

A “Spins–inside” Quantum Processor

8th Intl. Conf. on Post-Quantum Cryptography

26-28 June 2017, Utrecht, Netherlands

Lieven Vandersypen

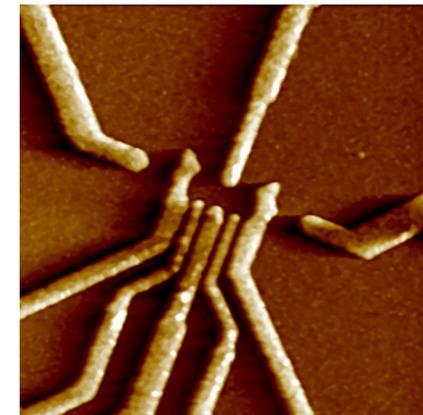
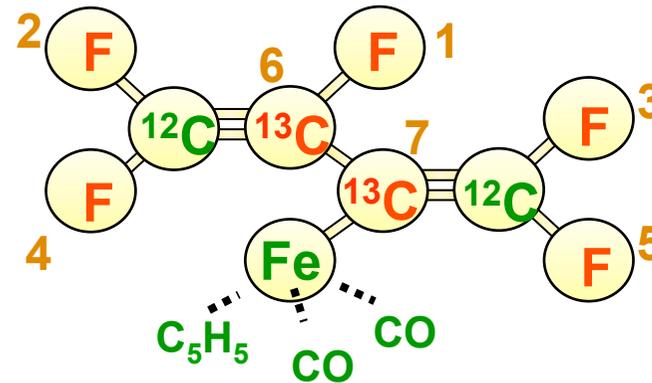
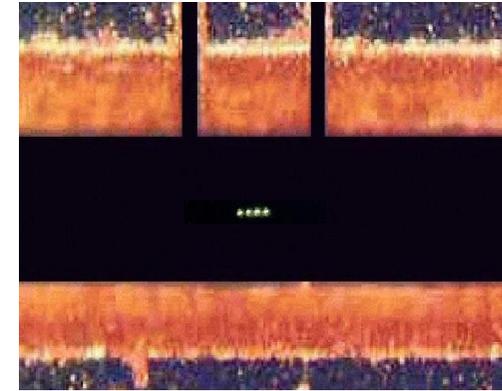
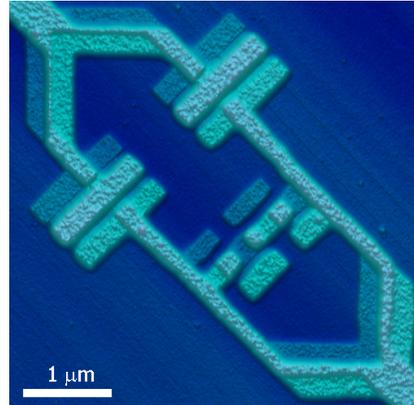


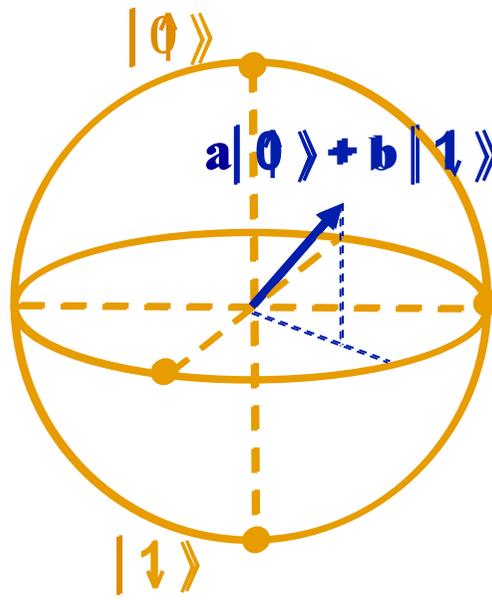
Can a quantum computer be built?

