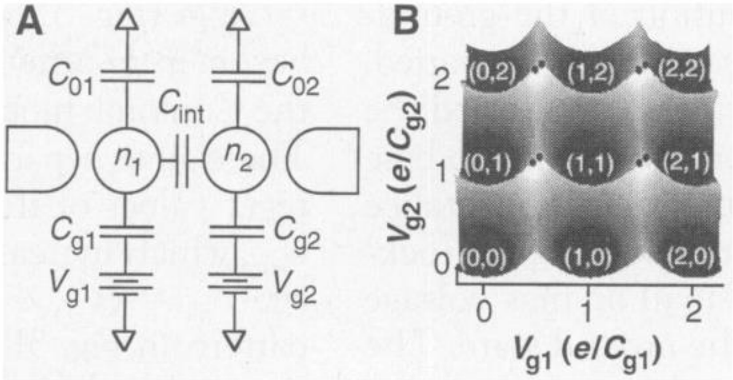
SCIENCE • VOL. 274 • 22 NOVEMBER 1996

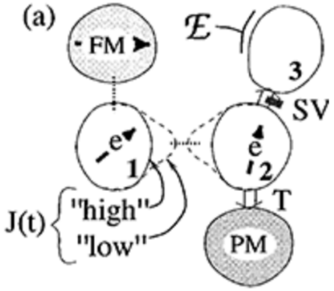
REPORTS

The Coulomb Blockade in Coupled Quantum Dots

C. Livermore,* C. H. Crouch, R. M. Westervelt,
K. L. Campman, A. C. Gossard

Individual quantum dots are often referred to as "artificial atoms." Two tunnel-coupled quantum dots can be considered an "artificial molecule." Low-temperature measurements were made on a series double quantum dot with adjustable interdot tunnel conductance that was fabricated in a gallium arsenide–aluminum gallium arsenide heterostructure. The Coulomb blockade was used to determine the ground-state charge configuration within the "molecule" as a function of the total charge on the double dot and the interdot polarization induced by electrostatic gates. As the tunnel conductance between the two dots is increased from near zero to $2e^2/h$ (where e is the electron charge





Quantum computation with quantum dots

In this paper, Loss and DiVincenzo laid out a proposal for quantum computation based on quantum dots. A detailed implementation of a universal set of one- and two-quantum-bit gates using the spin states of coupled single-electron quantum dots is presented. Following the proposal, significant theoretical and experimental achievements have made quantum dots another candidate platform for quantum computation.

Quantum computation with quantum dots
Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 (1998)

PHYSICAL REVIEW A
50th Anniversary Milestones

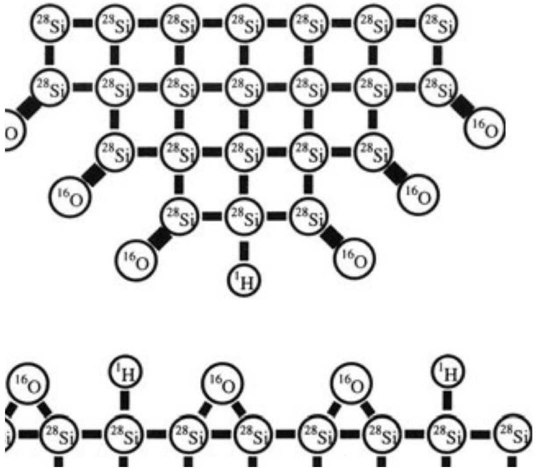
PHYSICAL REVIEW A VOLUME 51, NUMBER 2 FEBRUARY 1995

Two-bit gates are universal for quantum computation

David P. DiVincenzo
IBM Research Division, Thomas J. Watson Research Center, P. O. Box 218, Yorktown Heights, New York 10598
(Received 24 June 1994)

TABLE I. Important times for various two-level systems in quantum mechanics, which might be used as quantum bits. t_{switch} is the minimum time required to execute one quantum gate; it is estimated as $\hbar/\Delta E$, where ΔE is the typical energy splitting in the two-level system. t_ϕ is the phase coherence time as seen experimentally. t_ϕ is the upper bound on the length of time over which a complete quantum computation can be executed accurately. The ratio of these two times gives the largest number of steps permitted in a quantum computation using these quantum bits.

Quantum system	t_{switch} (sec)	t_ϕ (sec)	Ratio
Mössbauer nucleus [35]	10^{-19}	10^{-10}	10^{9}
electrons-GaAs [36]	10^{-13}	10^{-10}	10^{3}
electrons-Au [37,7]	10^{-14}	10^{-8}	10^{6}
trapped ions–In [38]	10^{-14}	10^{-1}	10^{13}
electron-spin [9]	10^{-7}	10^{-3}	10^{4}
electron–quantum-dot [39]	10^{-6}	10^{-3}	10^{3}
nuclear spin [21]	10^{-3}	10^{4}	10^{7}



Atomic-force microscope
quantum computer

"Gearbox quantum computer". Not realistic. But, was a motivation for two different directions in quantum computing research…

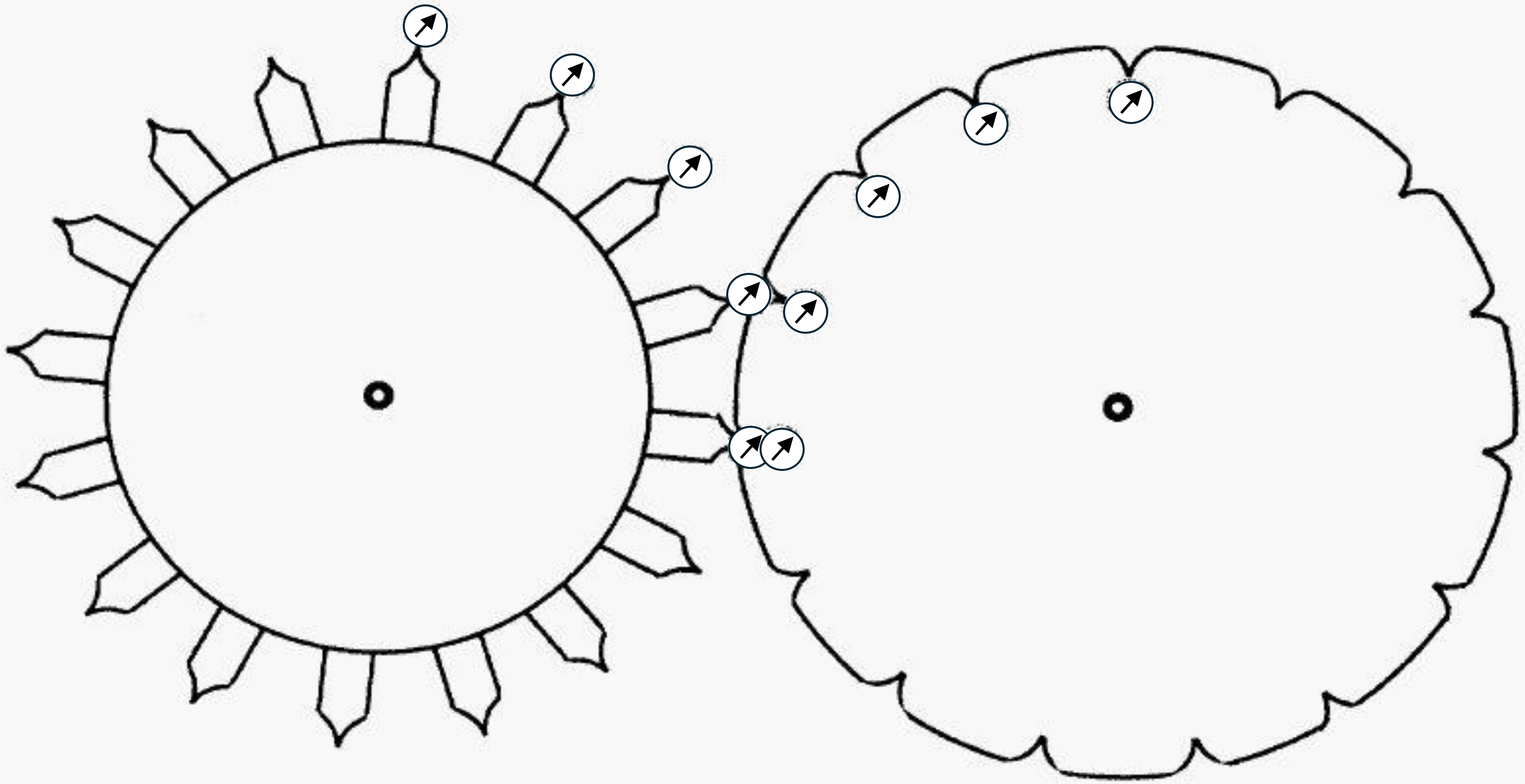
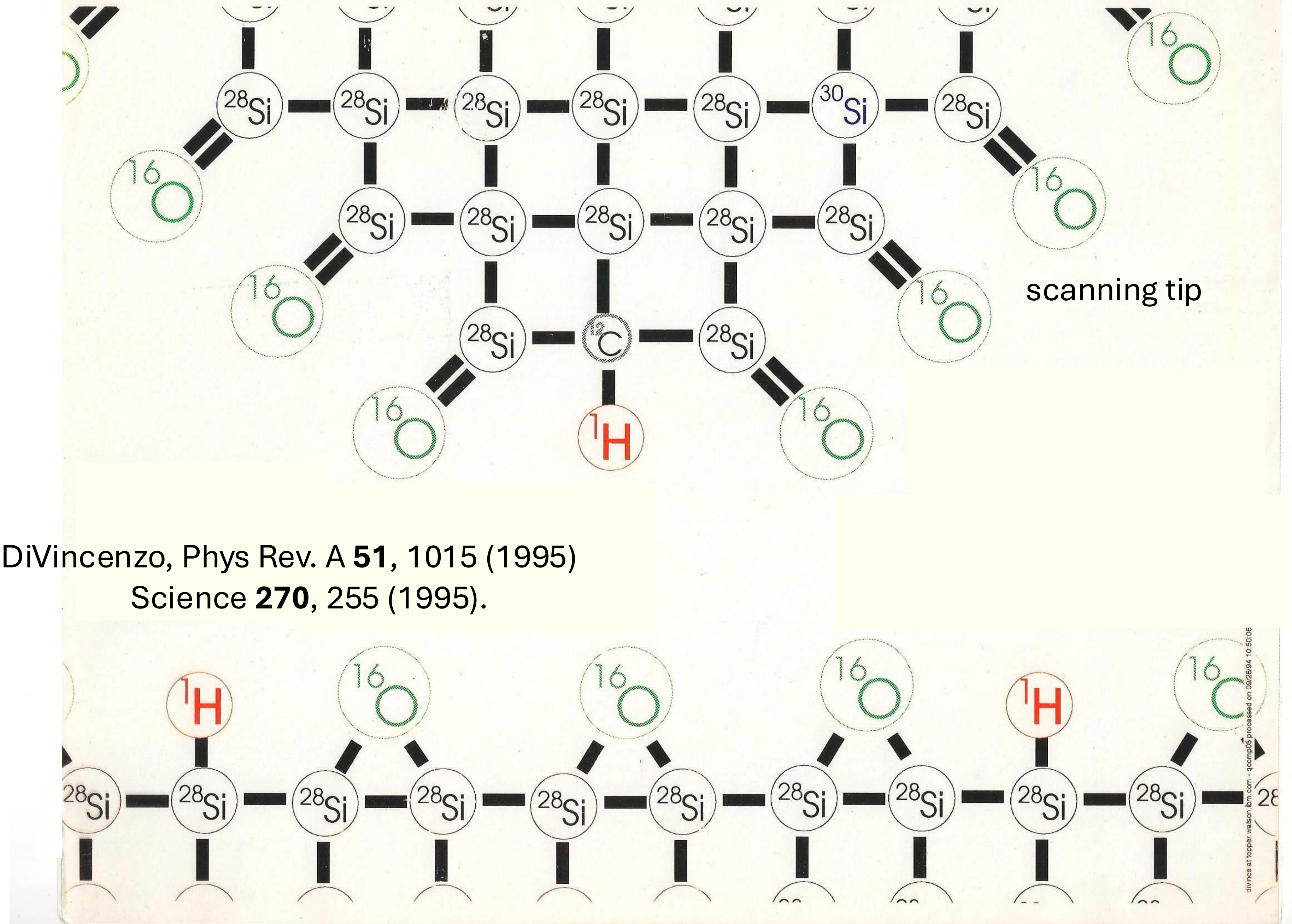


FIG. 1. The gearbox quantum computer. The two meshed gears operate classically, turning in synchrony. A single quantum spin-1/2 degree of freedom, discussed as a proton nuclear

