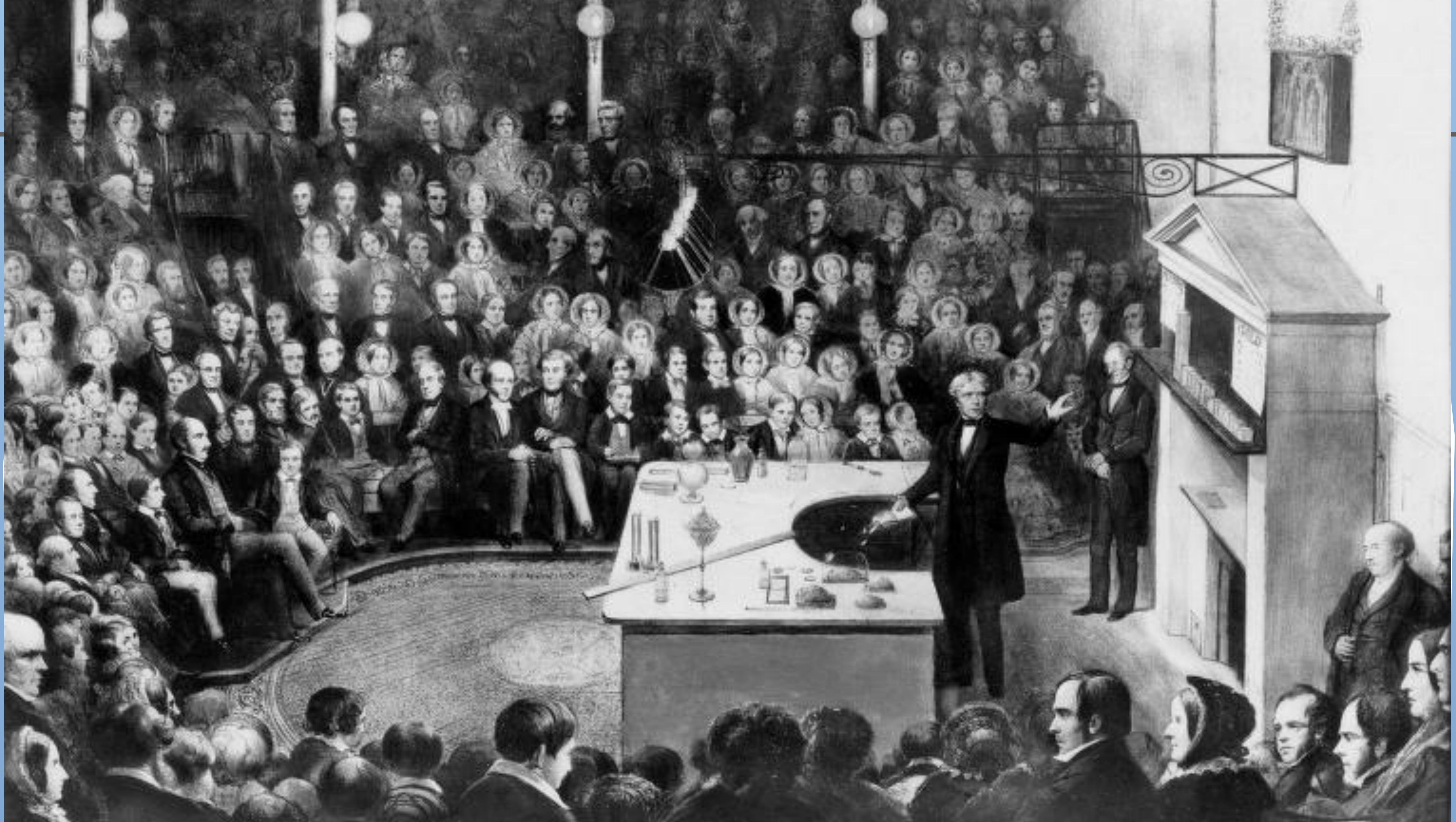
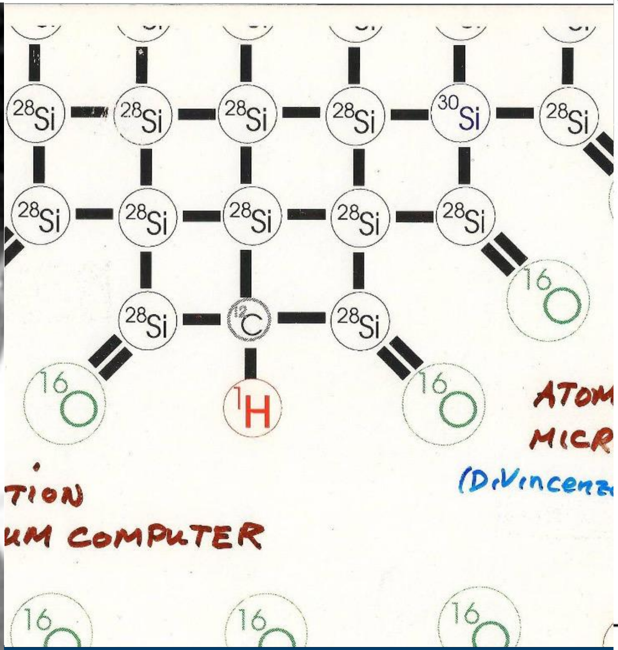
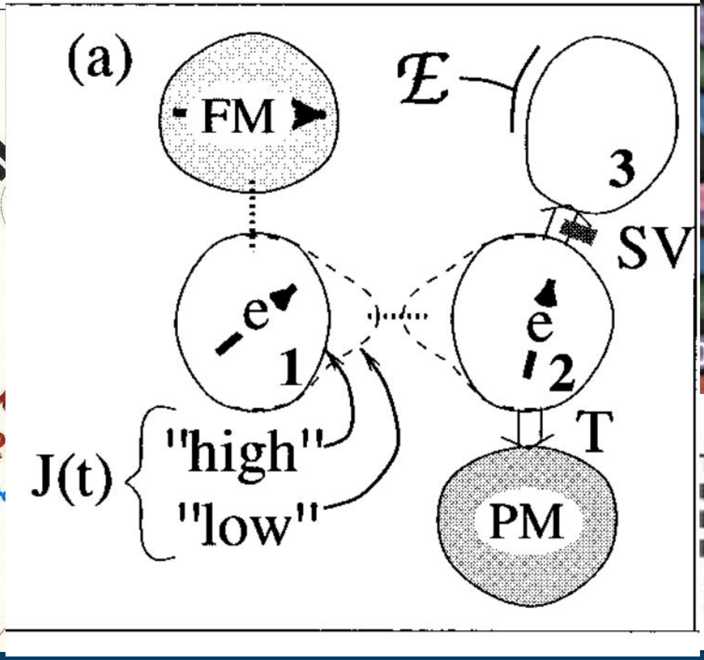
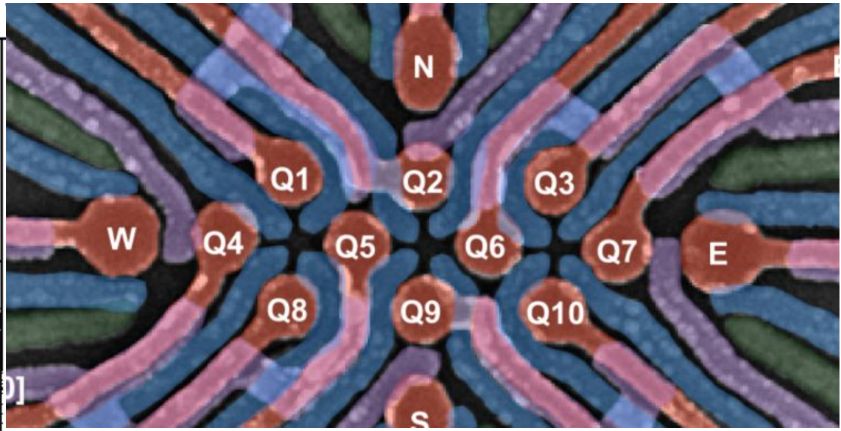
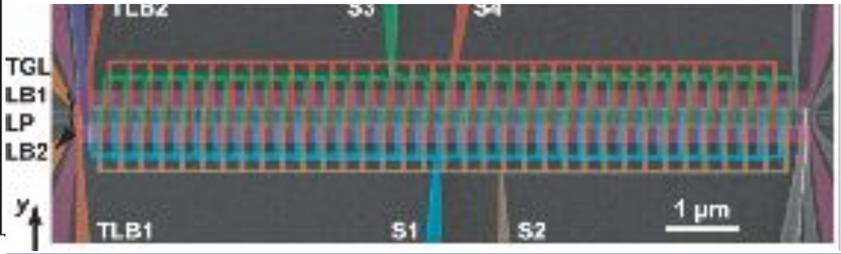










THE BEAUTIFUL PHYSICS OF SPIN QUBITS:

BUT ARE THEY A TECHNOLOGY?

17.01.2025 | DAVID DIVINCENZO

Outline

- 100 years ago – extra 2-level systems in nature
- Spin & quantum tunneling
- First spin qubit concepts
- Surprising path of experiments
- Difficulties slowly overcome
- Latest concepts
- Route to scalability?

“classically not-describable two-valuedness”

lichkeit des Elektrons berücksichtigt. Da eine solche Abhängigkeit aber nicht beobachtet wird (worüber sich Pauli mit den Briefen [68] und [69] an Landé Gewißheit verschaffen will), muß die Annahme falsch sein, d.h. der Atomrumpf kann keinen Drehimpuls besitzen.

Vermutlich wenige Tage nach Abfassung des Briefes an Landé [68] hat dann Pauli den zweiten Schritt vollzogen: Wenn es nicht der Atomrumpf ist, dann kann allein das Leuchtelektron die Dublettstruktur der Alkalien erzeugen und somit Sitz der magneto-mechanischen Anomalie sein. Im Brief [71] an Landé vom 24. November 1924 steht bereits dieses Ergebnis[2].