Post Quantum
Cryptography workshop

Leuven, 23-26 May 2006

Lieven Vandersypen





Exponential complexity of quantum bits

0 & 1

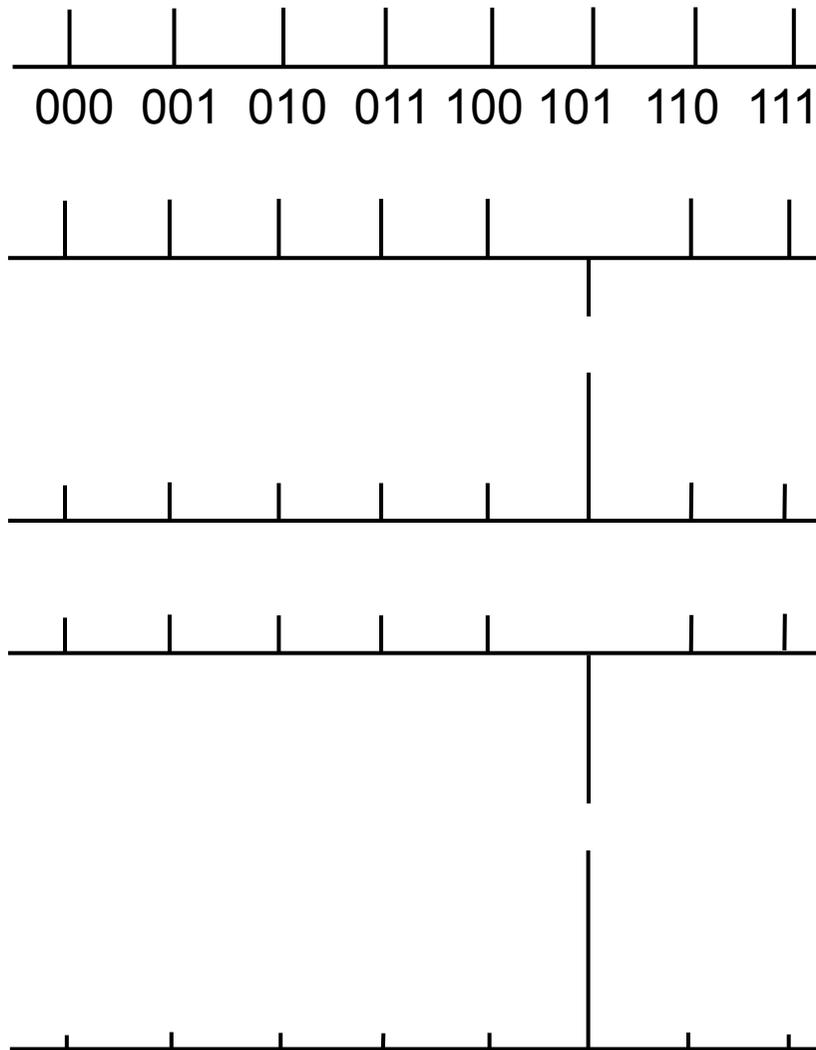
00 & 01 & 10 & 11

000 & 001 & 010 & 011 & 100 & 101 & 110 & 111

0000 & 0001 & 0010 & 0011 & 0100 & 0101 & 0110 & 0111 & 1000 & 1001 & 1010 & 1011 & 1100 & 1101 & 1110 & 1111