From DiVincenzo, "Two-bit gates are universal for quantum computing," Phys Rev. A **51**, 1015 (1995)

Example: early idea -- nanostructure for control of (nuclear) spin



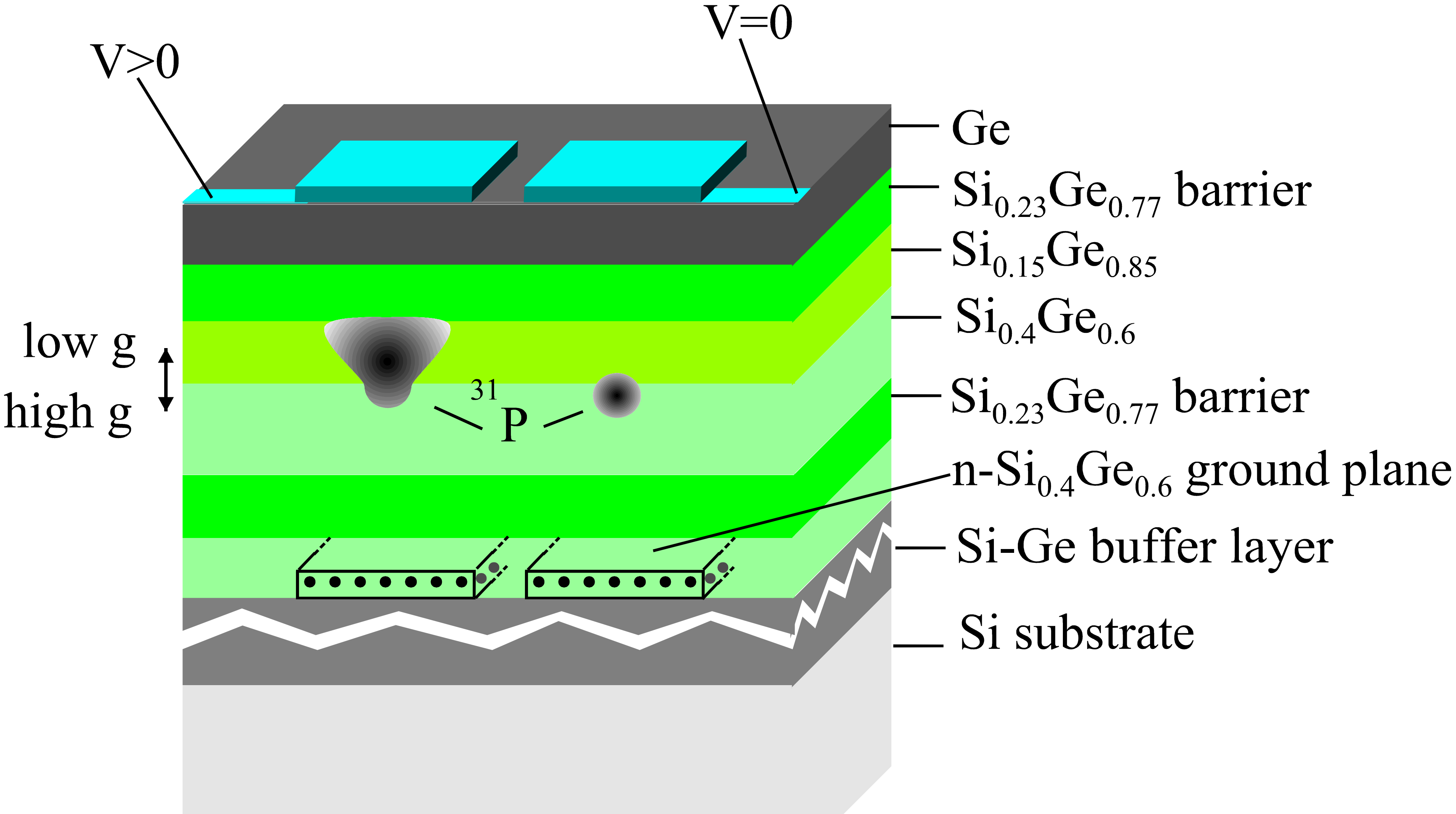
DiVincenzo, Phys Rev. A **51**, 1015 (1995)
Science **270**, 255 (1995).

Realistic spin qubit concepts --- 1996 -

Kane (1998) →

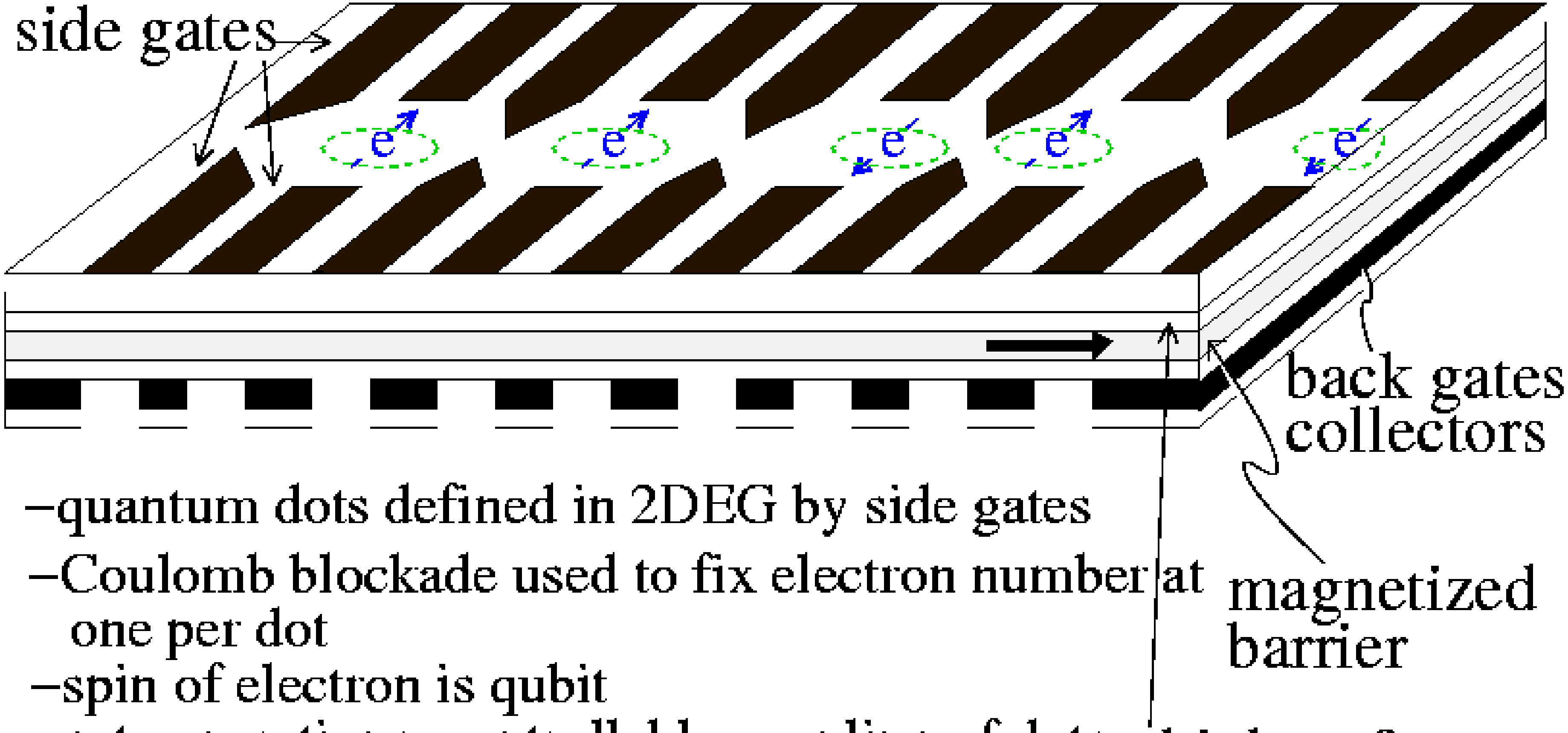
Concept device: spin-resonance transistor

R. Vrijen et al, Phys. Rev. A 62, 012306 (2000)



Quantum–dot array proposal:

Loss & DiVincenzo, Phys. Rev. A 57, 120 (1998).



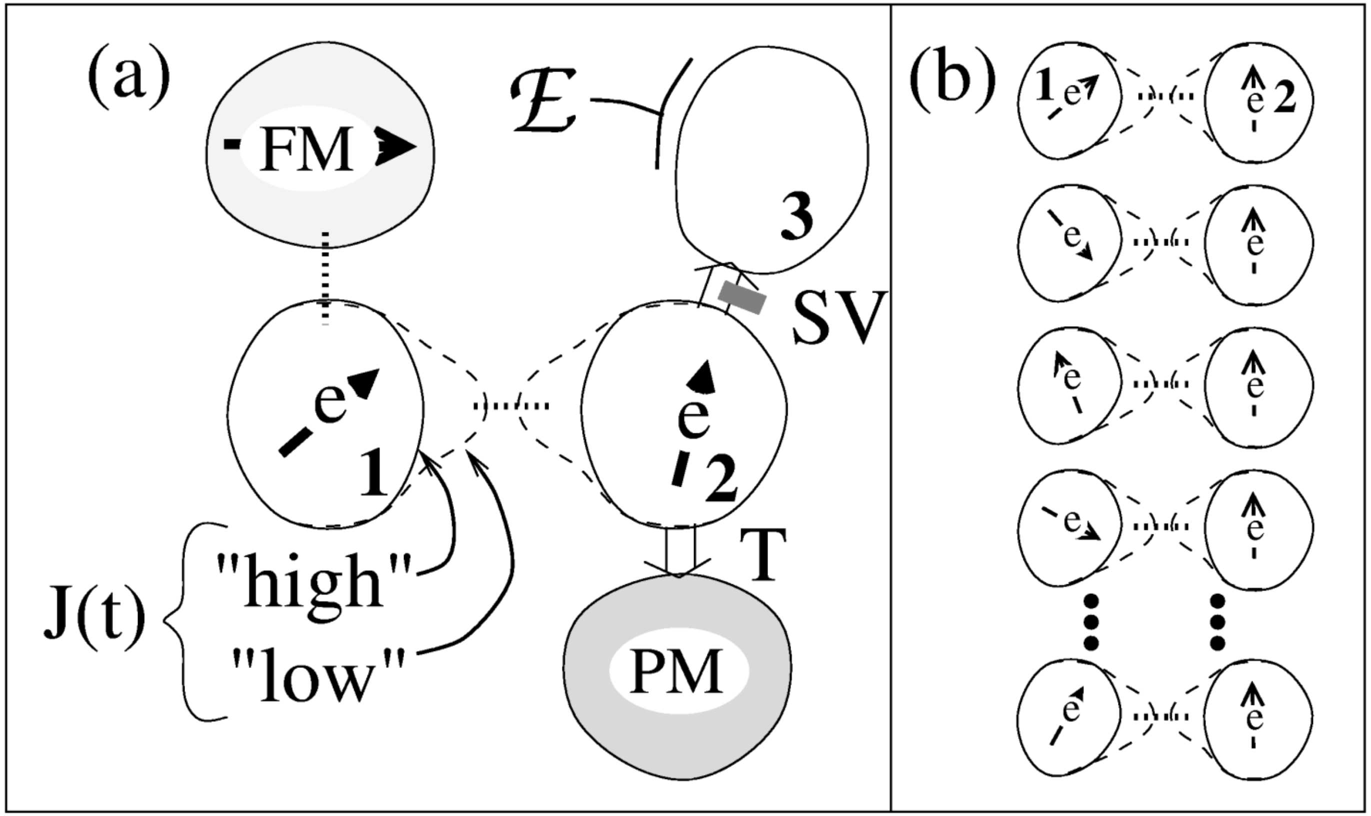
–quantum dots defined in 2DEG by side gates

–Coulomb blockade used to fix electron number at one per dot

–spin of electron is qubit

–gate operations: controllable coupling of dots by point–contact gate voltage

–readout by gatable magnetic barrier



Loss & DiVincenzo
quant-ph/9701055

FIG. 1. a) Schematic top view of two coupled quantum dots labeled 1 and 2, each containing one single excess electron (e) with spin 1/2. The tunnel barrier between the dots can be raised or lowered by setting a gate voltage "high" (solid equipotential contour) or "low" (dashed equipotential contour). In the low state virtual tunneling (dotted line) produces a time-dependent Heisenberg exchange $J(t)$. Hopping to an auxiliary ferromagnetic dot (FM) provides one method of performing single-qubit operations. Tunneling (T) to the paramagnetic dot (PM) can be used as a POV read out with 75% reliability; spin-dependent tunneling (through "spin valve" SV) into dot 3 can lead to spin measurement via an electrometer $\mathcal{E}$. b) Proposed experimental setup for initial test of swap-gate operation in an array of many non-interacting quantum-dot pairs. Left column of dots is initially unpolarized while right one is polarized; this state can be reversed by a swap operation (see Eq. (31)).