Am 2. Dezember 1924 ist dann die bekannte Arbeit „Über den Einfluß der Geschwindigkeitsabhängigkeit der Elektronenmasse auf den Zeemaneffekt“ (1925a) bei der Zeitschrift für Physik eingegangen, und hier finden sich die seither oft zitierten Worte, die Pauli selbst im Sperrdruck hervorheben ließ: „ Die abgeschlossenen Elektronenkonfigurationen sollen nichts zum magnetischen Moment und zum Impulsmoment des Atoms beitragen. Insbesondere werden bei den Alkalien die Impulswerte des Atoms und seine Energieänderungen in einem äußeren Magnetfeld im wesentlichen als eine alleinige Wirkung des Leuchtelektrons angesehen, das auch als der Sitz der magneto-mechanischen Anomalie betrachtet wird. Die Dublettstruktur der Alkalispektren sowie die Durchbrechung des Larmortheorems kommt gemäß diesem Standpunkt durch eine eigentümliche, klassisch nicht beschreibbare Art von Zweideutigkeit der quantentheoretischen Eigenschaften des Leuchtelektrons zustande.“

Spin was the first, but not the only example

Wolfgang Pauli: Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg U.a.: Band 1

Second use of “classically not describable two-valuedness”

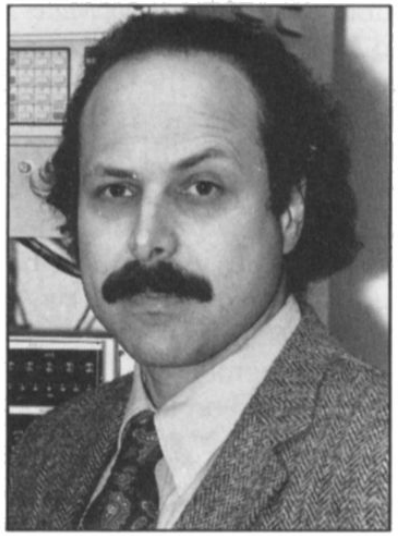
Über den Bau der Atomkerne. I.

Von **W. Heisenberg** in Leipzig.

Mit 1 Abbildung. (Eingegangen am 7. Juni 1932.)

Es werden die Konsequenzen der Annahme diskutiert, daß die Atomkerne aus Protonen und Neutronen ohne Mitwirkung von Elektronen aufgebaut seien. § 1. Die Hamiltonfunktion des Kerns. § 2. Das Verhältnis von Ladung und Masse und die besondere Stabilität des He-Kerns. § 3 bis 5. Stabilität der Kerne und radioaktive Zerfallsreihen. § 6. Diskussion der physikalischen Grundannahmen.

Durch die Versuche von Curie und Joliot[1]) und deren Interpretation durch Chadwick[2]) hat es sich herausgestellt, daß im Aufbau der Kerne ein neuer fundamentaler Baustein, das Neutron, eine wichtige Rolle spielt. Dieses Ergebnis legt die Annahme nahe, die Atomkerne seien aus Protonen und Neutronen ohne Mitwirkung von Elektronen aufgebaut[3]). Ist diese Annahme richtig, so bedeutet sie eine außerordentliche Vereinfachung für die Theorie der Atomkerne. Die fundamentalen Schwierigkeiten, denen man in der Theorie des β-Zerfalls und der Stickstoffkernstatistik begegnet, lassen sich nämlich dann reduzieren auf die Frage, in welcher Weise ein Neutron in Proton und Elektron zerfallen kann und welcher Statistik es genügt, während der eigentliche Aufbau der Kerne nach den Gesetzen der Quantenmechanik aus den Kraftwirkungen zwischen Protonen und Neutronen beschrieben werden kann.



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”:

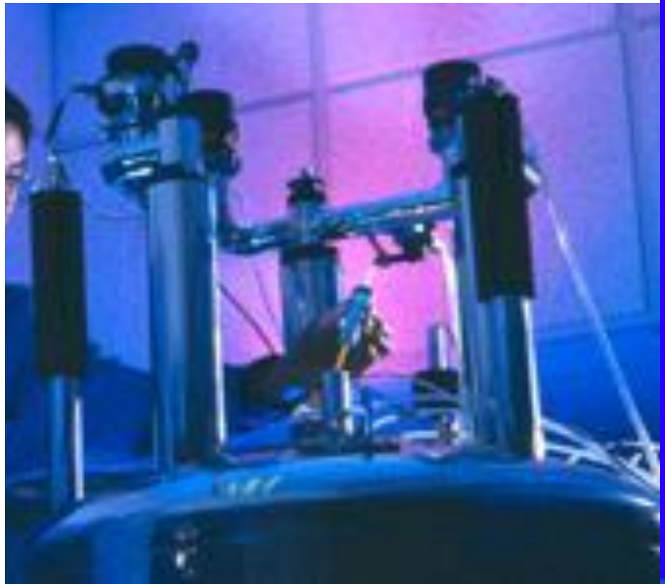
D. D. Awschalom, J. F. Smyth, G. Grinstein, D. P. DiVincenzo, and D. Loss, “Macroscopic quantum tunneling in magnetic proteins,” Phys. Rev. Lett. **68**, 3092 (1992); 71, 4276(E) (1993).

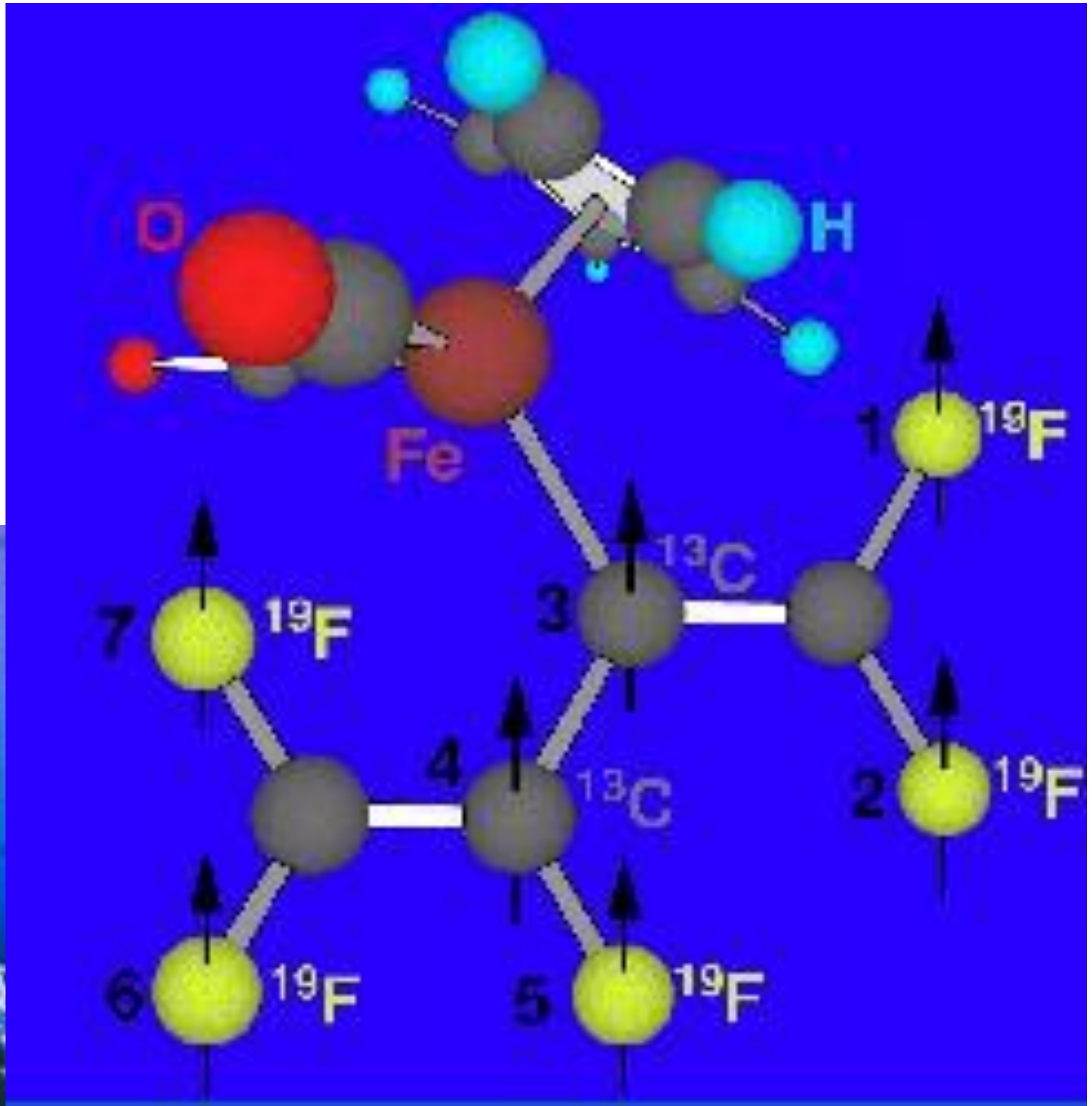
c. 1995:

NMR quantum computer – 7 qubit operation

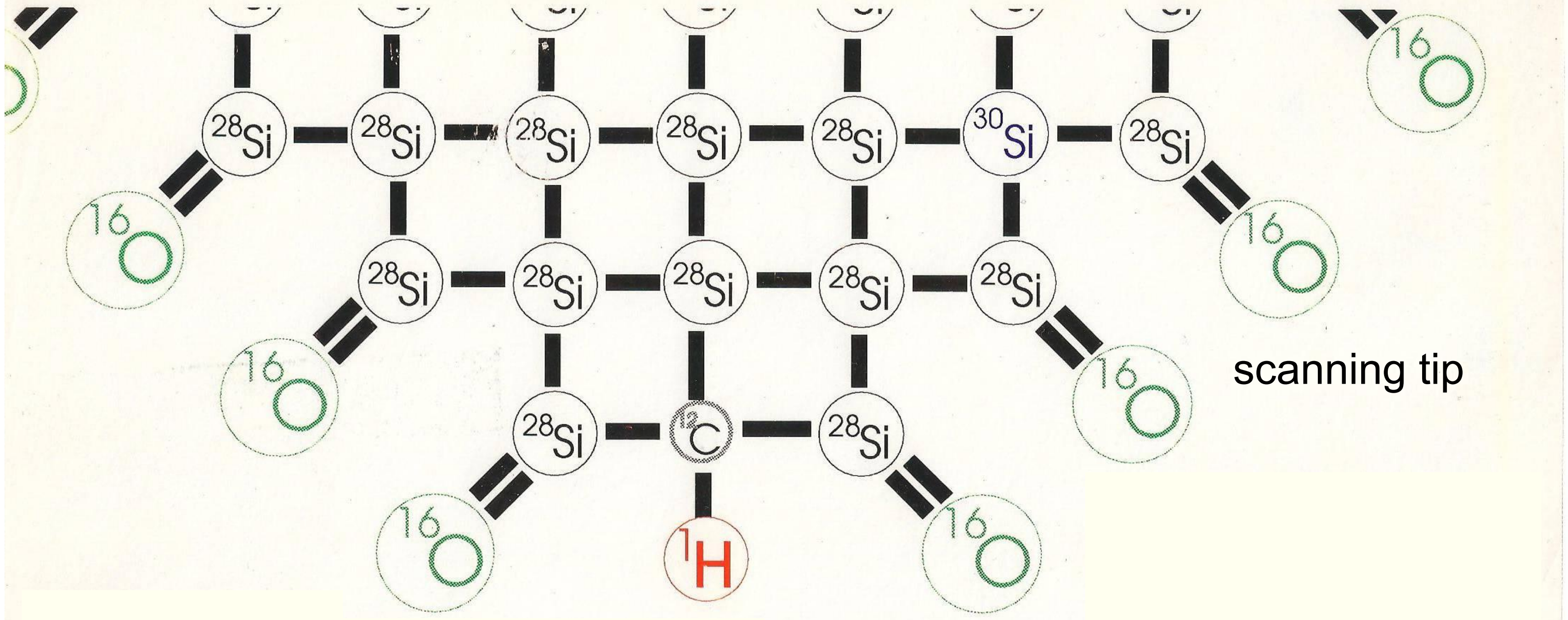
Nuclear spin =1/2 for F-19 and C-13

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

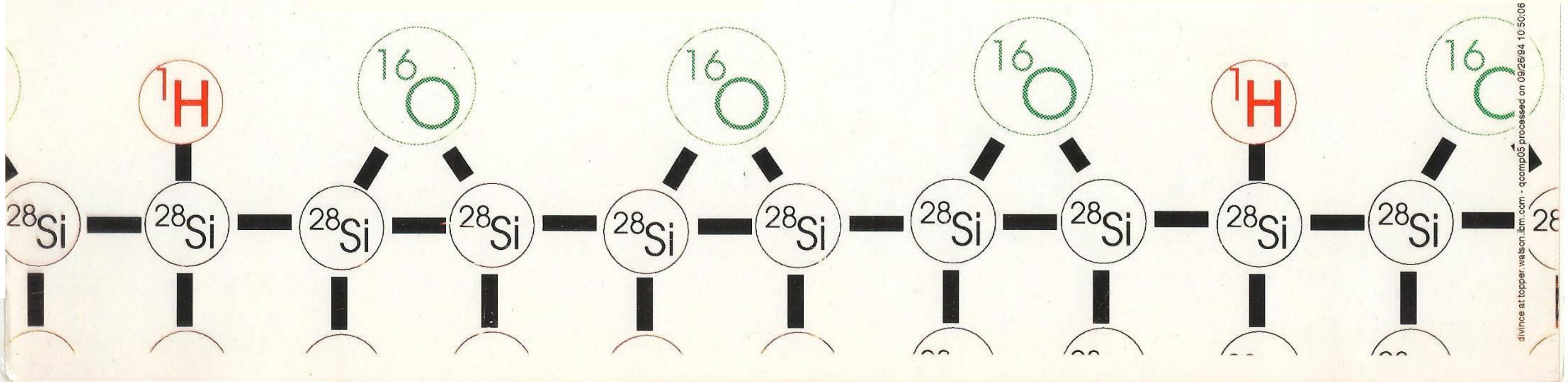




Example: early idea -- nanostructure for control of (nuclear) spin



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



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

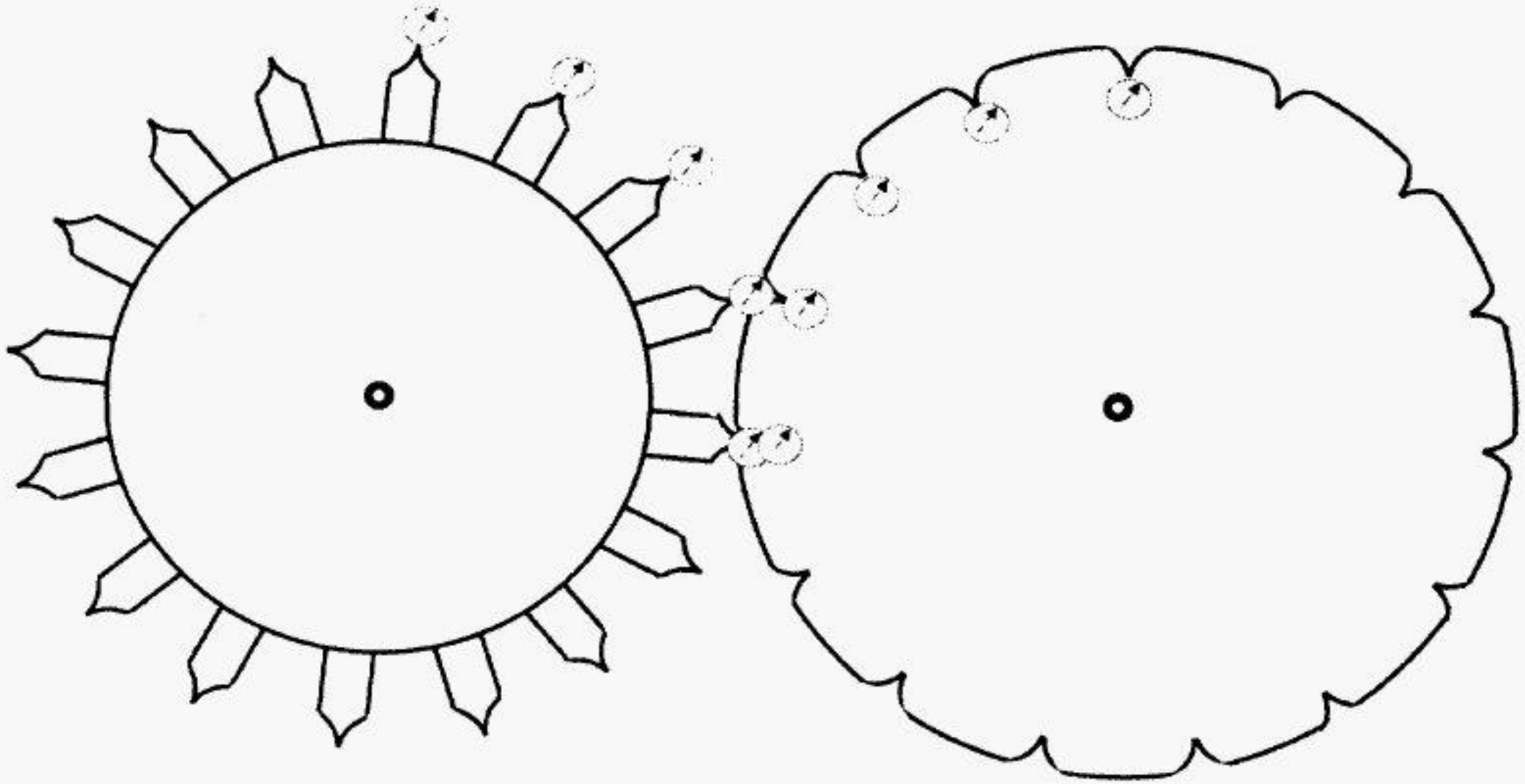


FIG. 1. The gearbox quantum computer. The two meshed gears operate classically, turning in synchrony. A single quantum spin-1/2 degree of freedom, discussed as a proton nuclear

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

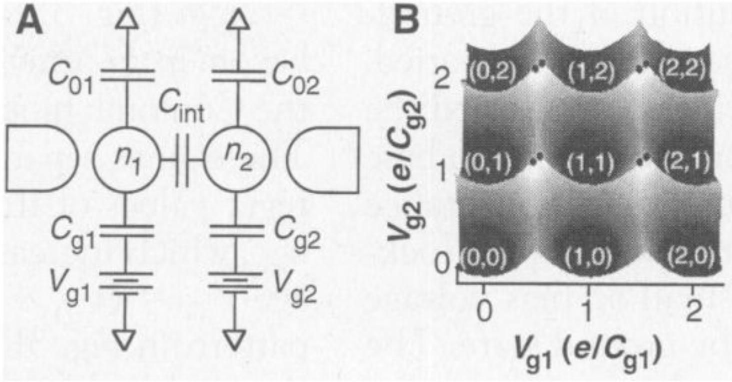
SCIENCE • VOL. 274 • 22 NOVEMBER 1996

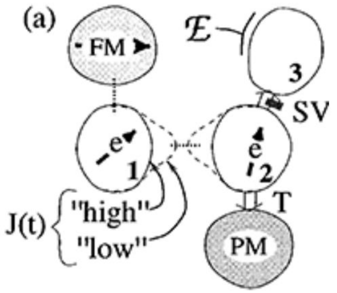
REPORTS

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





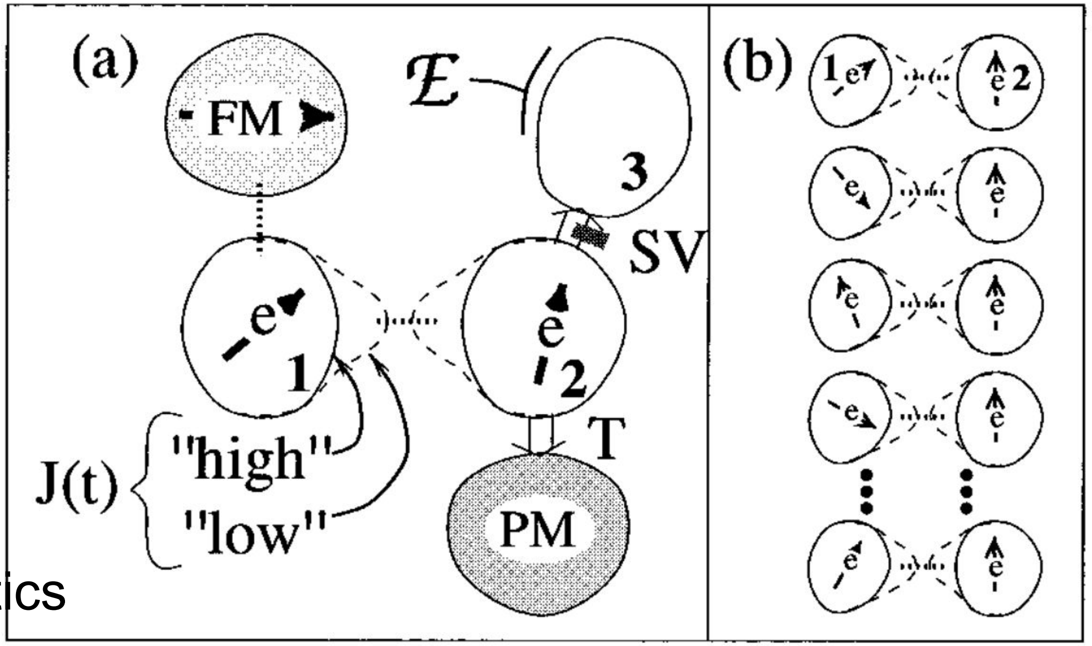
Quantum computation with quantum dots

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

Extrapolating Livermore et al. to a quantum computer (LD 1998):