50 qubits (2^{50} **complex** amplitudes)
exceed memory of largest supercomputer

How quantum computers compute



Create equal superposition



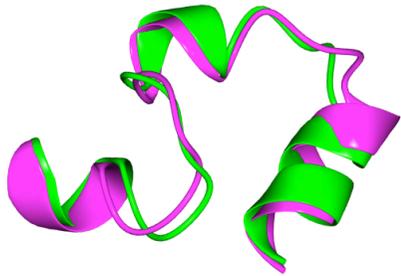
Unitary transformations



Desired answer emerges through interference

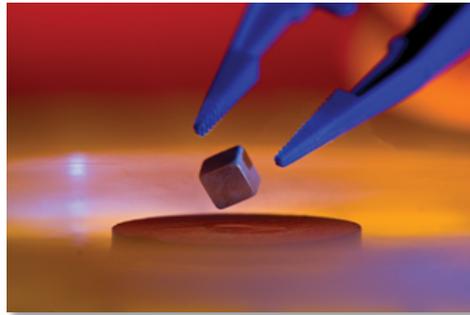
What quantum computers can do

Model complex molecules



Health: Quantum chemistry for medicine

Model complex materials



Energy: Room-temperature superconductivity

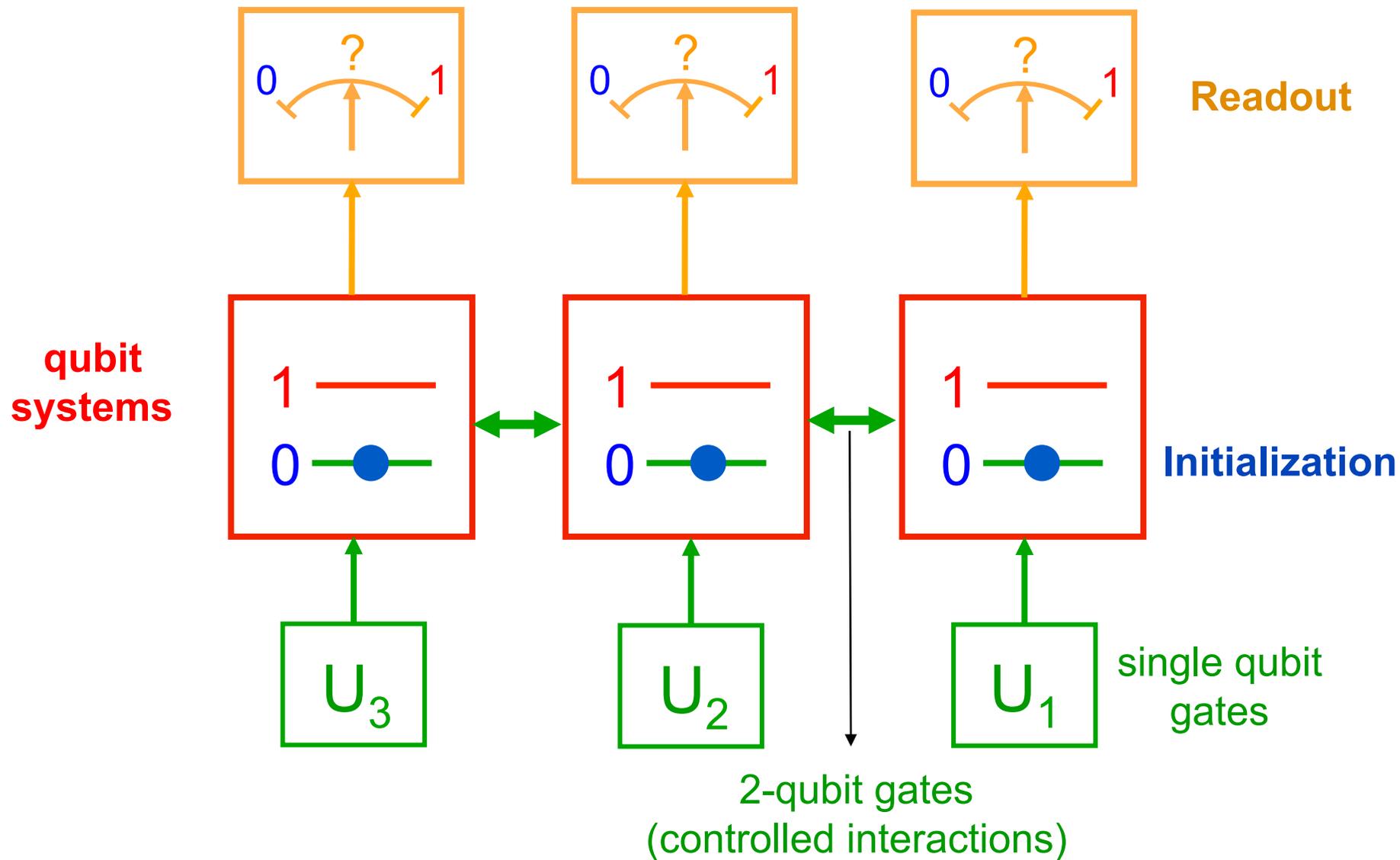
Solve complex math problems



Security: factoring and code breaking

Nobel 2012 citation: *“The quantum computer may **change our everyday lives** in this century in the same radical way as the classical computer did in the last century.”*

What does it take? (DiVincenzo criteria)