Can we get CNOT with just Heisenberg exchange?

Conventional answer– NO:

--because Heisenberg interaction has too much symmetry
--it cannot change
  S (total angular momentum quantum number)
  S_z (z component of total angular momentum)

Correct answer (Berkeley, MIT, Los Alamos) – YES:

--the trick: encode qubits in states of specific angular momentum quantum numbers

Specific scheme to get quantum gates with just Heisenberg exchange:

NATURE | VOL 408 | 16 NOVEMBER 2000 |

Universal quantum computation with the exchange interaction

D. P. DiVincenzo*, D. Bacon†‡, J. Kempe†§‖, G. Burkard¶ & K. B. Whaley†

* *IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598, USA*
† *Department of Chemistry,* ‡ *Department of Physics,* § *Department of Mathematics, University of California, Berkeley, California 94720, USA*
‖ *École Nationale Superieure des Télécommunications, 46 rue Barrault, 75634 Paris Cedex 13, France*
¶ *Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*

Most economical coding scheme:
1 qubit = 3 spins:

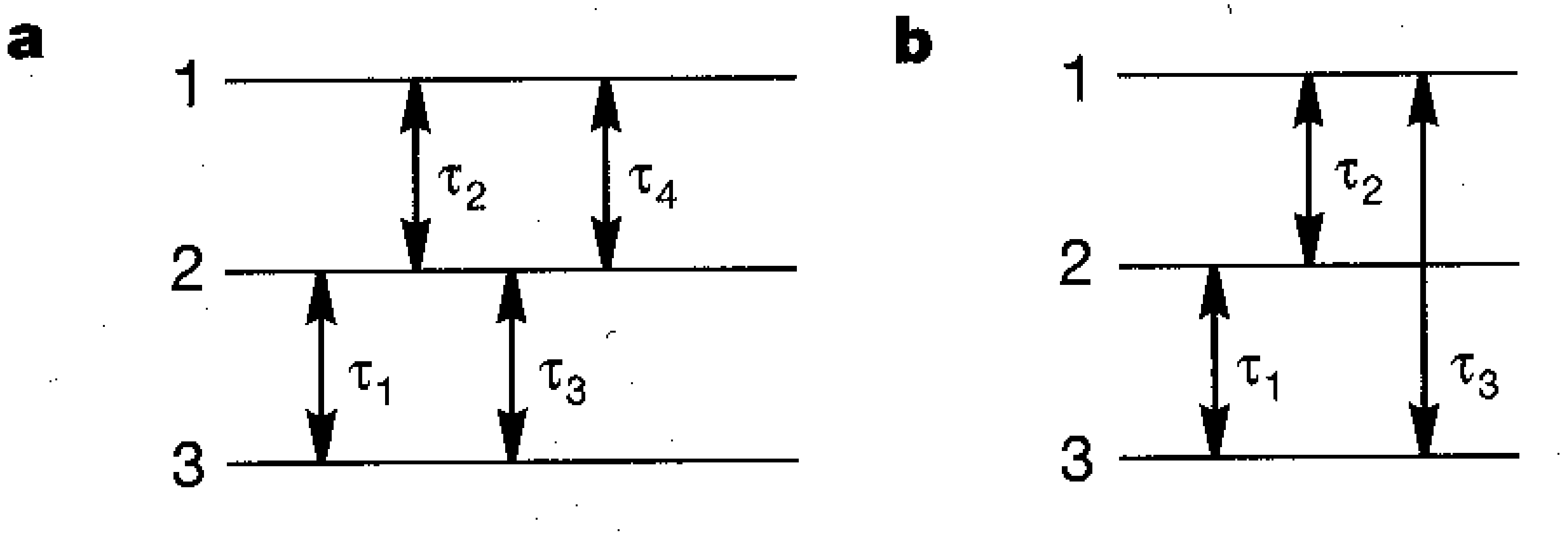
$$|0\rangle_L \propto |\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle$$

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)|\uparrow\rangle$$ (i.e., singlet times spin-up)

$$|1\rangle_L \propto 2|\uparrow\uparrow\downarrow\rangle - |\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle$$ (triplet on first two spins)

Because quantum numbers are fixed ($S=1/2$, $S_z=+1/2$), all gates on These logical qubits can be performed using SWAP:

Economical coded-gate implementations—results of simulations

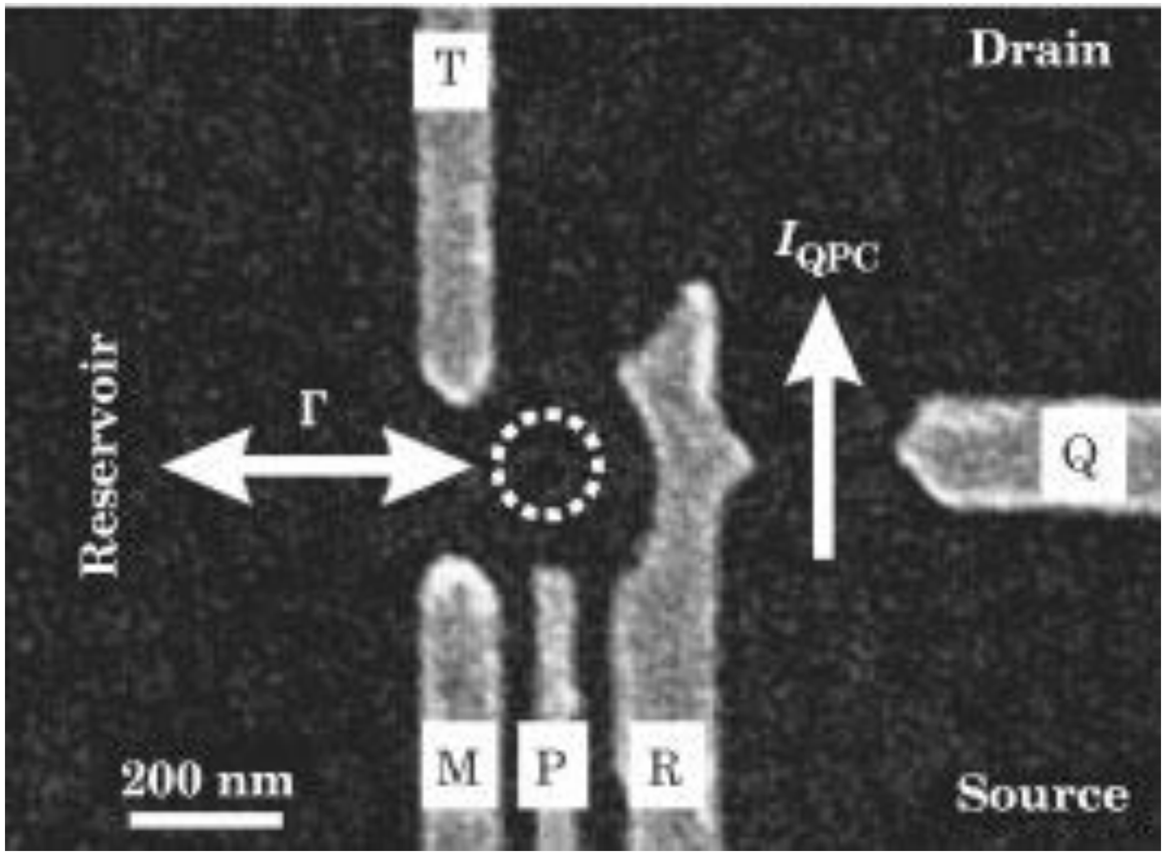


By varying interactions times shown,
all 1-qubit gates on coded qubits can be obtained with no more than 4 exchange operations (if only nearest-neighbor interactions) or 3 exchange interactions (if interactions between spin 1 and spin 3 are possible)

Spin qubits in the lab, 2000 -

In this quantum dot device, the group at Delft created
A spin qubit and achieved single-spin measurement on demand.

J. M. Elzerman, R. Hanson, L. H. Willems van Beveren,
B. Witkamp, L. M. K. Vandersypen, L. P. Kouwenhoven,
Nature **430**, 431 (2004)



Planned scheme for ESR of single dots (Hanson, PhD thesis, 2004)

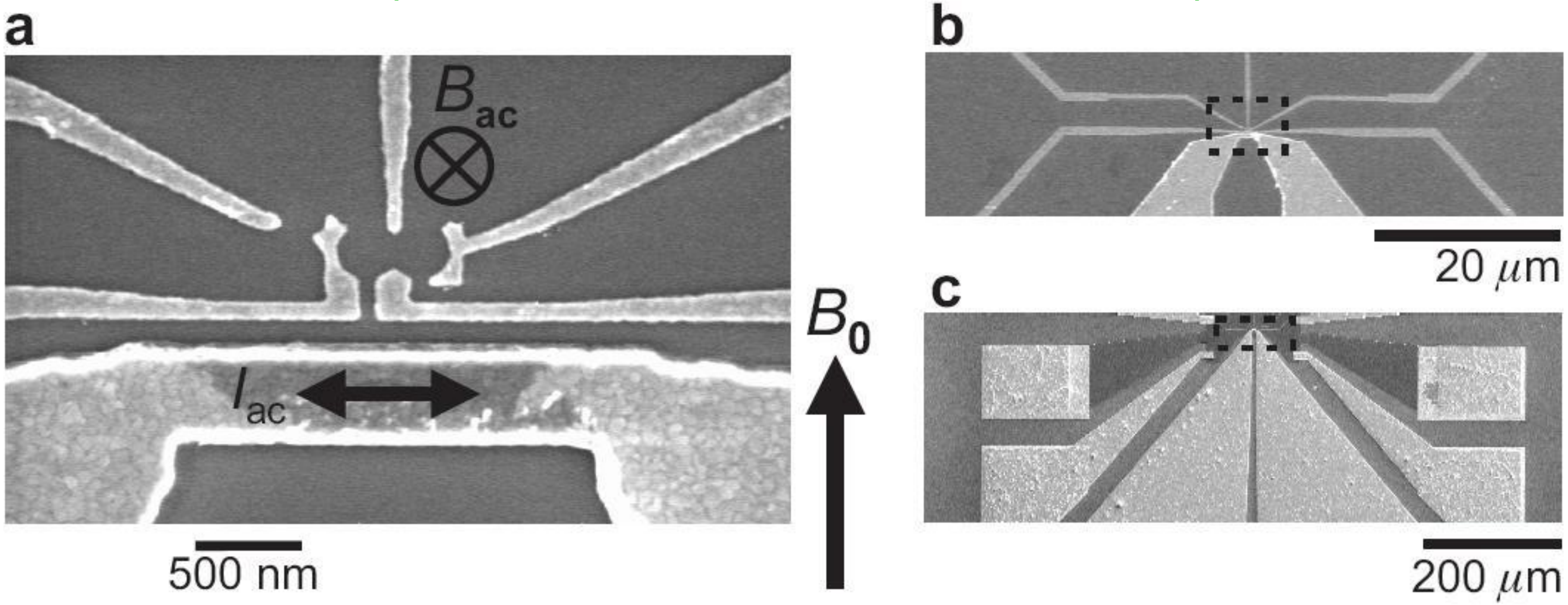
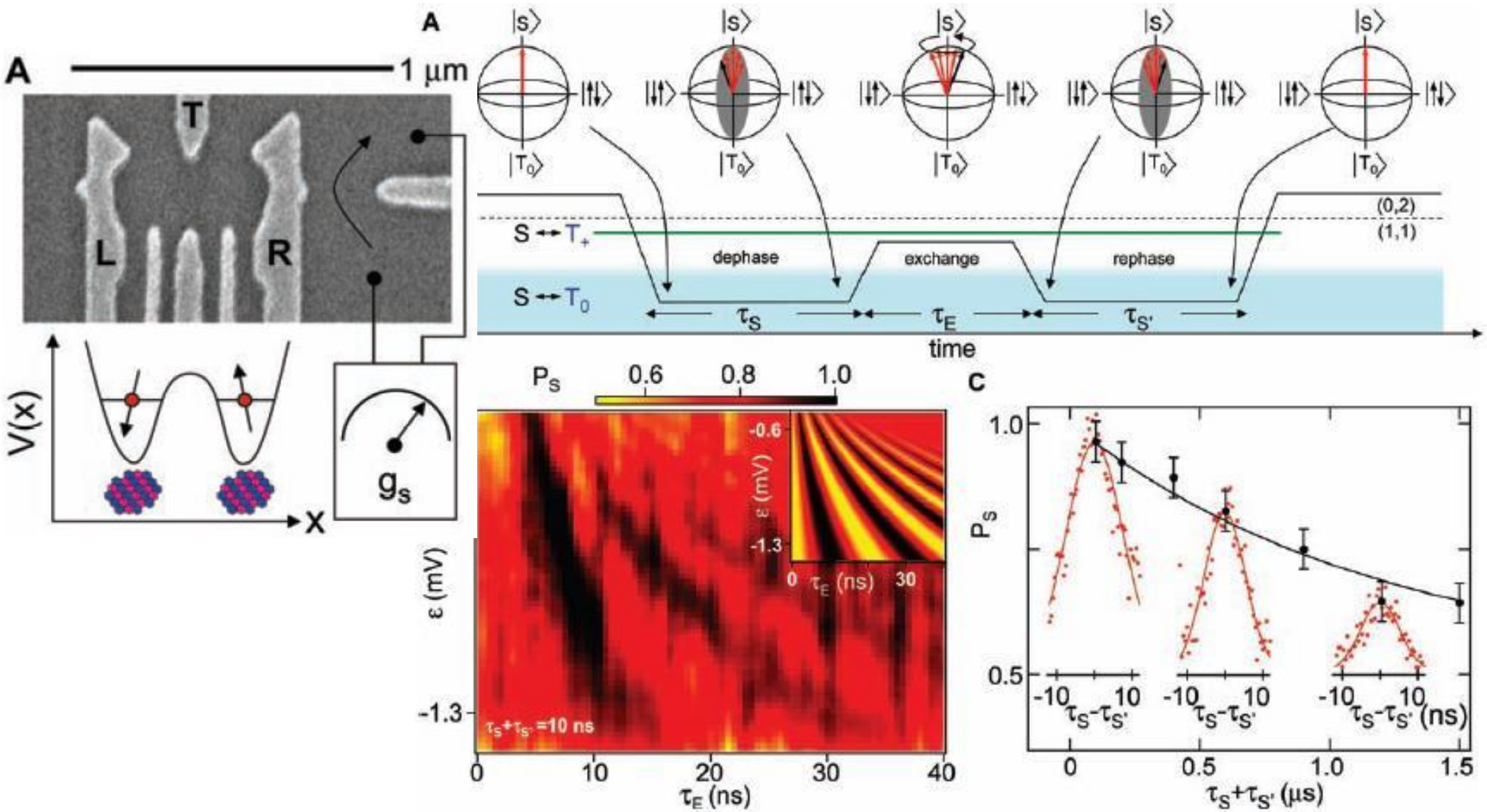