- Based on nonrelativistic ideas
  - Spin & orbit are uncoupled, except via particle statistics
  - Leads to very low coupling to some parts of the environment
  - Symmetry determined spin-spin coupling (Heisenberg)

- But, problems with nonrelativistic philosophy:
  - Strength of Heiserberg interaction sensitive to environmental electric fields
  - For control, invoke (relativistic) magnetic controls
- Other decoherence channels not really thought through (hyperfine effects)
- Very naïve from the point of view of scalability

PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

Quantum computation with quantum dots

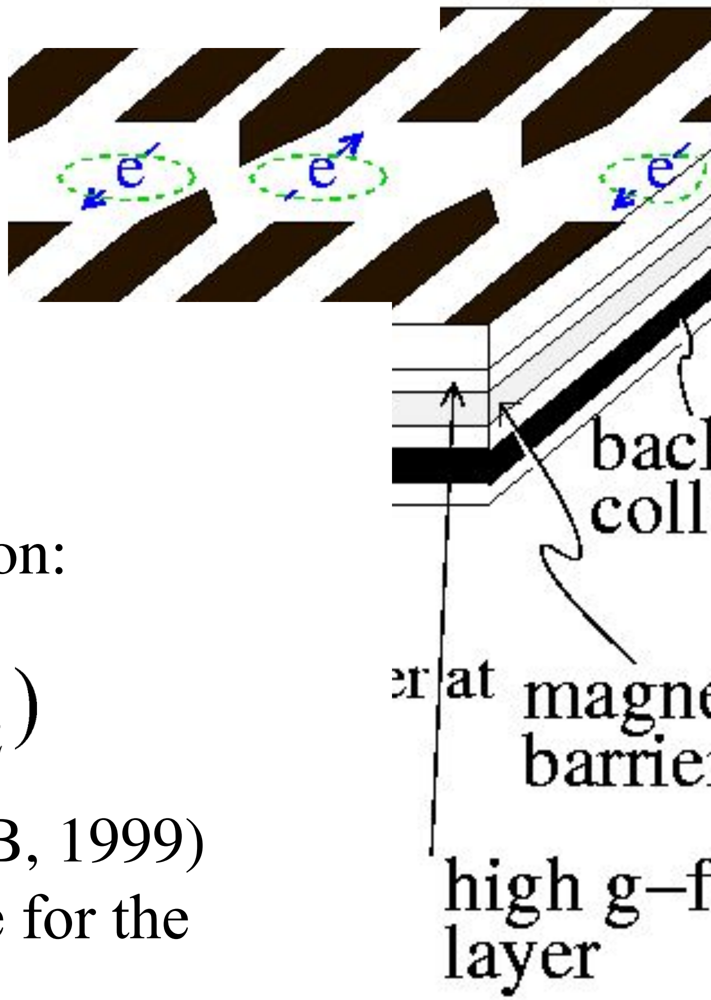
Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]
[1]*Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106-4030*
[2]*Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*
[3]*IBM Research Division, T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*

120 (1998

Gate operations with quantum dots (1):

--two-qubit gate:

Use the side gates to move electron positions horizontally, changing the wavefunction overlap



Pauli exclusion principle produces spin-spin interaction:

$$H = JS_1 \cdot S_2 = J(\sigma_{x1}\sigma_{x2} + \sigma_{y1}\sigma_{y2} + \sigma_{z1}\sigma_{z2})$$

Model calculations (Burkard, Loss, DiVincenzo, PRB, 1999)
For small dots (40nm) give *J~ 0.1meV,* giving a time for the "square root of swap" of

$$t \sim 40\ psec$$

NB: interaction is very short ranged, off state is accurately *H=0*.

Can we get CNOT with just Heisenberg exchange?
i.e., can Q. computing be done completely nonrelativistically?

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 & others) – YES:

--the trick: encode qubits in states of specific angular momentum quantum numbers, with tensor-power structure
-- examples of these sectors with N spins:
    Hilbert space dimension $2^{(N/4)}$ (singlet, S=0)
    Hilbert space dimension $2^{(N/3)}$ (S_z=+N/6, simultaneous in multiple S sectors)

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:

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

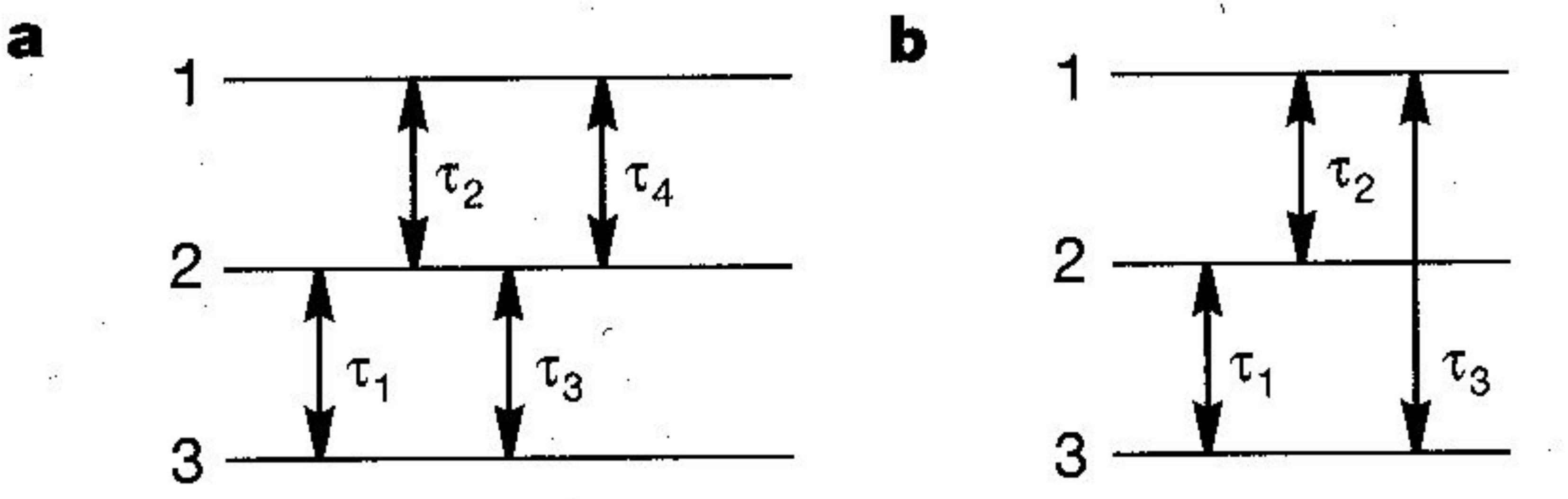
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)|\uparrow\rangle$$ (i.e., singlet times spin-up)

$$|1\rangle_L \propto 2|\uparrow\uparrow\downarrow\rangle - |\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle$$ (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:

from mrs2002

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)