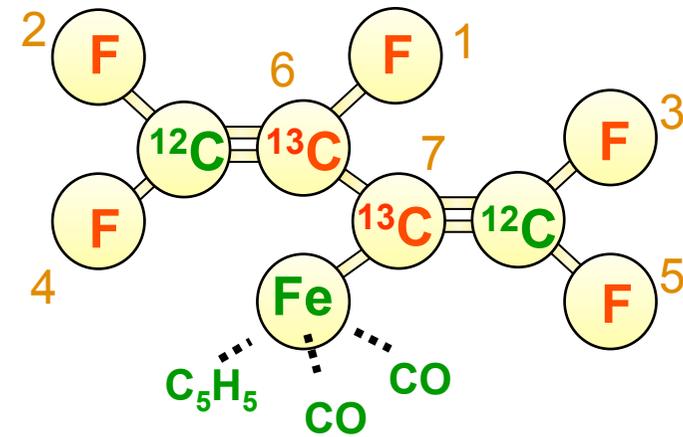
Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

Lieven M. K. Vandersypen^{*†}, Matthias Steffen^{*†}, Gregory Breyta^{*}, Costantino S. Yannoni^{*}, Mark H. Sherwood^{*} & Isaac L. Chuang^{*†}

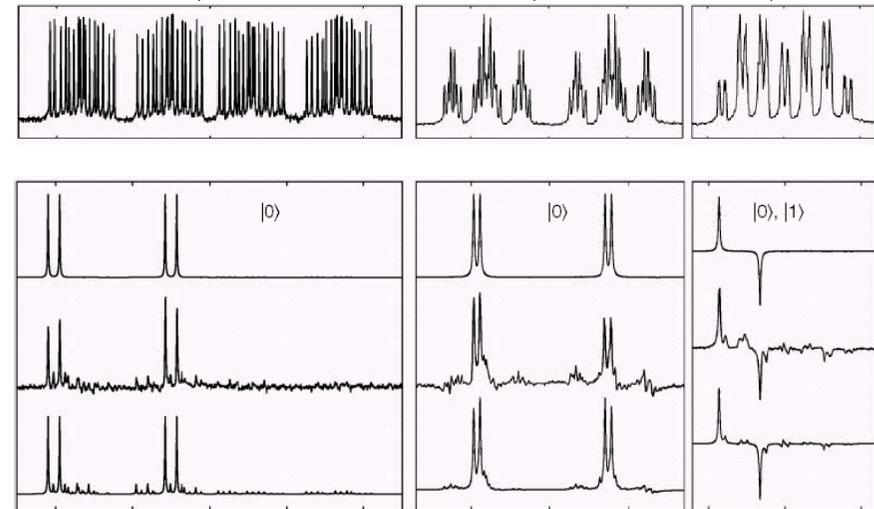
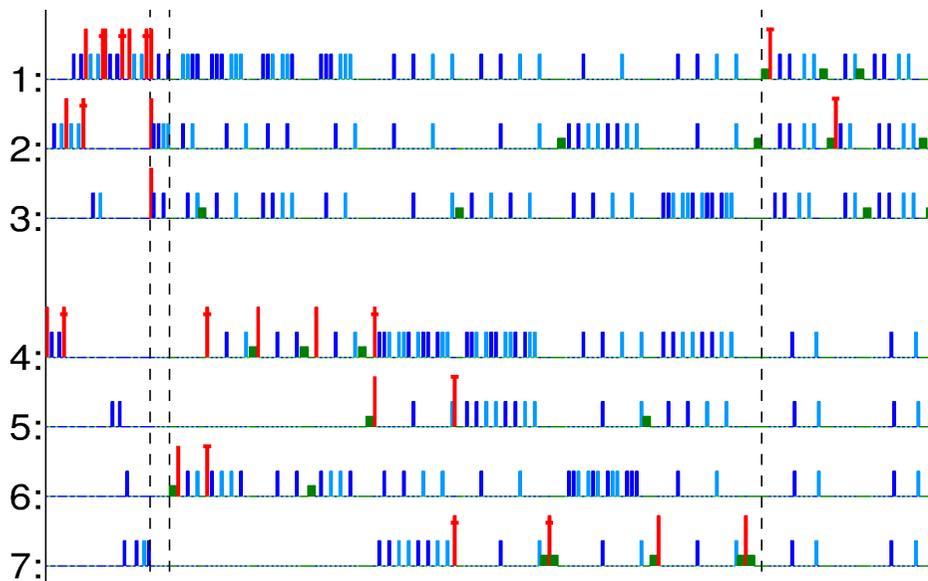
^{*}IBM Almaden Research Center, San Jose, California 95120, USA