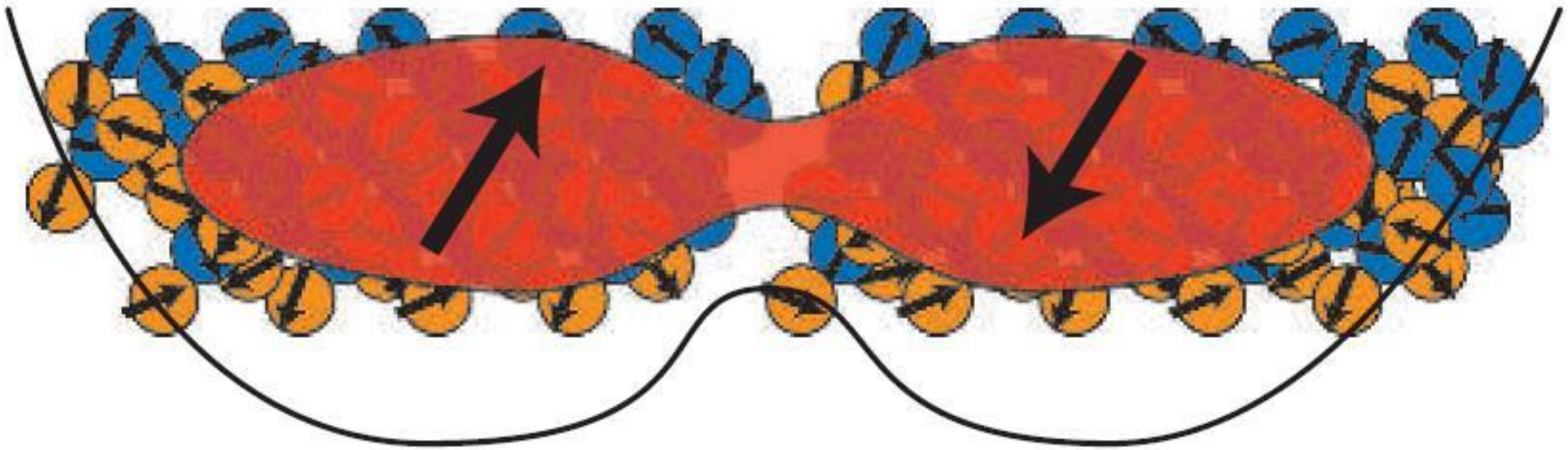
Figure 9.2: Scanning electron micrographs showing of the on-chip gold wire to apply microwaves to a nearby double quantum dot. This device was fabricated by Wouter Naber. **(a)** An AC current through the wire, I_{ac}, generates an oscillating magnetic field, B_{ac}, perpendicular to the plane. If the AC frequency is resonant with the Zeeman splitting induced by a large static in-plane magnetic field, B_0, an electron spin on the dot will rotate. **(b)-(c)** Zoom-outs of (a), showing the coplanar stripline which is designed to have 50 Ω impedance.

In this quantum dot device, the group at Harvard created
A coded 2-spin qubit and demonstrated long coherence times.

J. R. Petta et al., *Science* **309**, 2180 (2005)

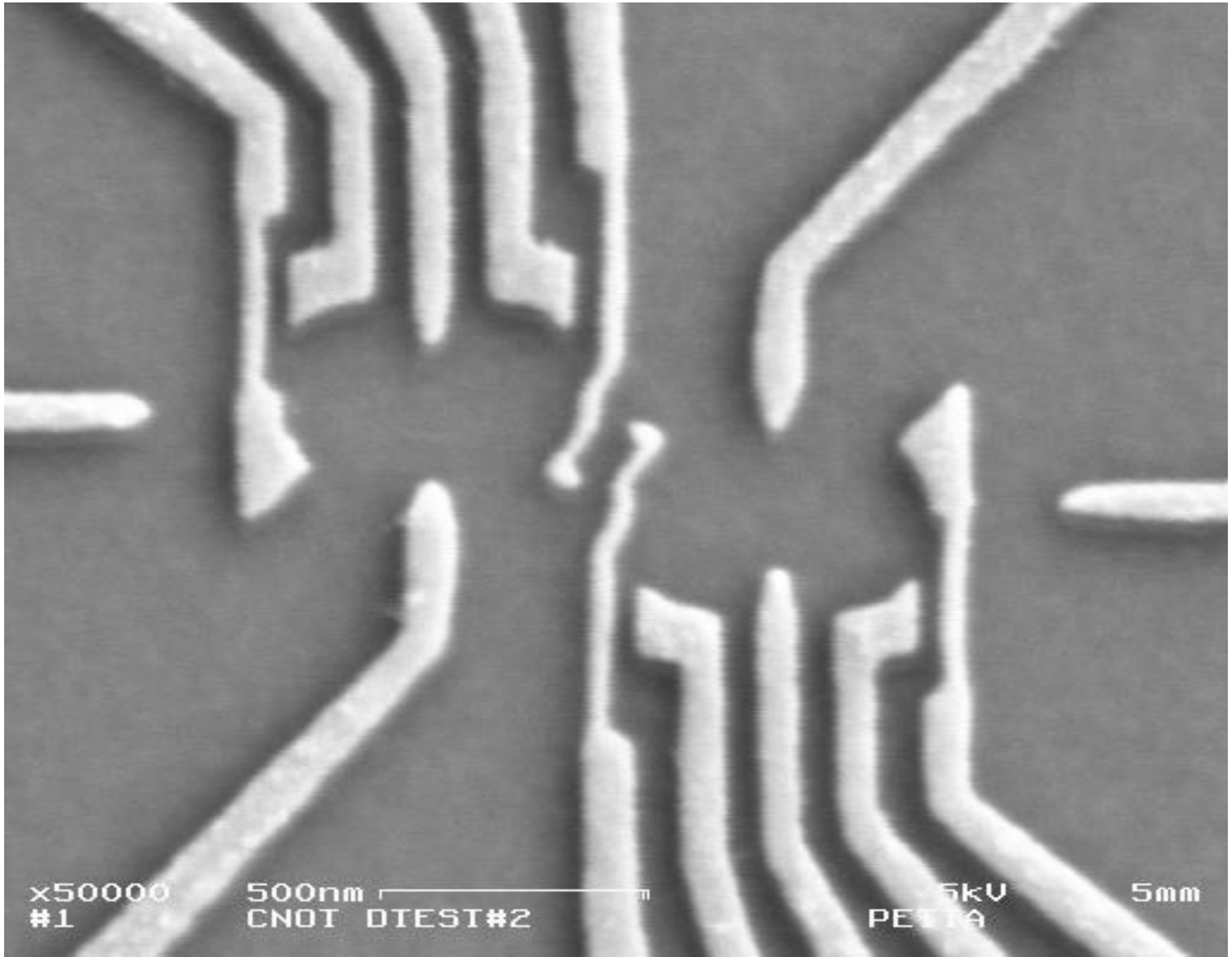


Cartoon of double quantum dot



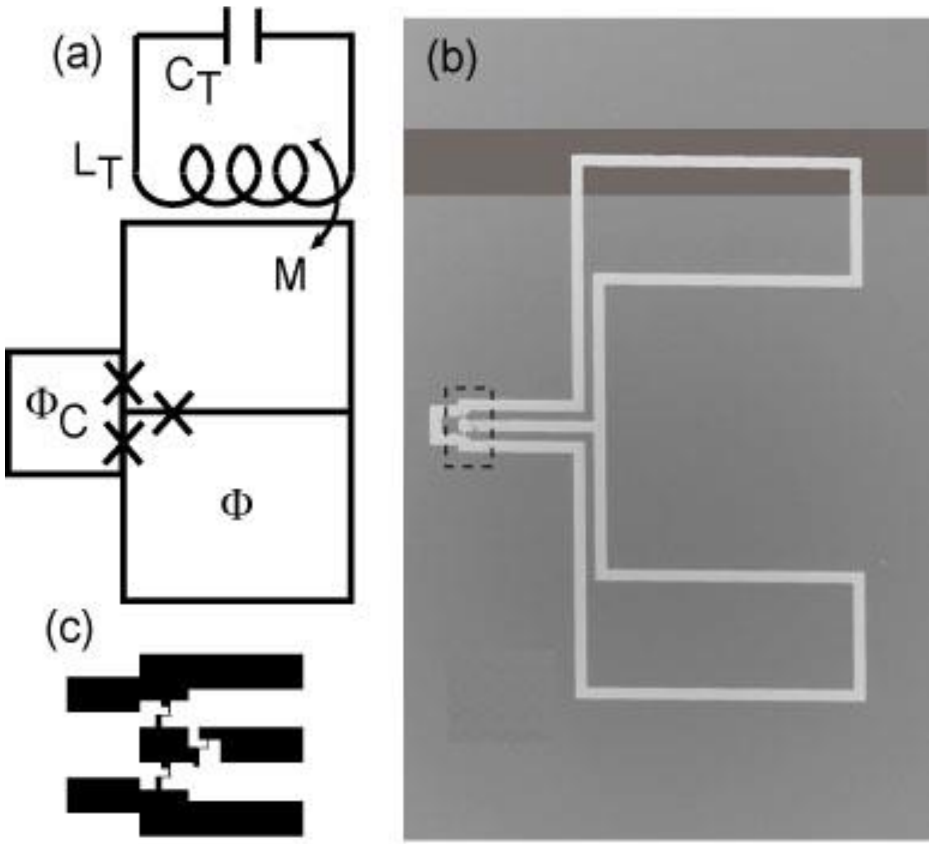
Electrons coupled,
Exchange coupled to thousands of nuclear spins

A real four-dot device, courtesy of J. Petta



First superconducting qubits in the lab, 2000 -

IBM Josephson junction qubit



"qubit = circulation of electric current in one direction or another (????)