Focus of R&D at HRL research lab (Malibu) for many years

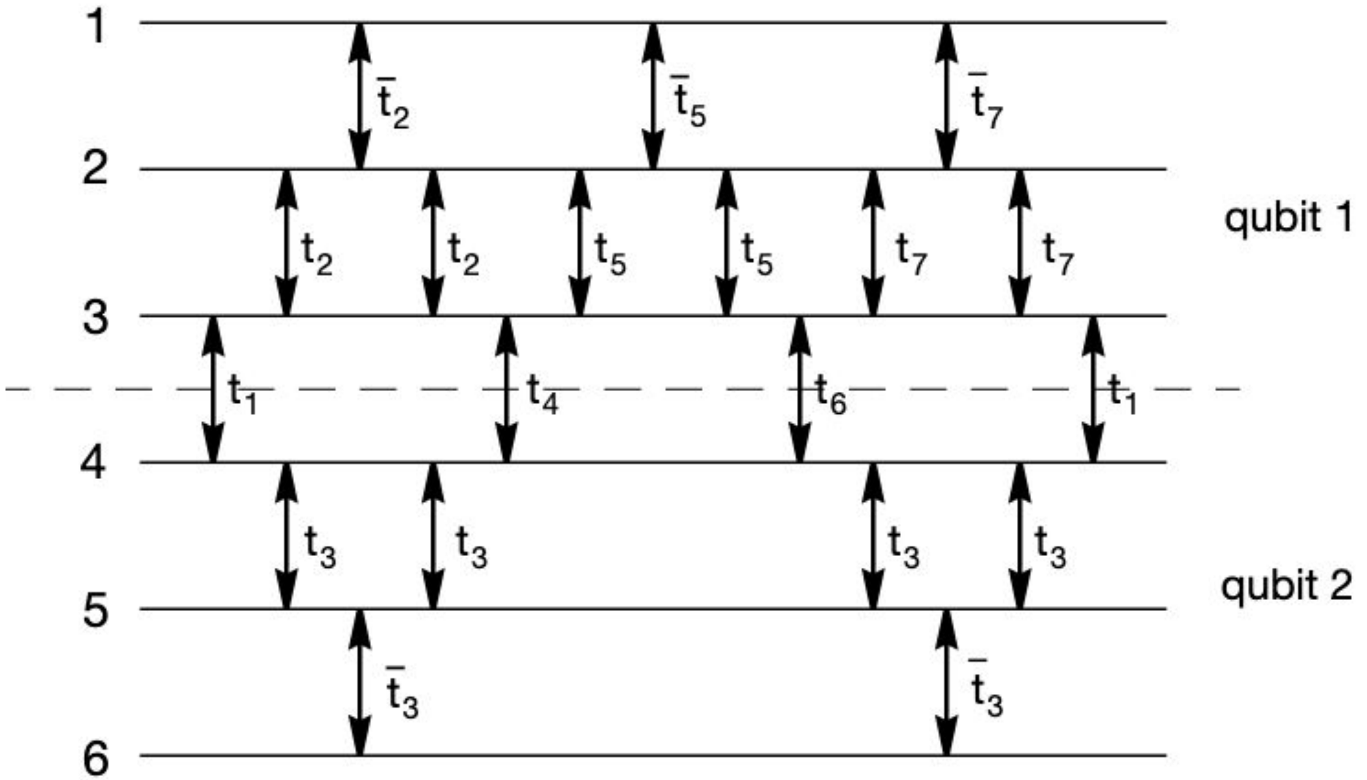
CNOT on two coded qubits

-minimal solution
19 interactions,
doable in 13 time steps

-essentially unique

-gate accuracy $\sim 10^{-5}$
with precision shown

-nearest-neighbor
seems best



$t_1=0.410899(2)$

$t_2=0.207110(20)$

$t_3=0.2775258(12)$

$t_4=0.640505(8)$

$t_5=0.414720(10)$

$t_6=0.147654(12)$

$t_7=0.813126(12)$

$\tan(\pi t_i)\tan(\pi \bar{t}_i) = -2$

Simple features of scheme for coded computation

--Initialization: turn on uniform B field and strong antiferromagnetic Heisenberg exchange between spins 1 and 2. Then

$$|0\rangle_L \propto \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)|\uparrow\rangle$$

is the ground state of the system.

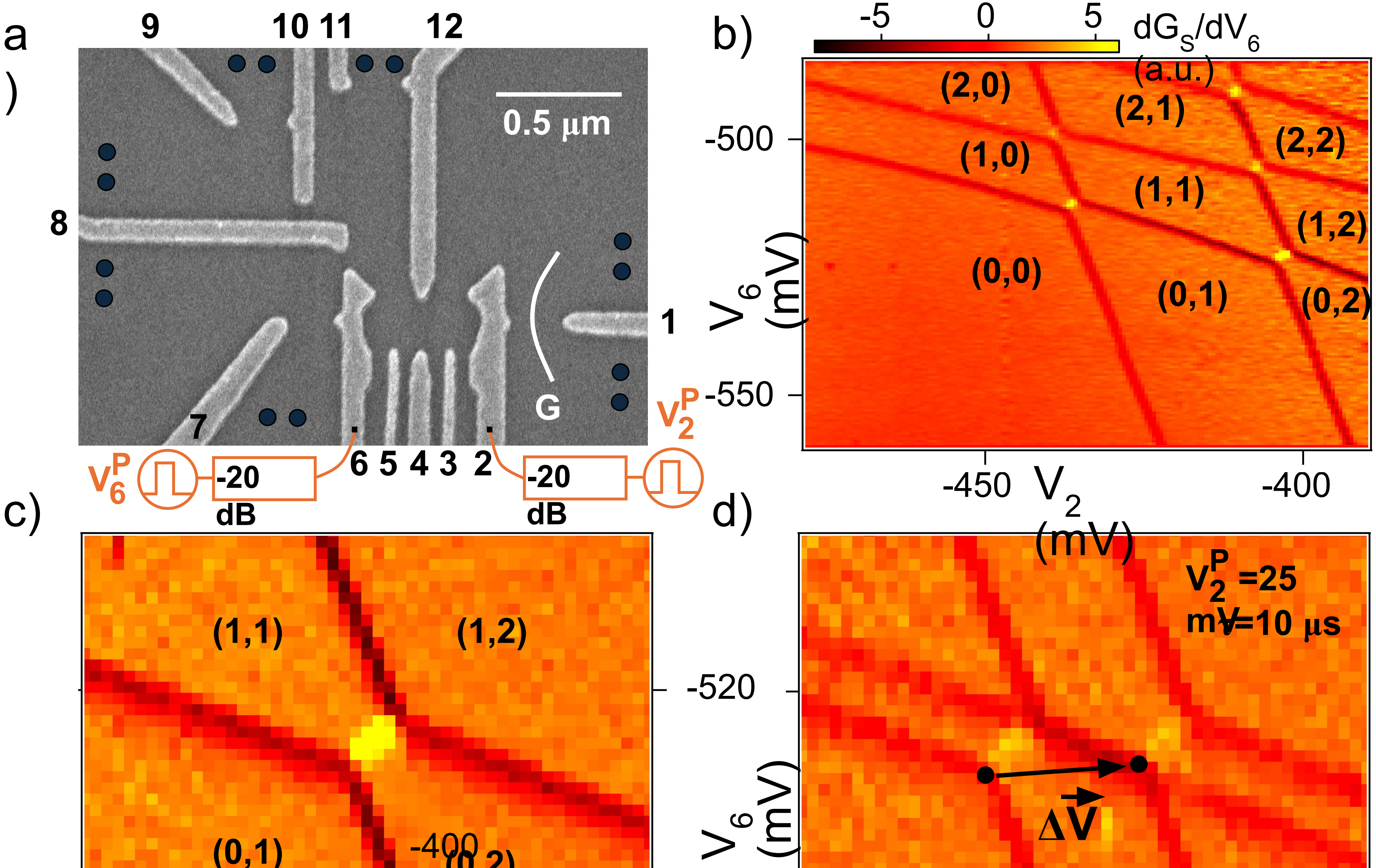
--Measurement: coded qubit is measured by determining whether spins 1 and 2 are in a relative singlet or triplet. Somewhat easier than single-spin measurements.

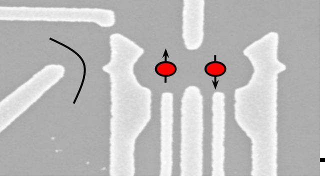
c. 2005

Details of Charlie Marcus group structures and measurements

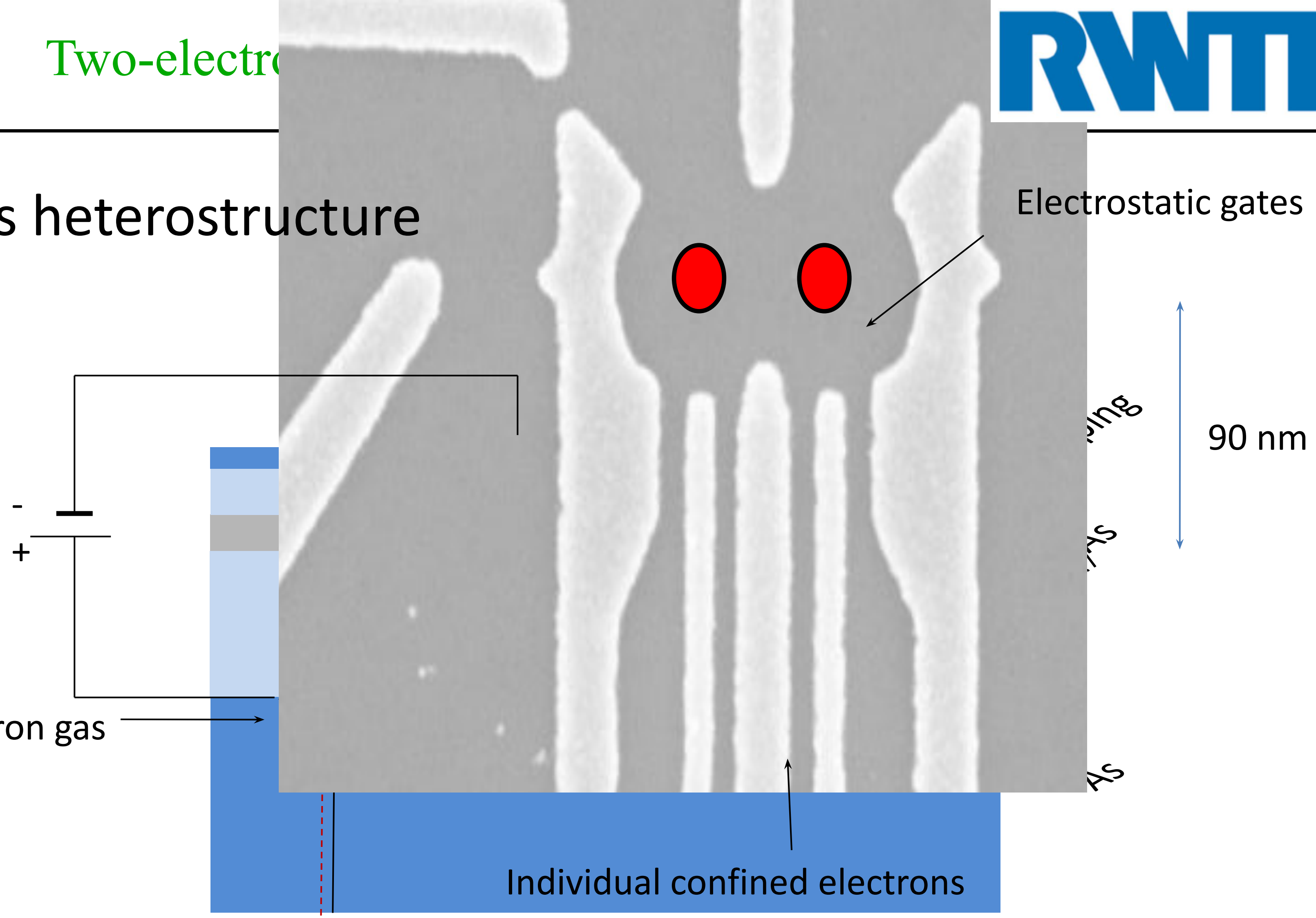
-- full electric circuit, measurement by spin-charge conversion