[†]Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4075, USA

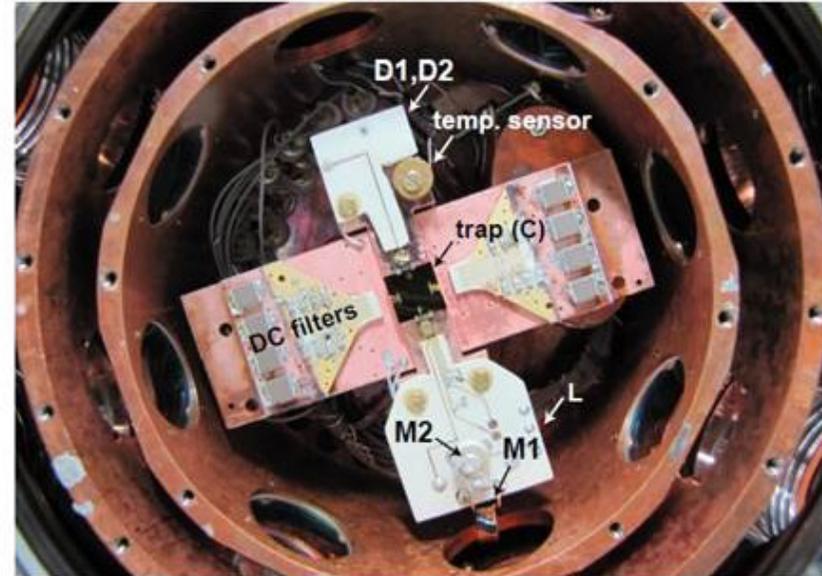
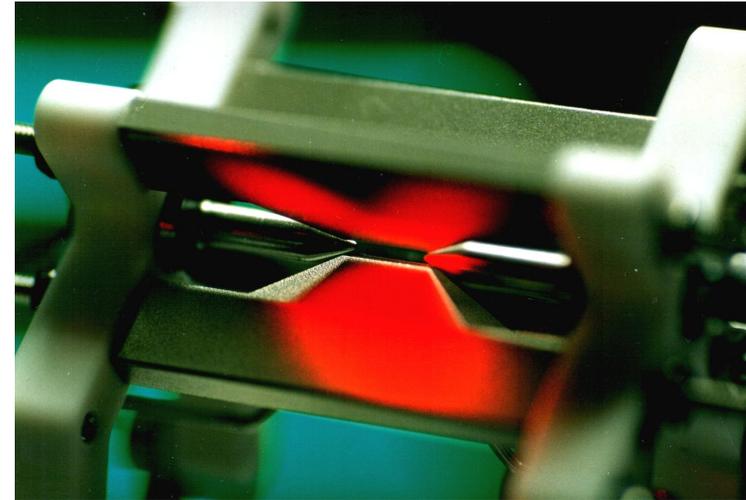
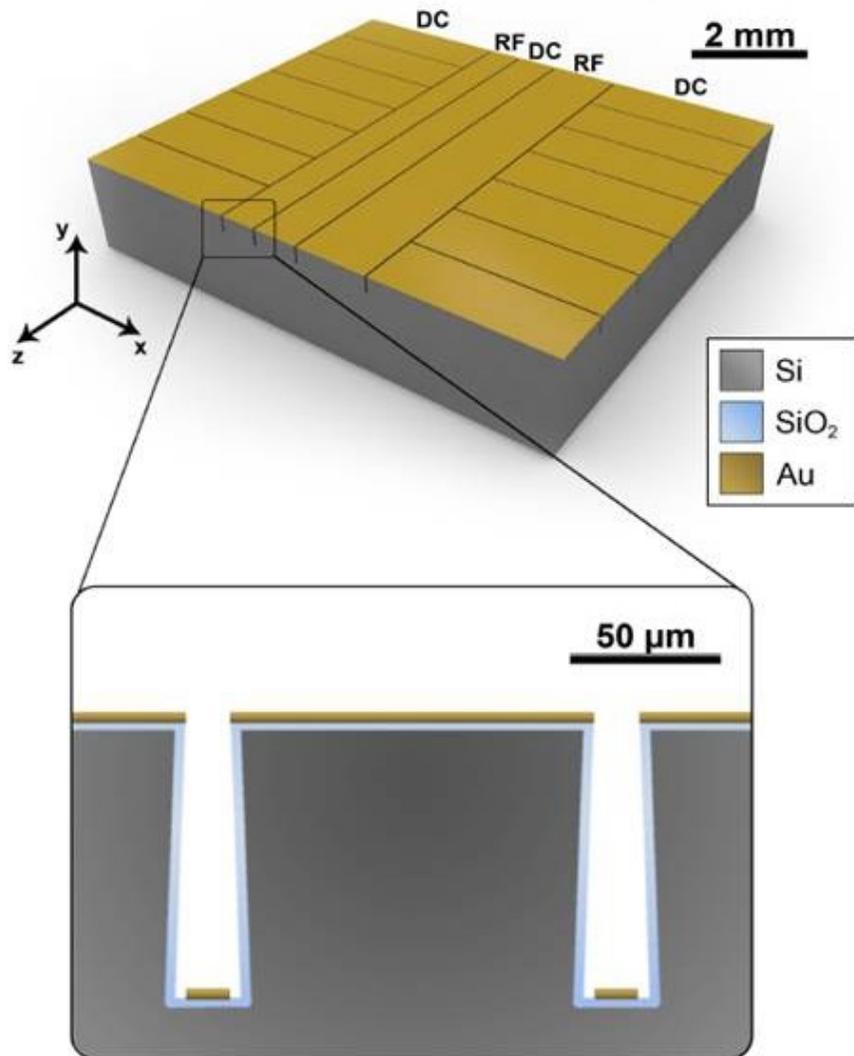
NATURE | VOL 414 | 20/27 DECEMBER 2001