Low-bandwidth control scheme for an oscillator stabilized Josephson qubit

R. H. Koch, J. R. Rozen, G. A. Keefe, F. M. Milliken, C. C. Tsuei, J. R. Kirtley, and D. P. DiVincenzo
IBM Watson Research Ctr., Yorktown Heights, NY 10598 USA

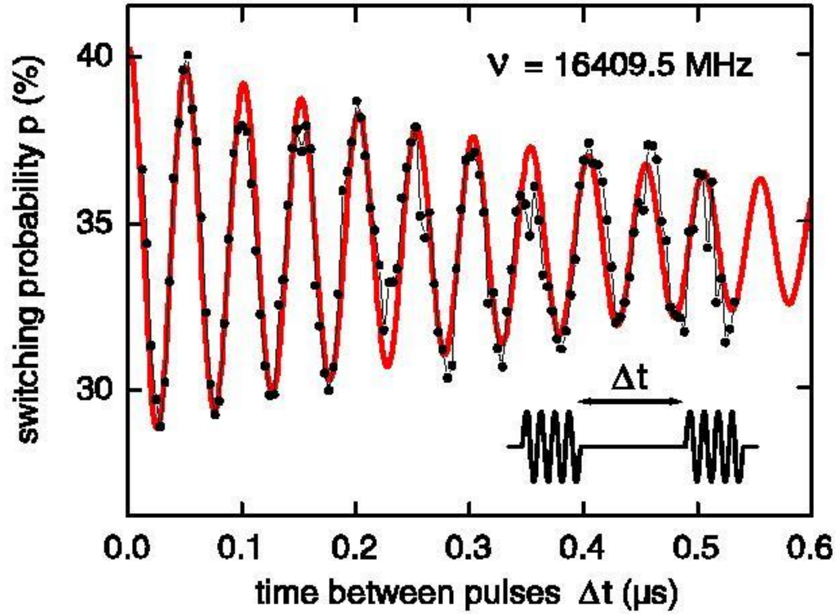
(Dated: November 16, 2004)

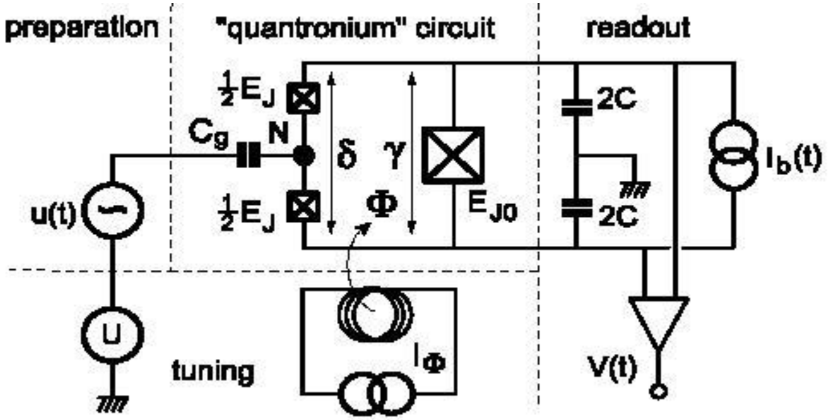
Josephson junction qubit -- Saclay

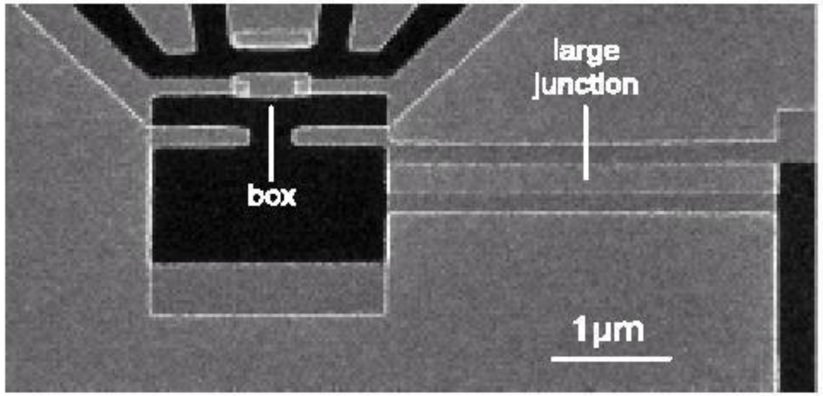
Manipulating the quantum state of an electrical circuit

Science 296, 886 (2002)

D. Vion, A. Aassime, A. Cottet, P. Joyez, H. Pothier, C. Urbina, D. Esteve and M.H. Devoret



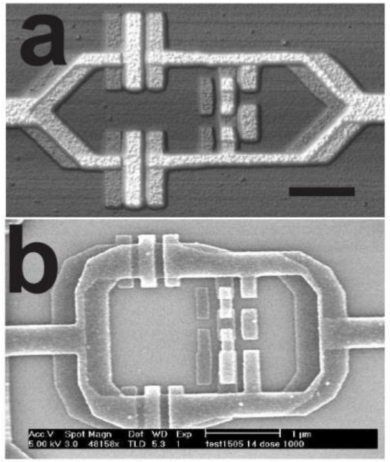




Oscillations show rotation of qubit at constant rate, with noise.

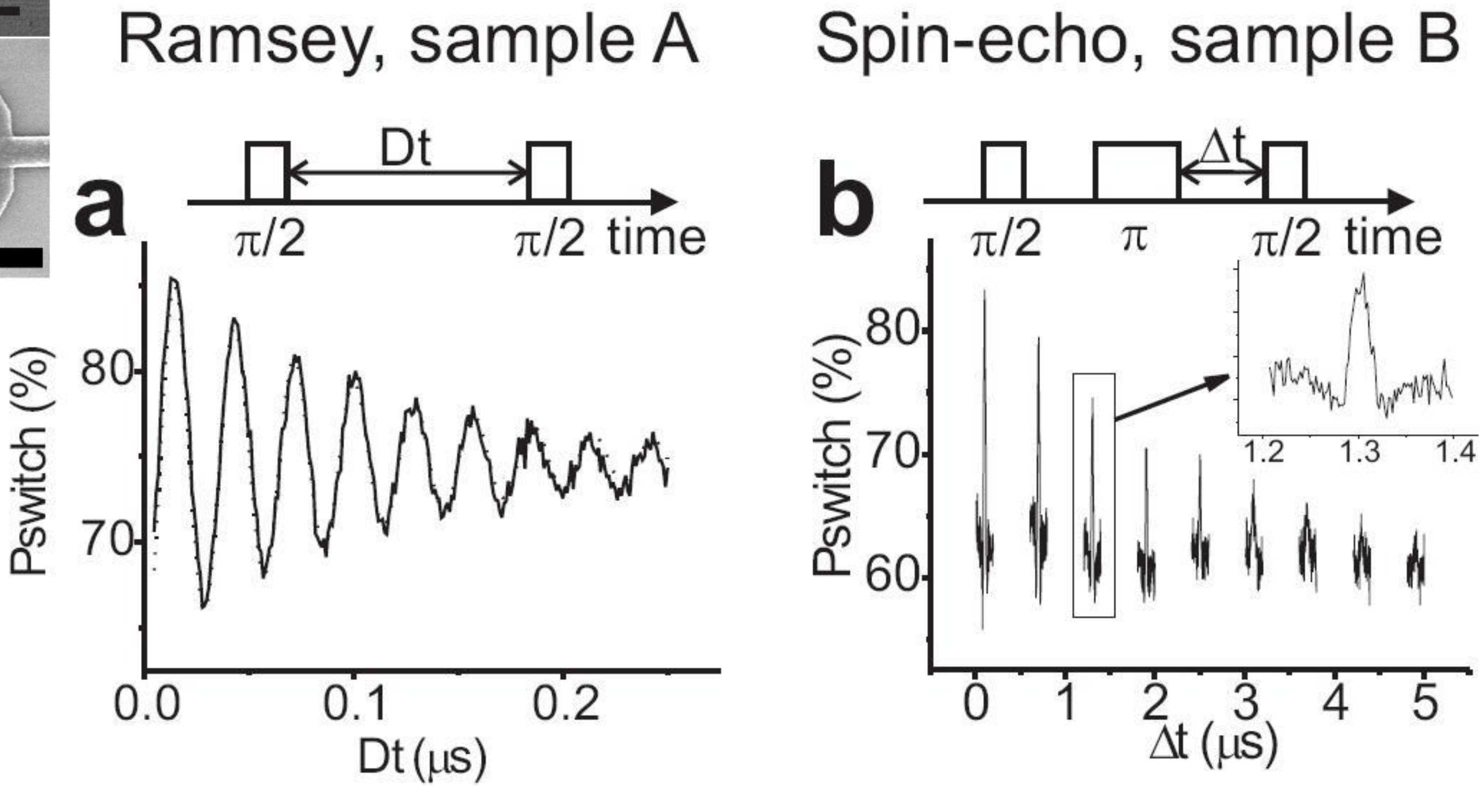
Where’s the qubit?

Delft qubit:



Relaxation and dephasing in a flux qubit PRL (2004)

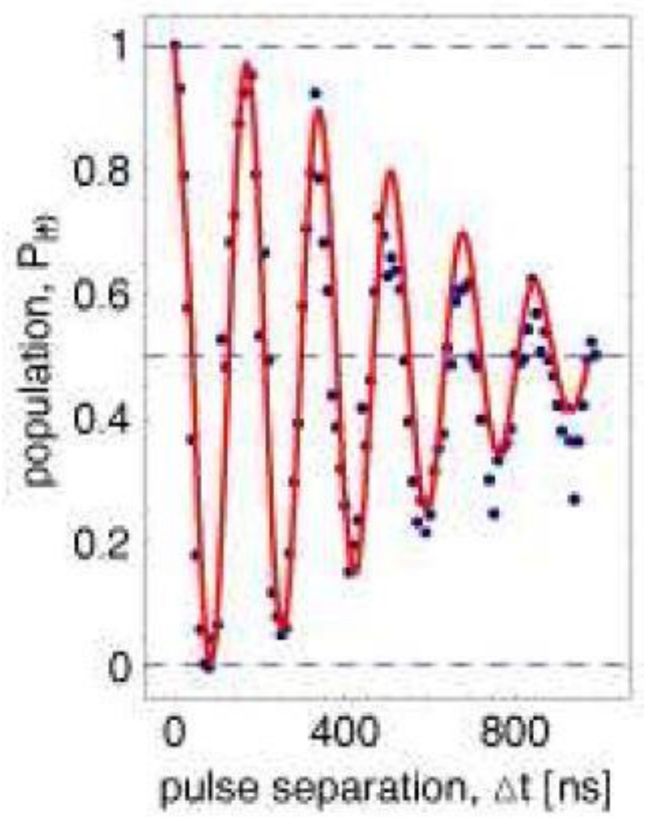
P. Bertet[1], I. Chiorescu[1*], G. Burkard[2], K. Semba[1,3], C. J. P. M. Harmans[1], D.P. DiVincenzo[2], J. E. Mooij[1]

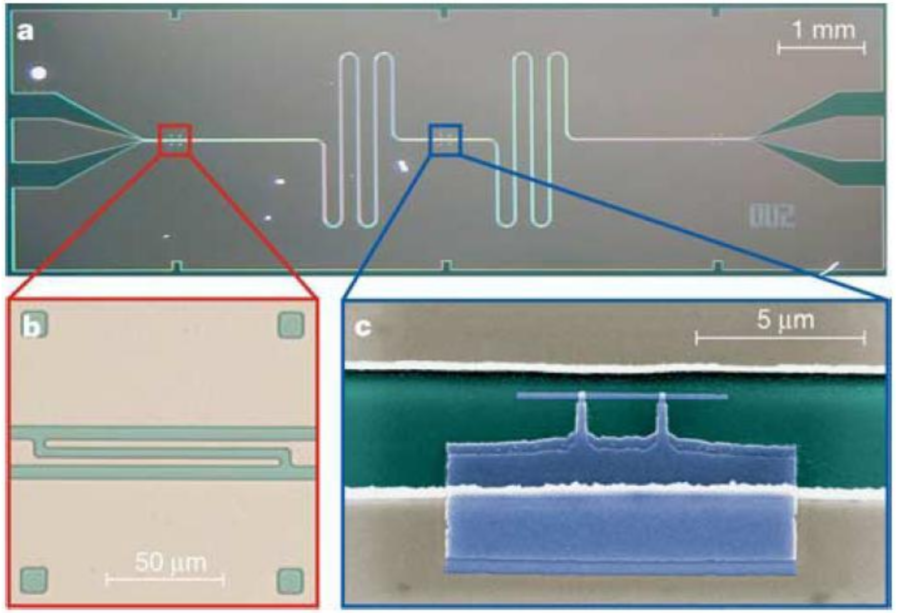


-Coherence time up to 4usec
-Improved long term stability
-Scalable?