-- charging honeycomb, termination at empty dots





GaAs heterostructure

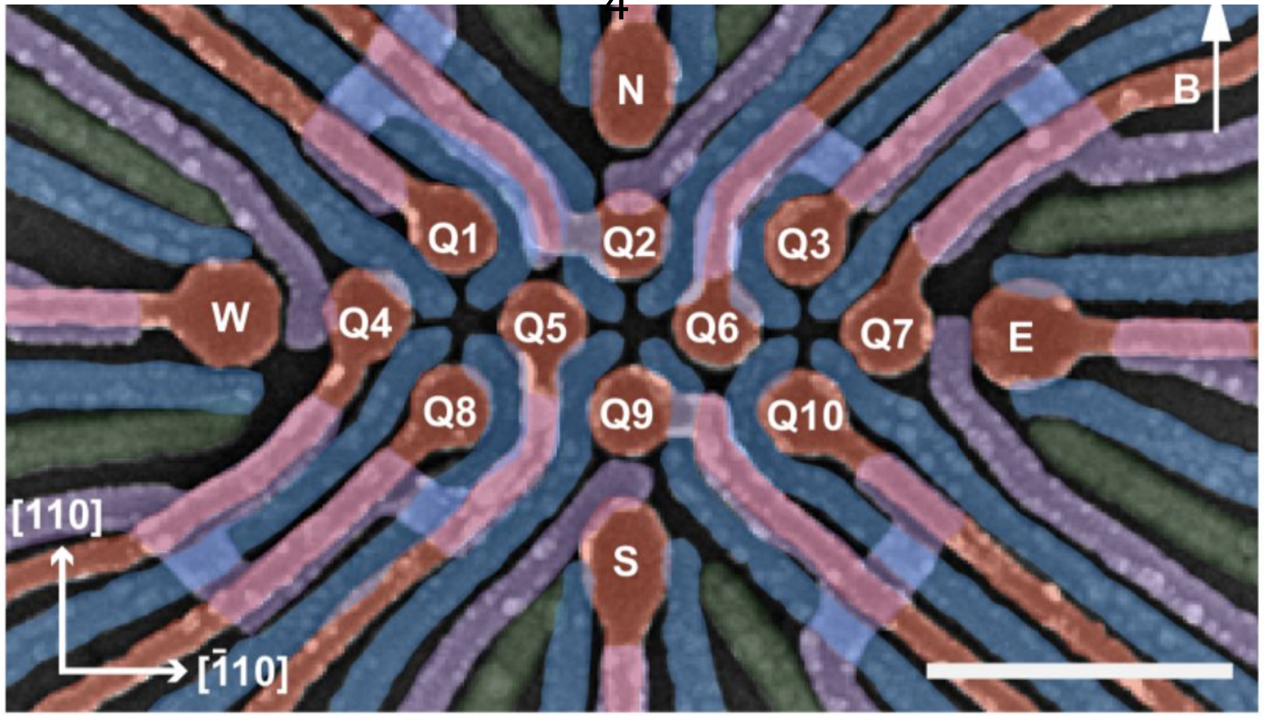


- Lengthy efforts to mitigate hyperfine effects (Ga & As nuclei)
- Gradual realization: Si and Ge are better (many spin-zero nuclei)

Thanks to Hendrik Bluhm, RWTH

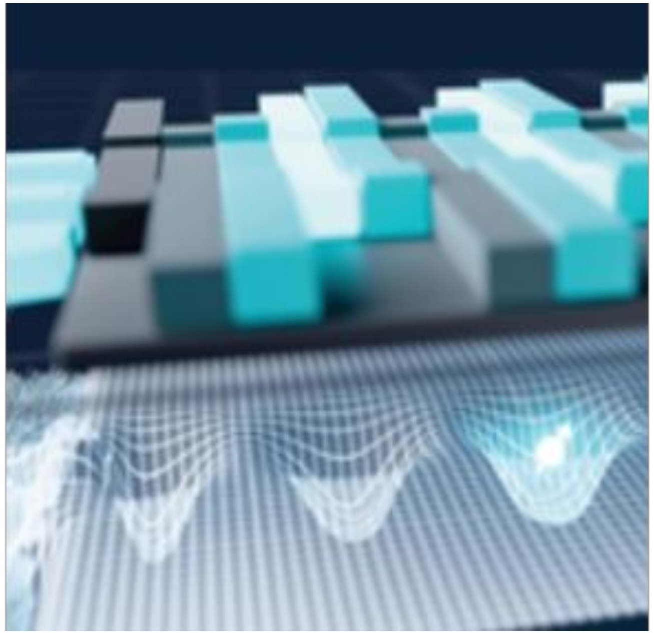
- Present developments:
  - Much improved spin qubits with Si/Ge
  - >99% gate fidelities (not 99.9%)
  - Multiqubit structures are working (~16)
  - Boast: “million qubits on a chip”
    - Very misguided – not scalable!

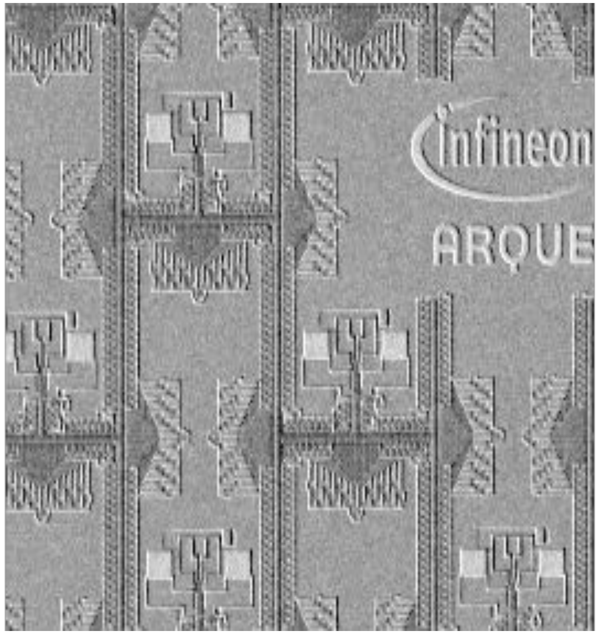
2024



300nm

- Partial solution for scalability problem:
  - Electron shuttle:
    - Move single electron in gated structure by several microns
    - OK state fidelity now achieved
    - Leads to Infineon/ARQUE scalable architecture
    - Problem: extra valley quantum number





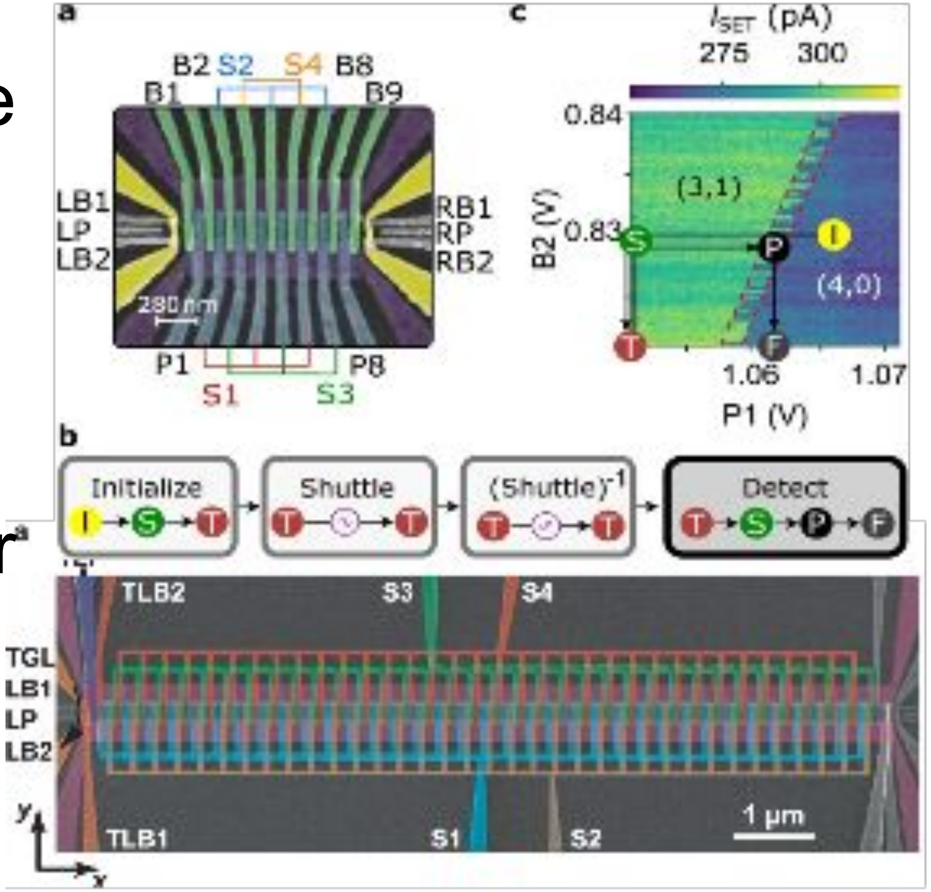
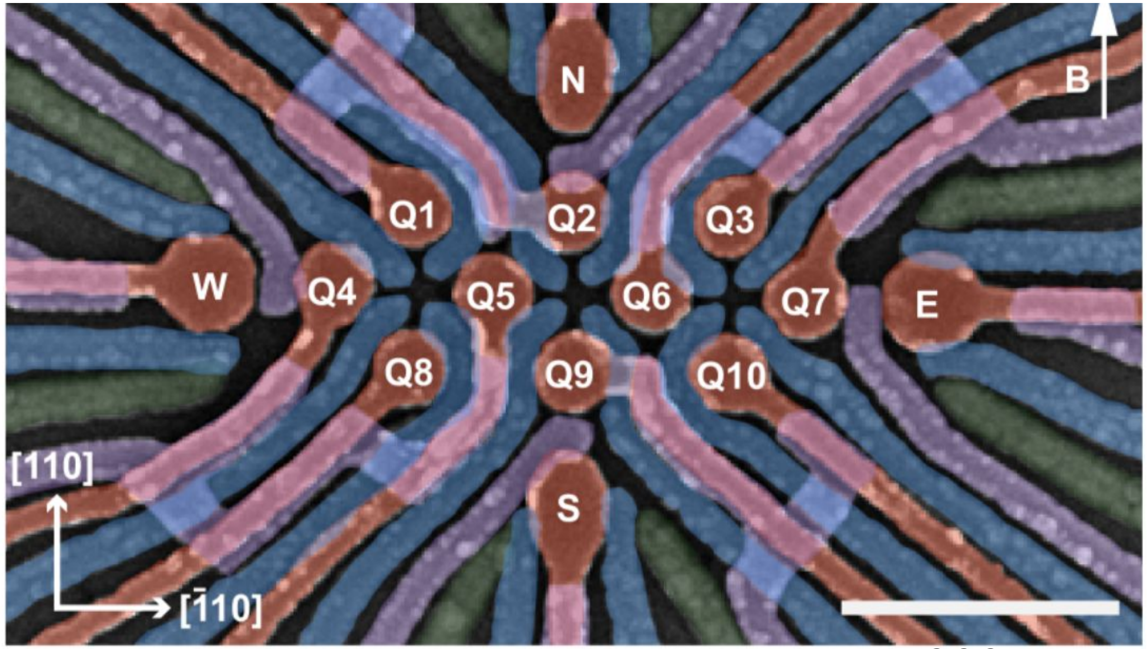


Figure 5. Top: Si/Ge shuttle structure successfully used for remote EPR-pair generation. Bottom: Recent-generation experimental electron shuttle.