$$15 = 3 \times 5 \dots$$



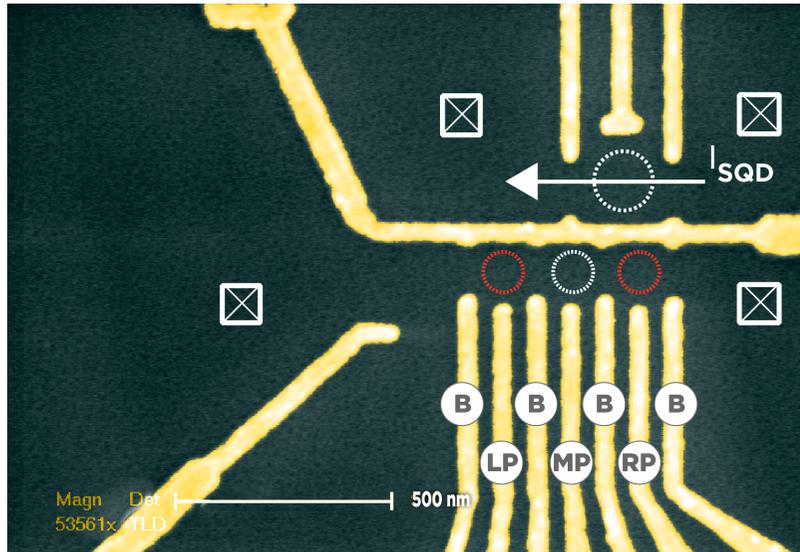
Trapped ions



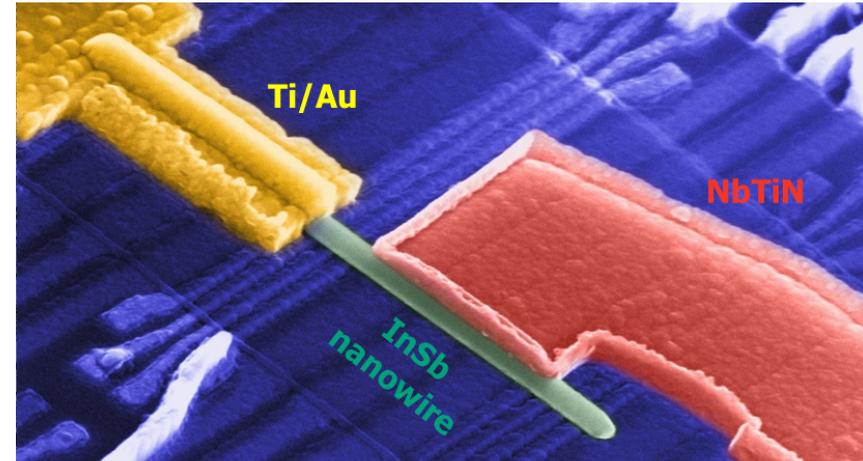
Advance 1: Qubits can be built on a chip!

(Delft examples)