“Yale” Josephson junction qubit

Nature, 2004





Approaching Unit Visibility for Control of a Superconducting Qubit with Dispersive Readout

A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, J. Majer, S. M. Girvin, and R. J. Schoelkopf

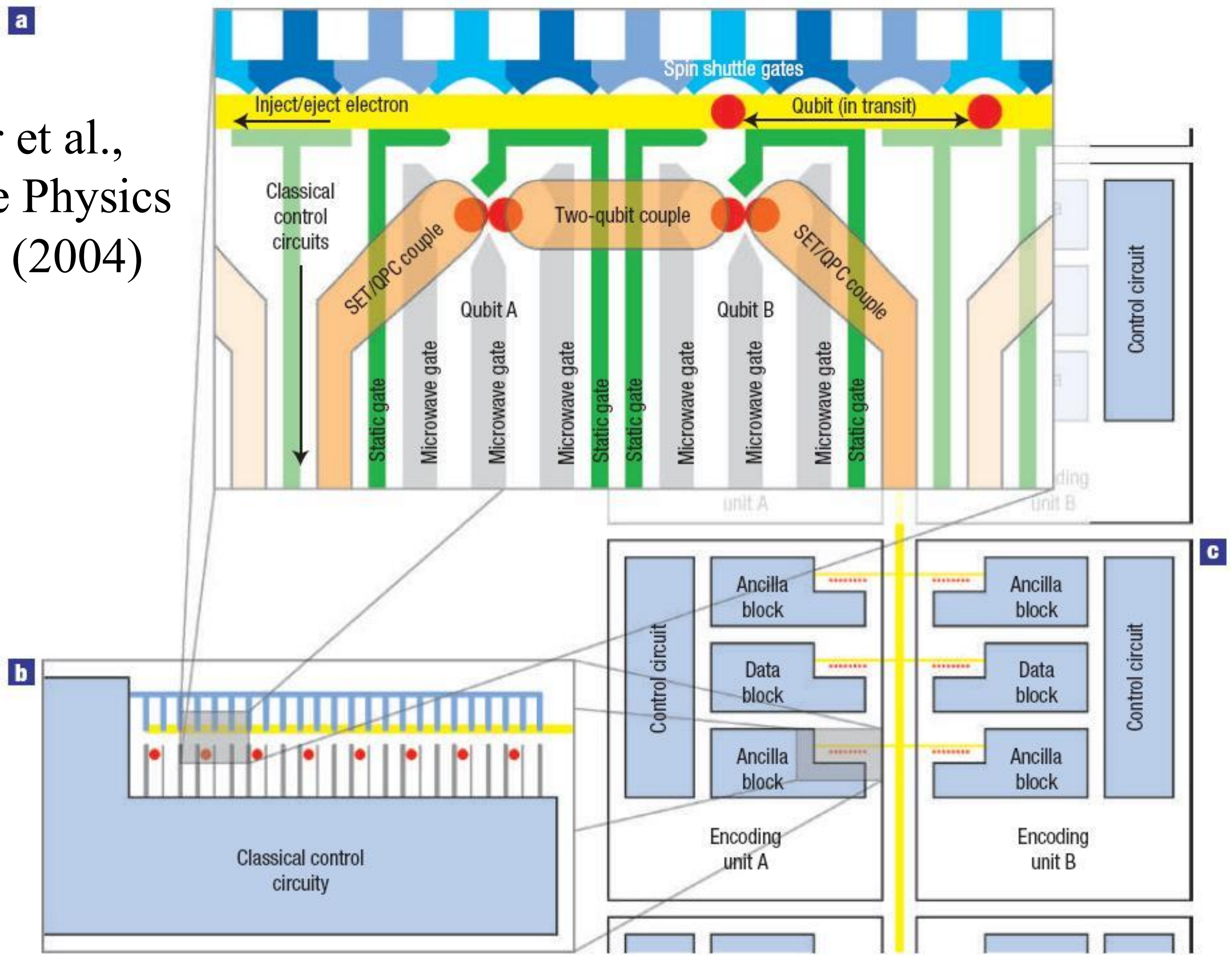
arXiv:cond-mat/0502645 v1 27 Feb 2005

Coherence time again c. 0.5 us (in Ramsey fringe experiment)
But fringe visibility > 90% !

Dreams of a QC, 2000 – (also 1971)

Concept quantum computer architecture

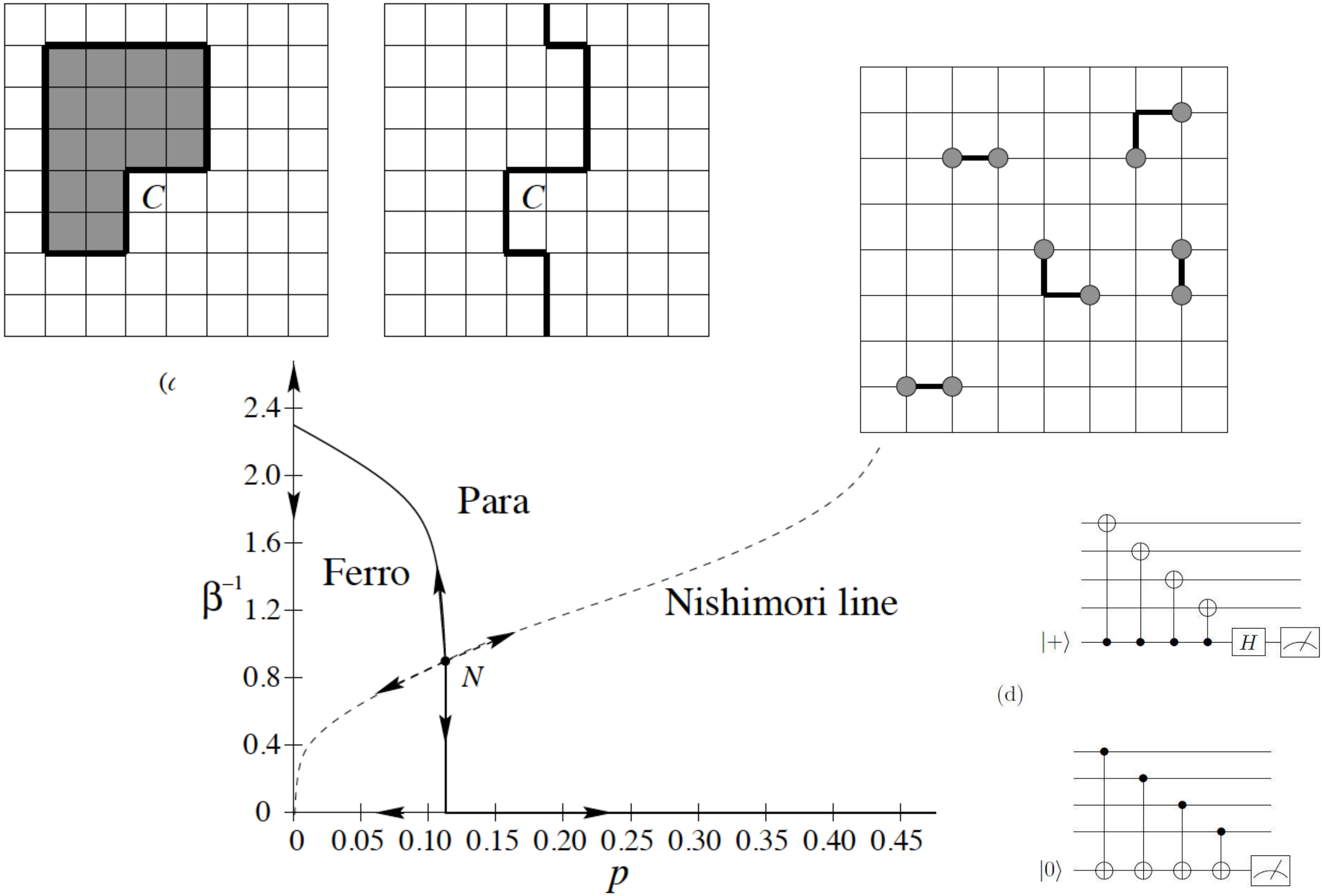
Taylor et al., Nature Physics **1**, 177 (2004)



arXiv:quant-ph/0110143

Topological quantum memory*

Eric Dennis,(1)† Alexei Kitaev,(2)‡ Andrew Landahl,(2)§ and John Preskill(2)**



For $n = 2$ the Hamiltonian contains the products of spins lying at the boundary of the faces $B^{(2)}$,

$$-\beta H_{22} = K\sum_{ij} S(i,j+\tfrac{1}{2})\,S(i+1,j+\tfrac{1}{2}) \times S(i+\tfrac{1}{2},j)\,S(i+\tfrac{1}{2},j+1) + h\sum_{ij}[S(i,j+\tfrac{1}{2}) + S(i+\tfrac{1}{2},j)], \qquad (3.9)$$

JOURNAL OF MATHEMATICAL PHYSICS VOLUME 12, NUMBER 10 OCTOBER 1971

Duality in Generalized Ising Models and Phase Transitions without Local Order Parameters*

Franz J. Wegner†
Department of Physics, Brown University, Providence, Rhode Island 02912
† On leave from the Kernforschungsanlage Jülich, Germany, where part of this work was done.

5. CONCLUSION

In 1966 Mermin and Wagner[27] proved that there is no spontaneous magnetization in the two-dimensional isotropic Heisenberg model. On the other hand, there is evidence from high temperature expansions of the magnetic susceptibility[28] that this system undergoes a phase transition. This raises the question of whether or not it is possible to have a phase transition without a local order parameter. In this paper we have exhibited systems which undergo phase transitions but which do not have a local order parameter.

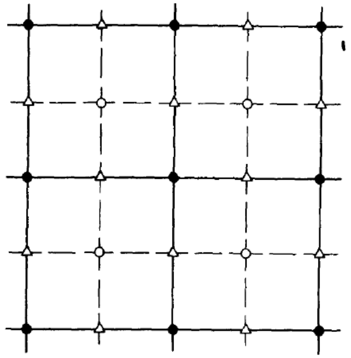


FIG. 2. The square lattice and its dual.

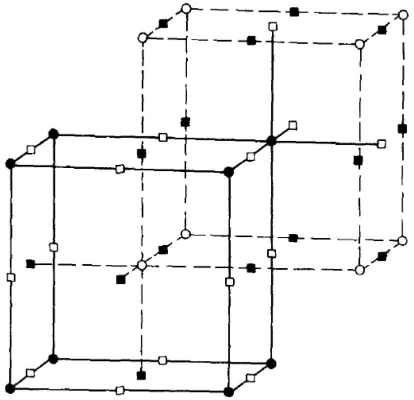
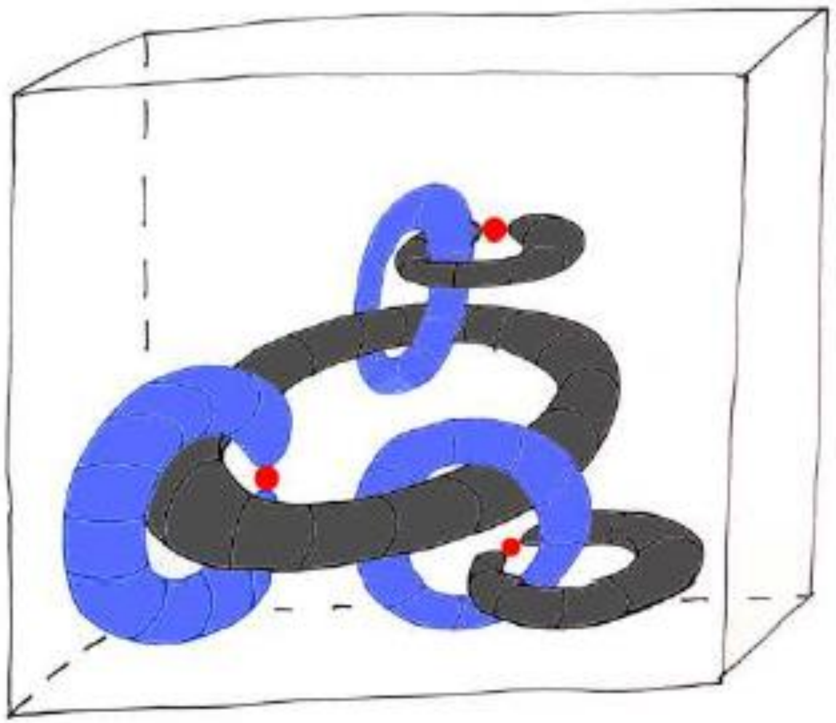


FIG. 3. The simple cubic lattice and its dual.