- New development:
  - Several problems solved by going to **holes**
  - Different heterostructure, primarily Ge



300nm

Veldhorst
Scappucci

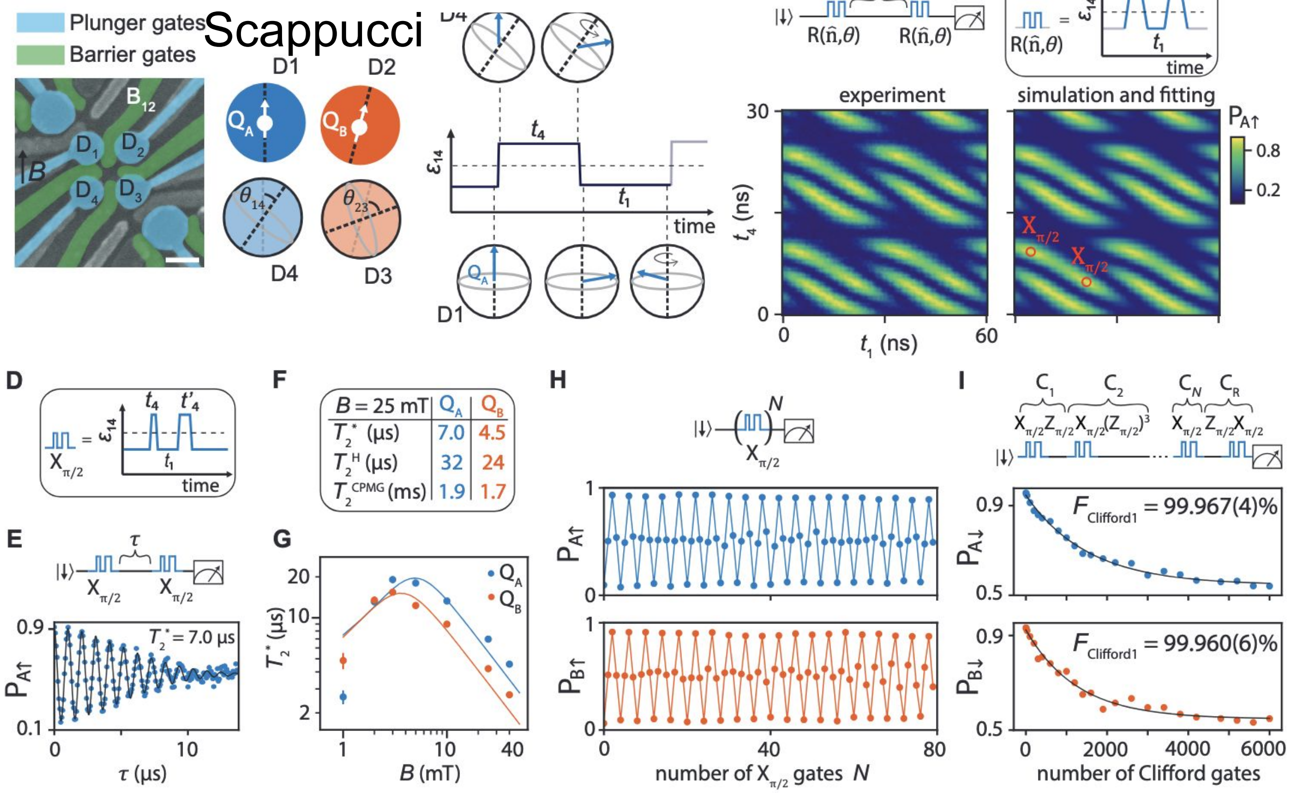


Figure 1: **High-fidelity hopping-based single-qubit operations and long qubit coherence times at low magnetic field. (A)** (left) Scanning electron microscopy image of the 2×2 quan-

Operating semiconductor quantum processors with hopping spins

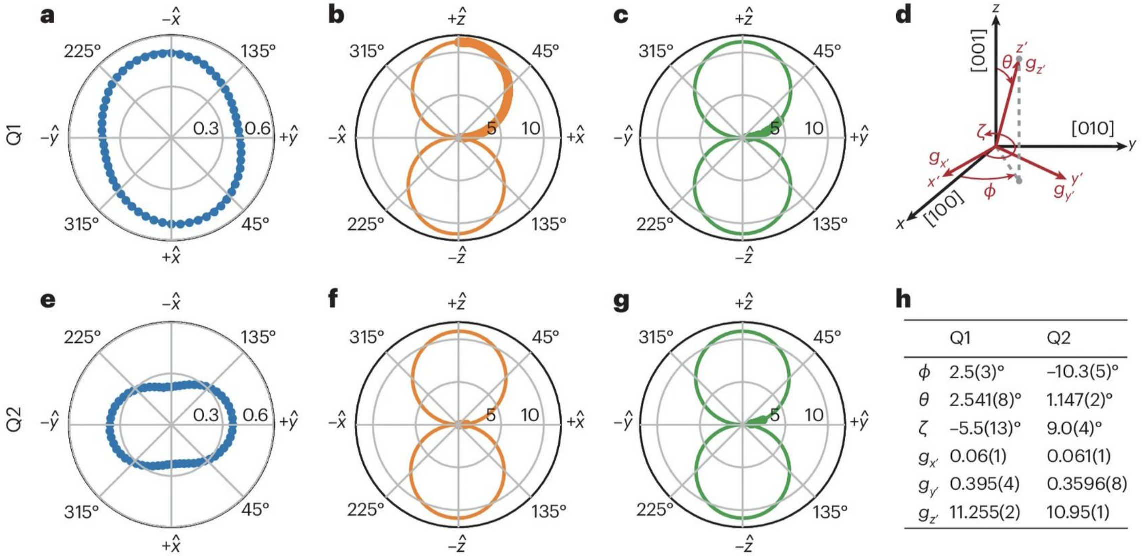
CHIEN-AN WANG, VALENTIN JOHN, HANIFA TIDJANI, CÉCILE X. YU, ALEXANDER S. IVLEV, CORENTIN DÉPREZ, FLOOR VAN RIGGELEN-DOELMAN, BENJAMIN D. WOODS, NICO W. HENDRICKX, [...], AND MENNO VELDHORST +9 authors Authors Info & Affiliations

SCIENCE • 25 Jul 2024 • Vol 385, Issue 6707 • pp. 447-452 • DOI: 10.1126/science.ado5915

- Completely different from Loss/DiVincenzo paradigm, *highly relativistic*:
  - Holes, as described by Luttinger Hamiltonian, have complex anisotropy
  - g factor structure
    - $g_{zz} >> 2$
    - $g_{xx}, g_{yy} \sim 0$
    - Principal axes slightly rotated

Fig. 2: Measurement of the hole *g*-tensor.

From: Sweet-spot operation of a germanium hole spin qubit with highly anisotropic noise sensitivity



h

	Q1	Q2
ϕ	2.5(3)°	−10.3(5)°
θ	2.541(8)°	1.147(2)°
ζ	−5.5(13)°	9.0(4)°
$g_{x'}$	0.06(1)	0.061(1)
$g_{y'}$	0.395(4)	0.3596(8)
$g_{z'}$	11.255(2)	10.95(1)

a–**c**,**e**–**g**, Cross-section of $\overleftrightarrow{g}$ of Q1 (**a**–**c**) and Q2 (**e**–**g**) in the *x*–*y* plane (**a**,**e**), *x*–*z* plane (**b**,**f**) and *y*–*z* plane (**c**,**g**) of the magnet frame. Dots indicate measurements of g^* and the solid line corresponds to the fit of $\overleftrightarrow{g}$. Exemplary resonance spectra used to extract $\overleftrightarrow{g}$ are plotted in Supplementary Fig. 1. **d**, Diagram indicating the *zyz* Euler rotation angles φ, θ and ζ of the principle *g*-tensor axes $\mathbf{g}_{x'}$, $\mathbf{g}_{y'}$ and $\mathbf{g}_{z'}$. The approximate crystal directions are indicated in square brackets. **h**, Overview of the three *zyz* Euler angles φ, θ and ζ for the rotation of a *g*-tensor with principle components $g_{x'}$, $g_{y'}$ and $g_{z'}$ for Q1 and Q2.

Back to article page ›

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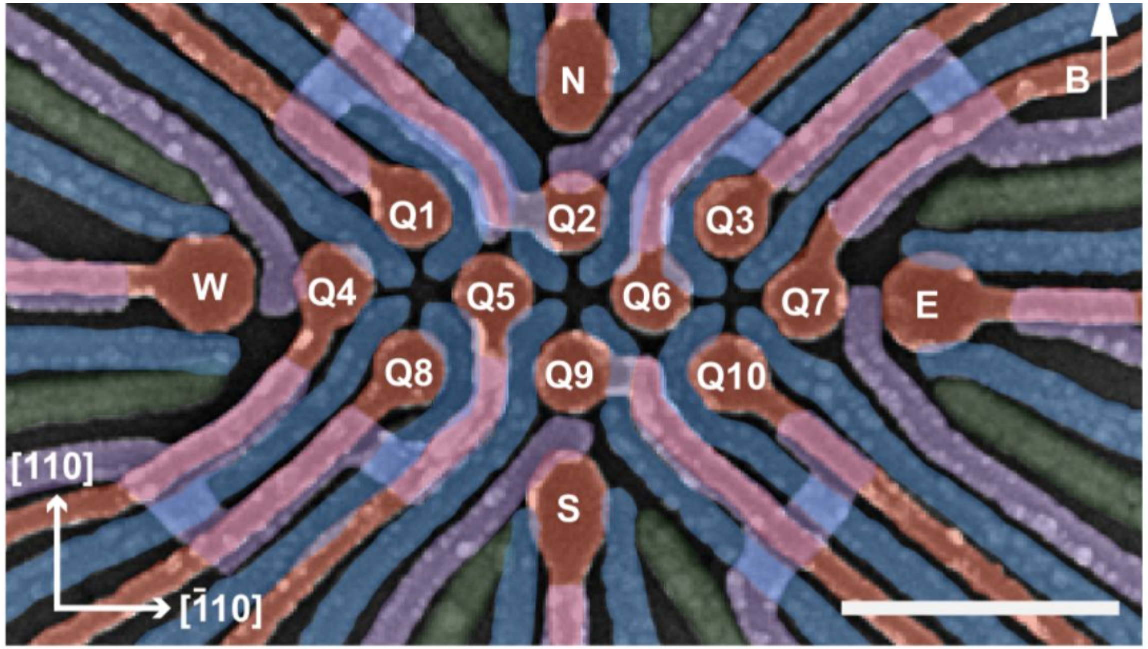
- Completely different from Loss/DiVincenzo paradigm, *highly relativistic*
  - Holes, as described by Luttinger Hamiltonian, have complex anisotropy
  - g factor structure
    - g_{zz}>>2
    - g_{xx}, g_{yy} ~ 0
    - Principle axes slightly rotated
  - But, successful gates by LD mechanism:
  - Hole transferred to dot with rotated principle axes, causes Bloch-vector rotation
  - Excellent fidelity achieved



300nm

Operating semiconductor quantum processors with hopping spins

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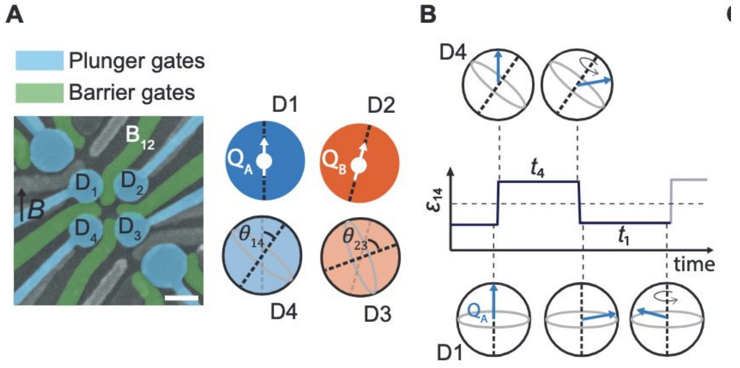

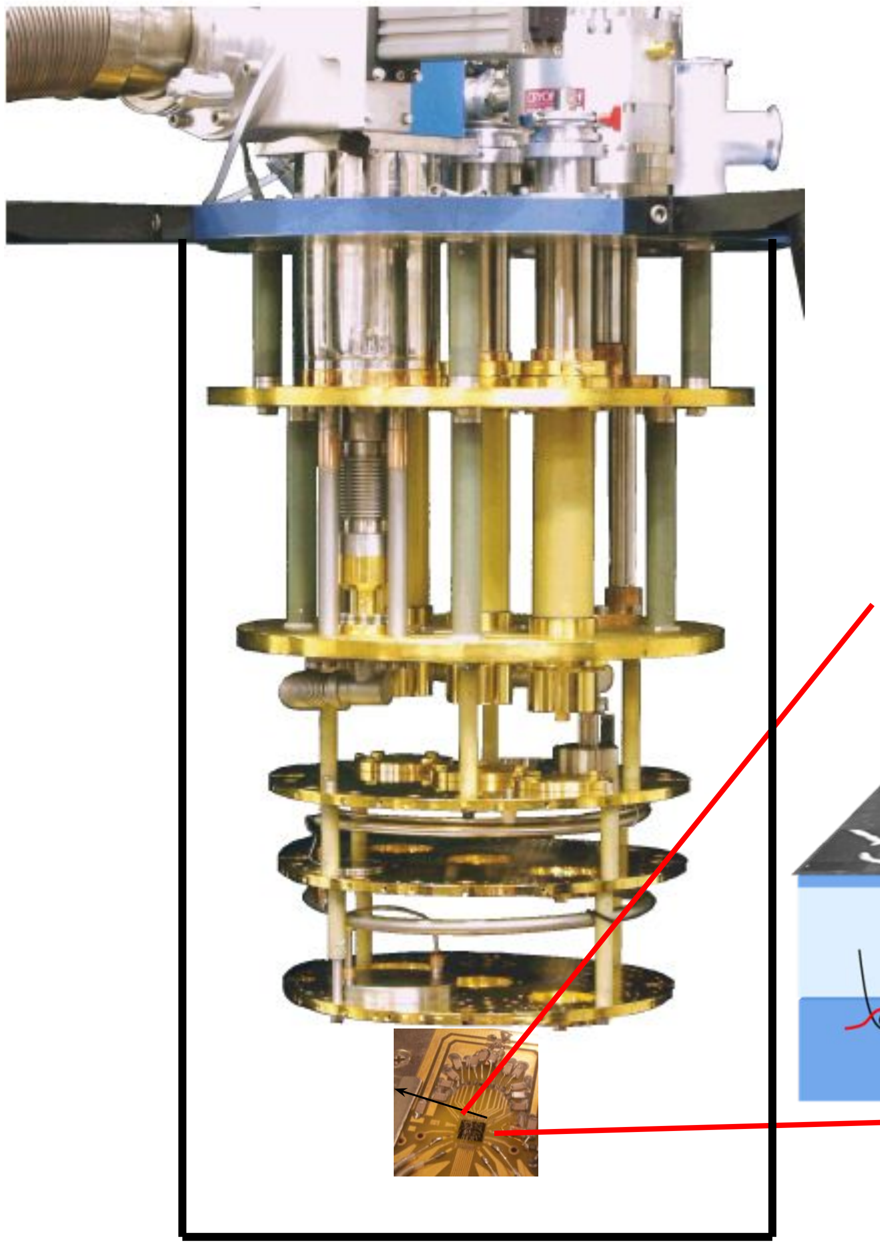

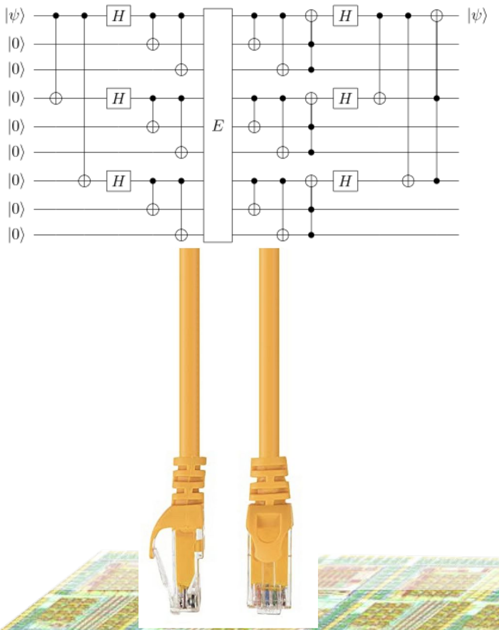

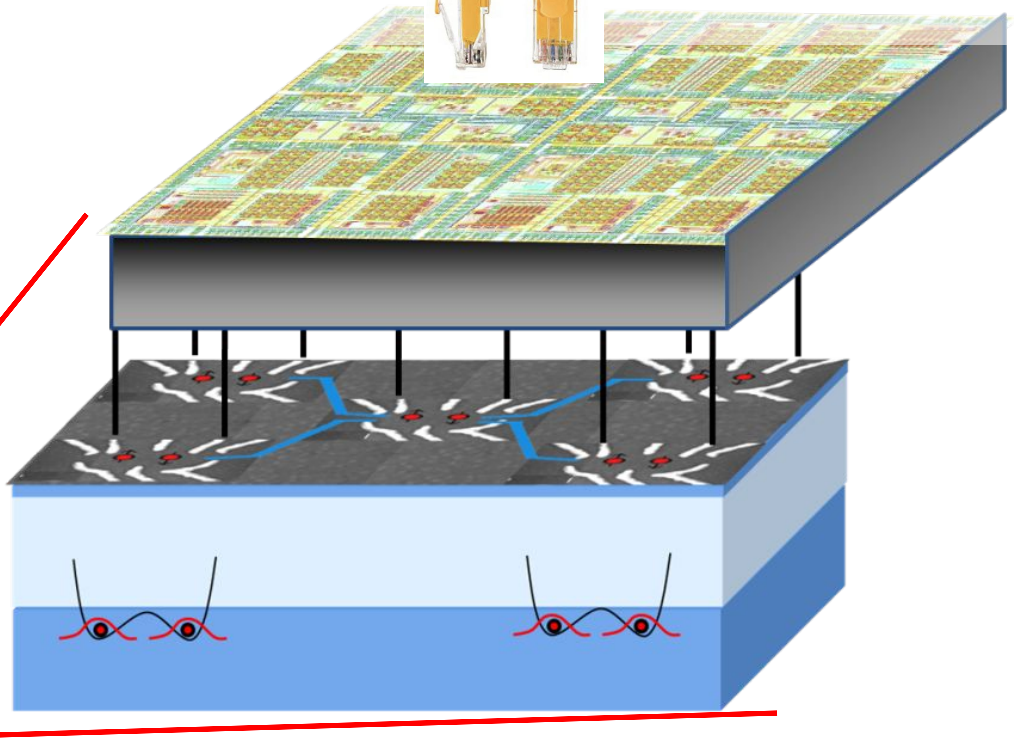

- Prospective architecture:
- Cold control circuits
- Very few cables into cryostat
- my skepticism:
    - Power consumption
    - minaturization

Observations

- Spin qubits: “moderate success”
- Explores many interesting physics ideas
- Problems of excessive decoherence, extra degrees of freedom slowly overcome
- Novel discussions of scaling route, many problems can be foreseen
- Revived modern attention to beautiful aspects (e.g., Kohn-Luttinger picture) of semiconductor physics