A fault-tolerant one-way quantum computer

R. Raussendorf[1], J. Harrington[2] and K. Goyal[1]

quant-ph/0510135



3D cluster state
with “tubes”

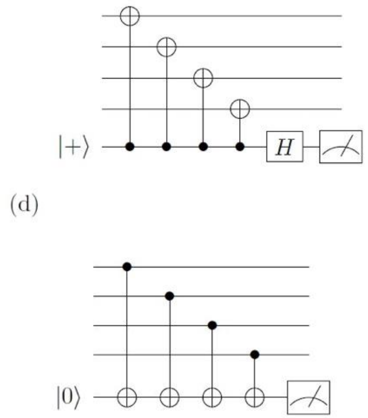
Figure 1: Topological error correction for the $QC_{\mathcal{C}}$.

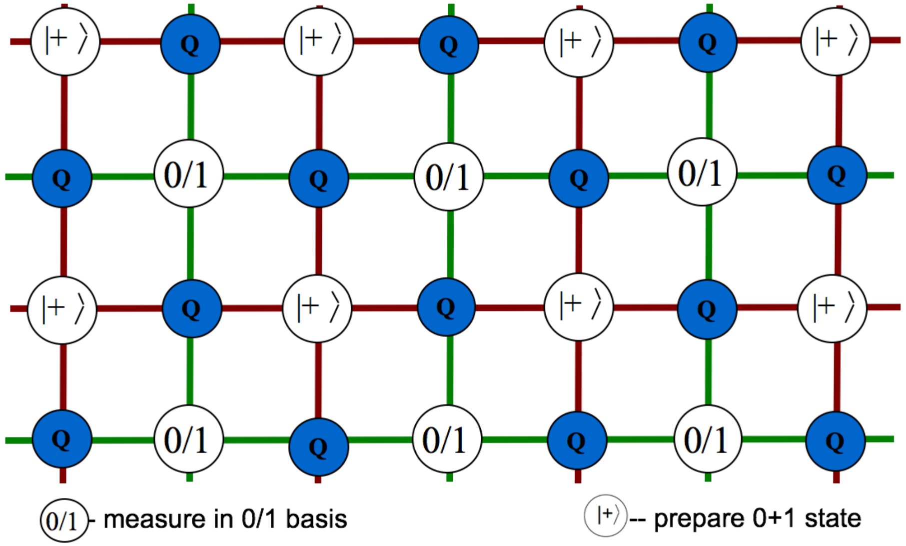
Signs of impending change in some mathematical doodles…

Fault-tolerant quantum computation with high threshold in two dimensions

Robert Raussendorf[1] and Jim Harrington[2] quant-ph/0610082 (PRL)

- Do repetitive pattern in large patches, except for "smooth" and "rough" holes where nothing is done
- Holes define qubits; algorithm performed by braiding holes
- measurements give error correction info
- adopted magic state injection and distillation, compatible with universal quantum computation
- **theoretical fault tolerance threshold is 0.75%**





Quantum Measurements and Gates by Code Deformation

H. Bombin and M.A. Martin-Delgado arXiv:0704.2540

The primitive for "moving holes" is code deformation

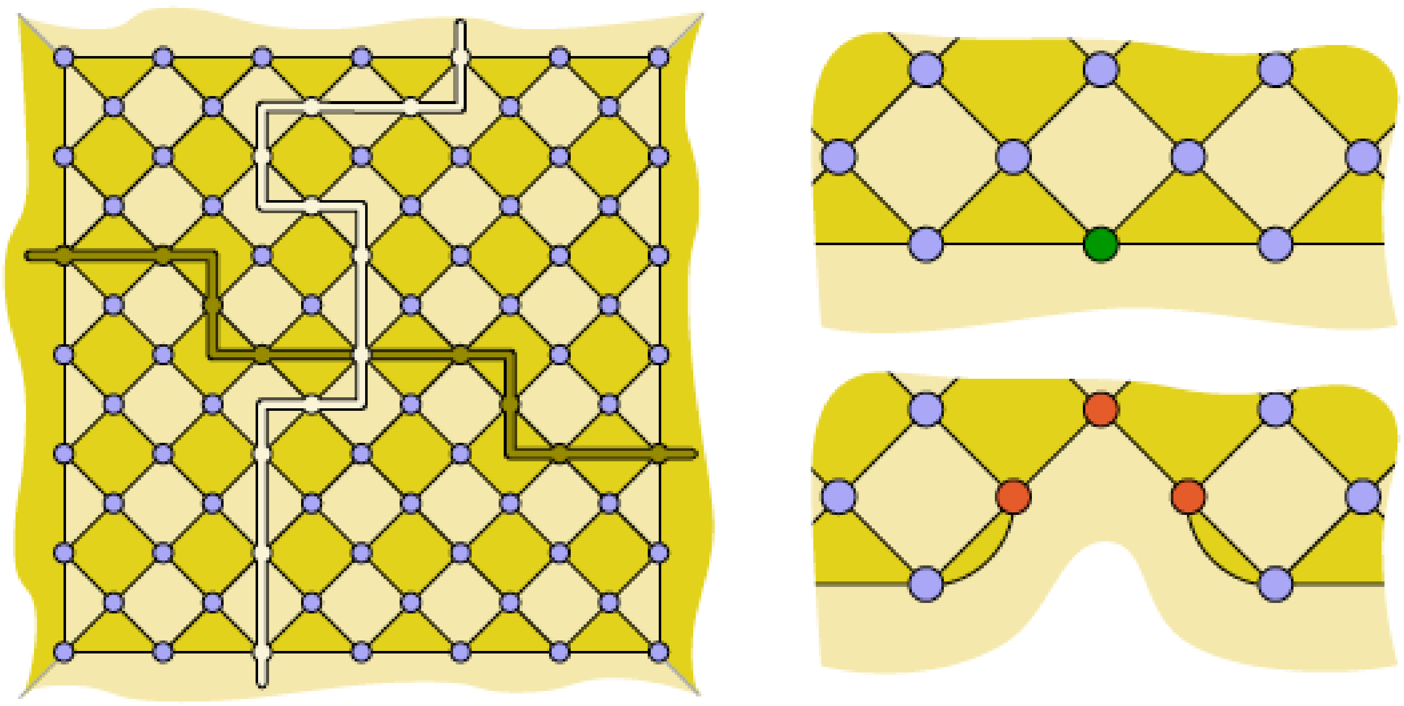
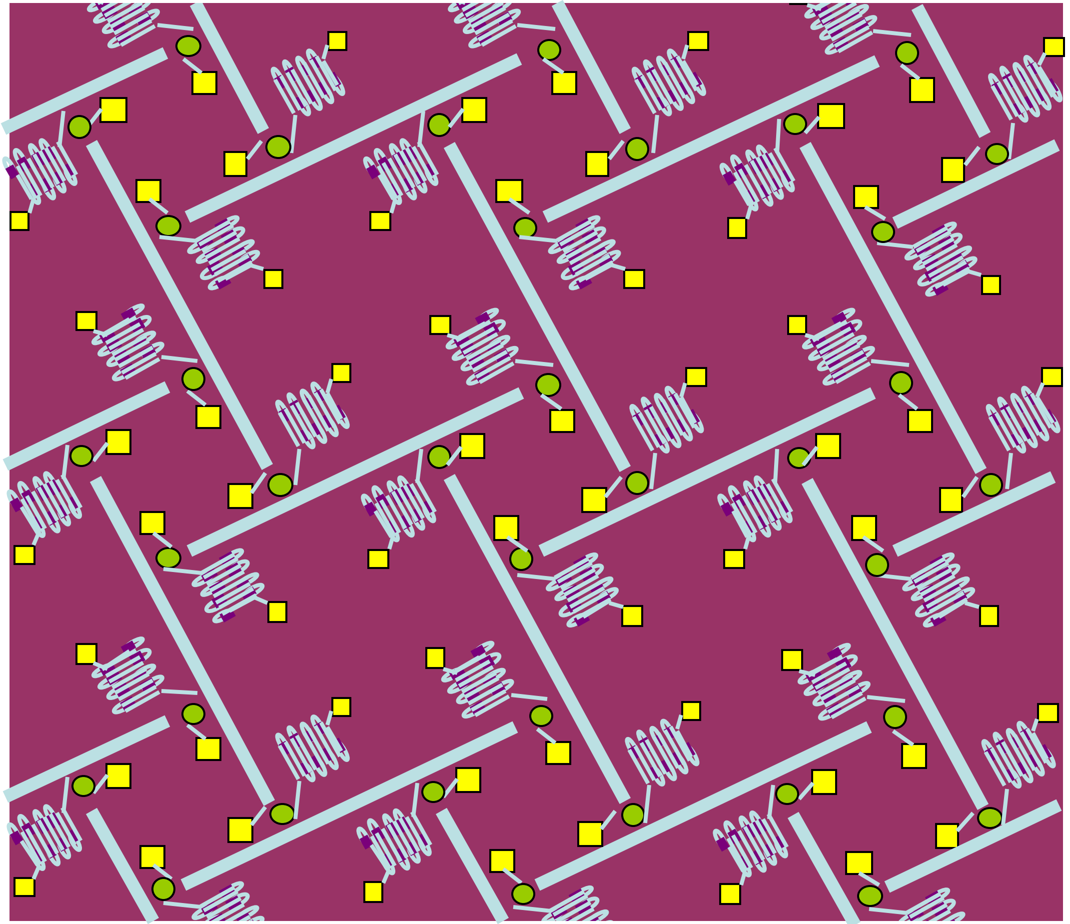
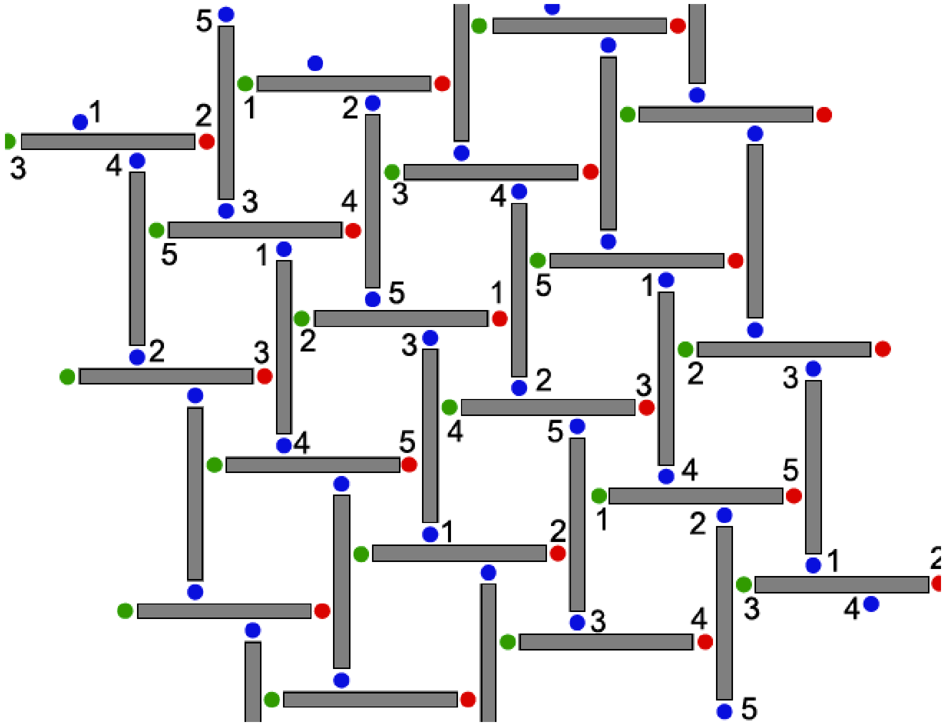

(a) (b)

FIG. 2: (a) A surface code with a dark-light-dark-light border structure. It encodes a single qubit. Nontrivial strings that correspond to the encoded X and Z operators are displayed. (b) An elementary deformation. In case that after the removal of the green qubit the new two-sited plaquette operators have negative eigenvalue, Z operators are applied at red qubits. (c) The

IBM concepts of surface code fabric with Superconducting qubits and coupling resonators



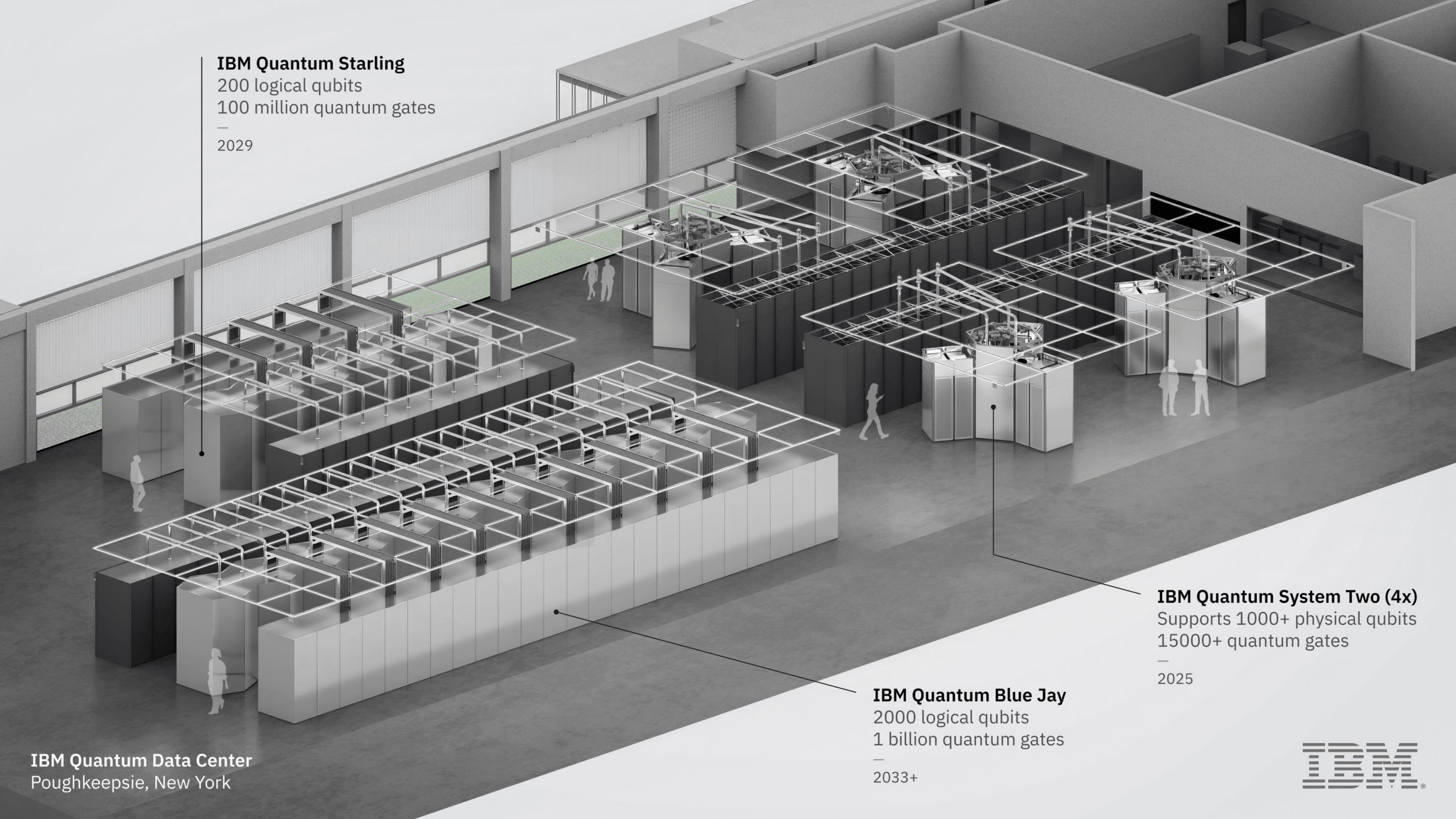
DP. DiVincenzo, “Fault tolerant architectures for superconducting qubits,”
Phys. Scr. T **137** (2009) 014020.



Frequency arrangement for surface code on a superconducting lattice

US 20140264283 A1

Inventors Jay M. Gambetta, John Smolin

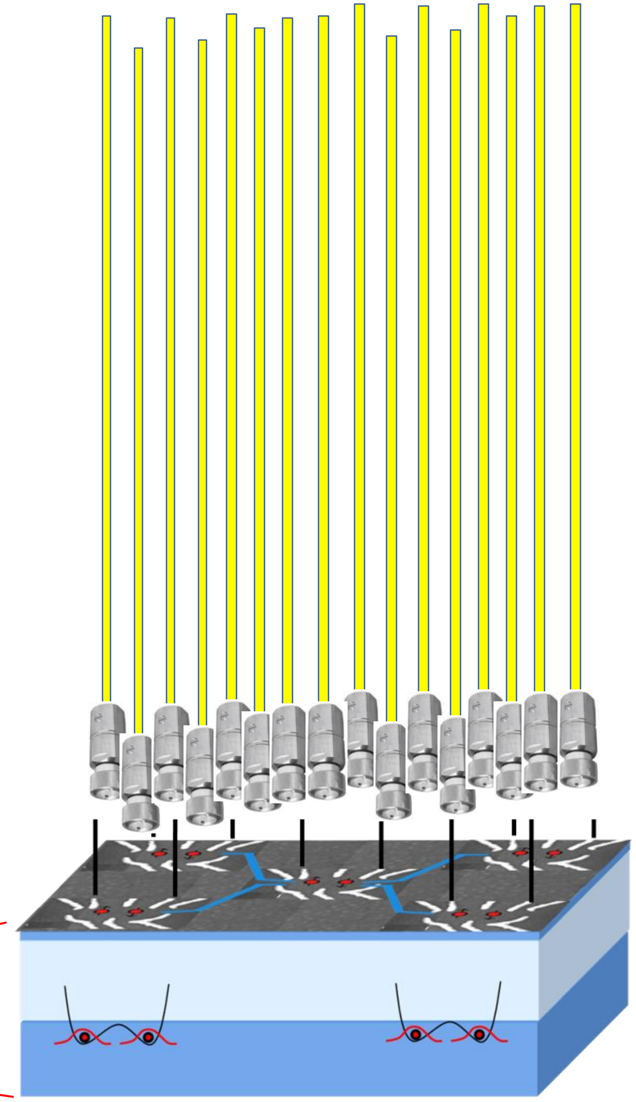

IBM Quantum Starling
200 logical qubits
100 million quantum gates
—
2029
IBM Quantum System Two (4x)
Supports 1000+ physical qubits
15000+ quantum gates
—
2025
IBM Quantum Blue Jay
2000 logical qubits
1 billion quantum gates
—
2033+
IBM Quantum Data Center
Poughkeepsie, New York

The ugly part of the architecture – meter-long cable runs to control-room instrumentation

Thanks to H. Bluhm, RWTH

Workhorse „dilution“ refrigerator

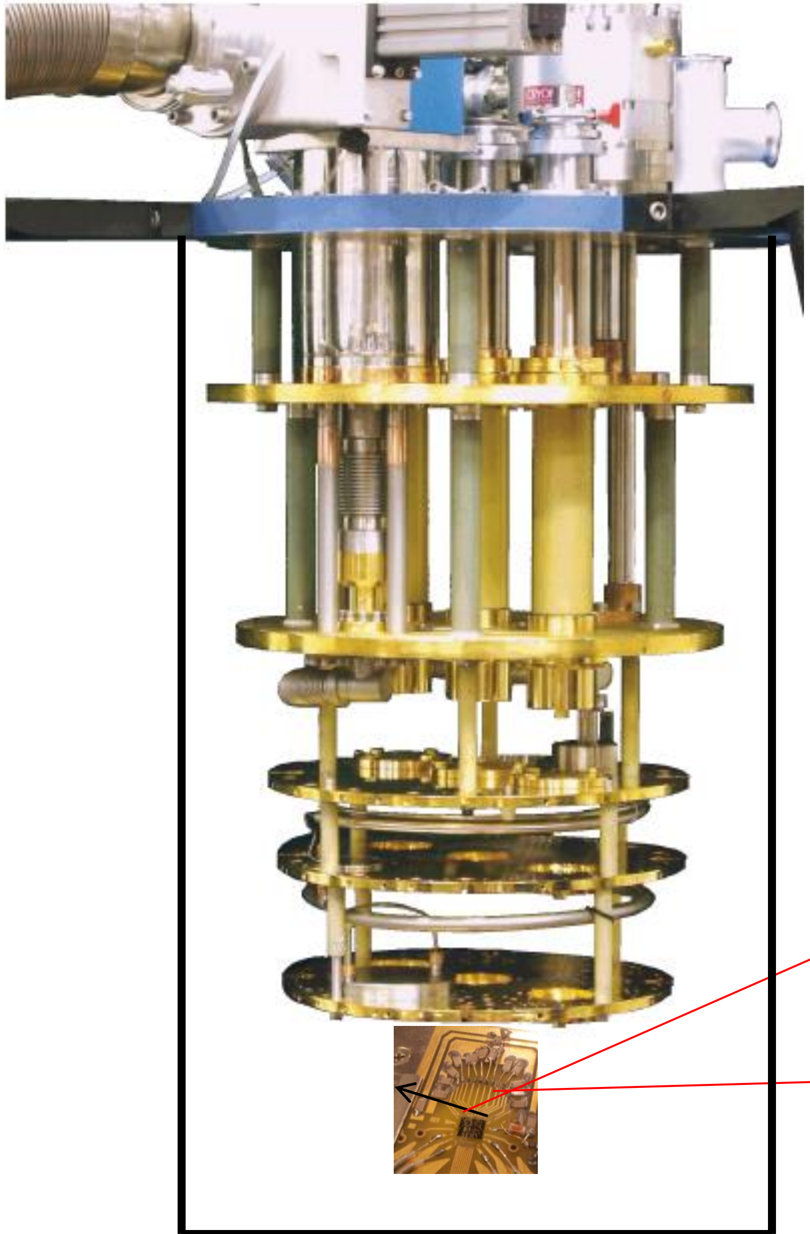
1 meter



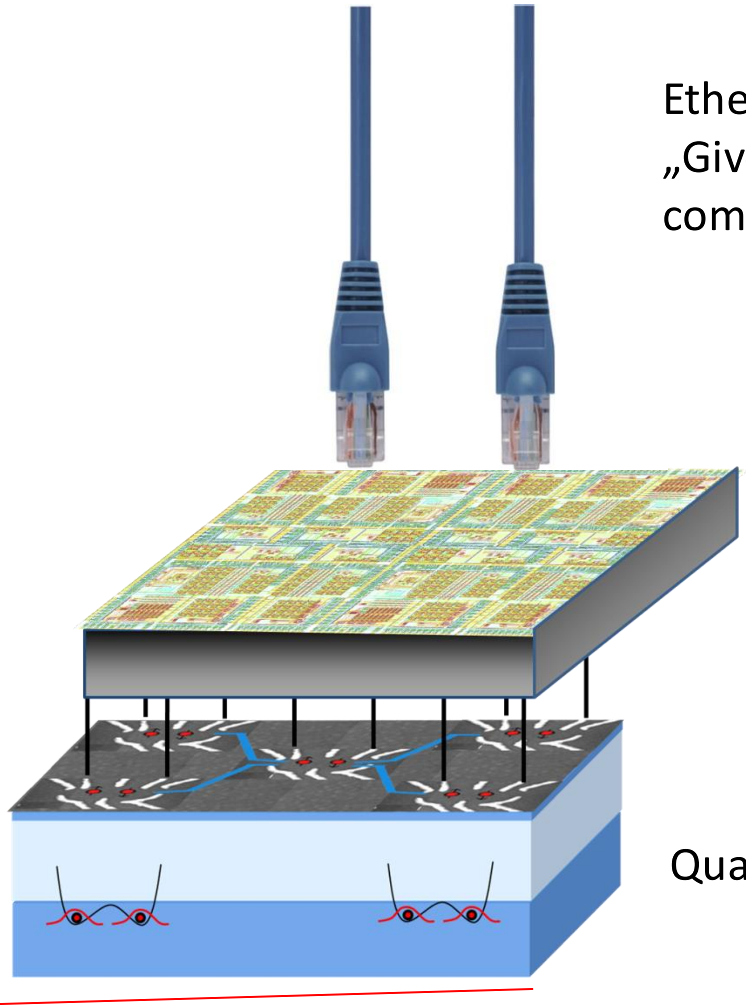
Number of cables
~ 2x the number of qubits

Millions of qubits ???

Vision: Scalable architecture – needs cold analog & digital electronics



Thanks to H. Bluhm, RWTH



Ethernet –
„Give your quantum computer an IP address“

Signal generators, amplifiers, isolators, ADCs, DACs

Operating temperature: 4K

Quantum chip: T=0.02K

Outline

- My early life with computers --- the ENIAC
- Earliest understanding of quantum computers, and qubits
- Earliest IBM influences – Landauer, Bennett, and others
- First qubits, and some false starts
- 2000 and on:
  - Spin qubits
  - Superconducting qubits – first models
  - Dreams of an architecture