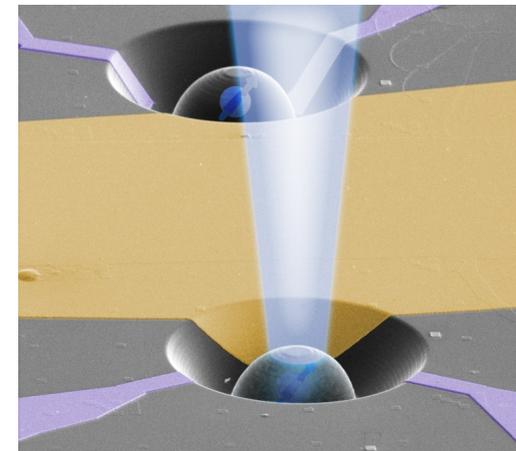
Semiconductor quantum dots



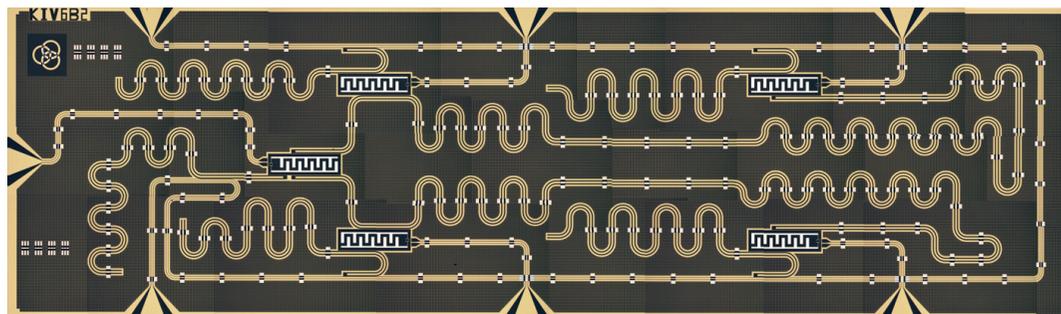
Semiconductor-superconductor hybrids



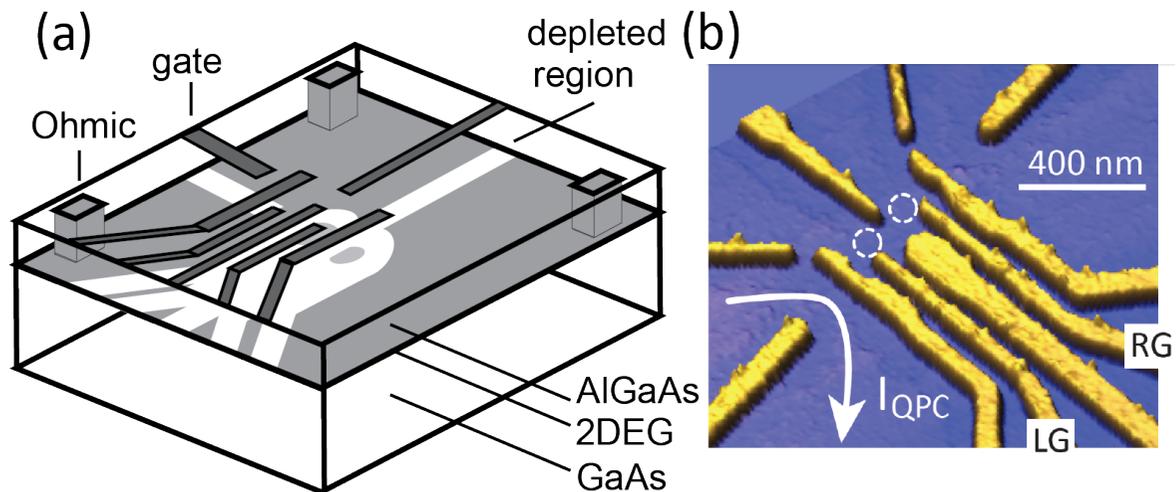
Impurities in diamond or silicon



Superconducting circuits



All-electrical semiconductor quantum dots

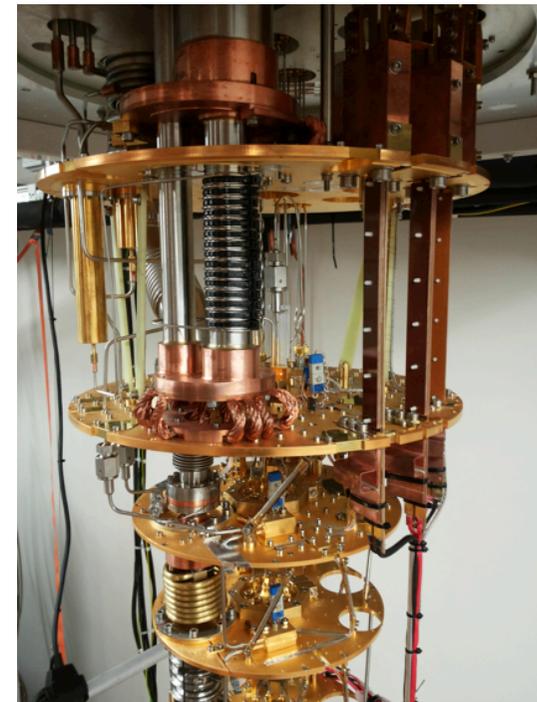


*Artificial atoms
and molecules*

Discrete # charges, quantized orbitals

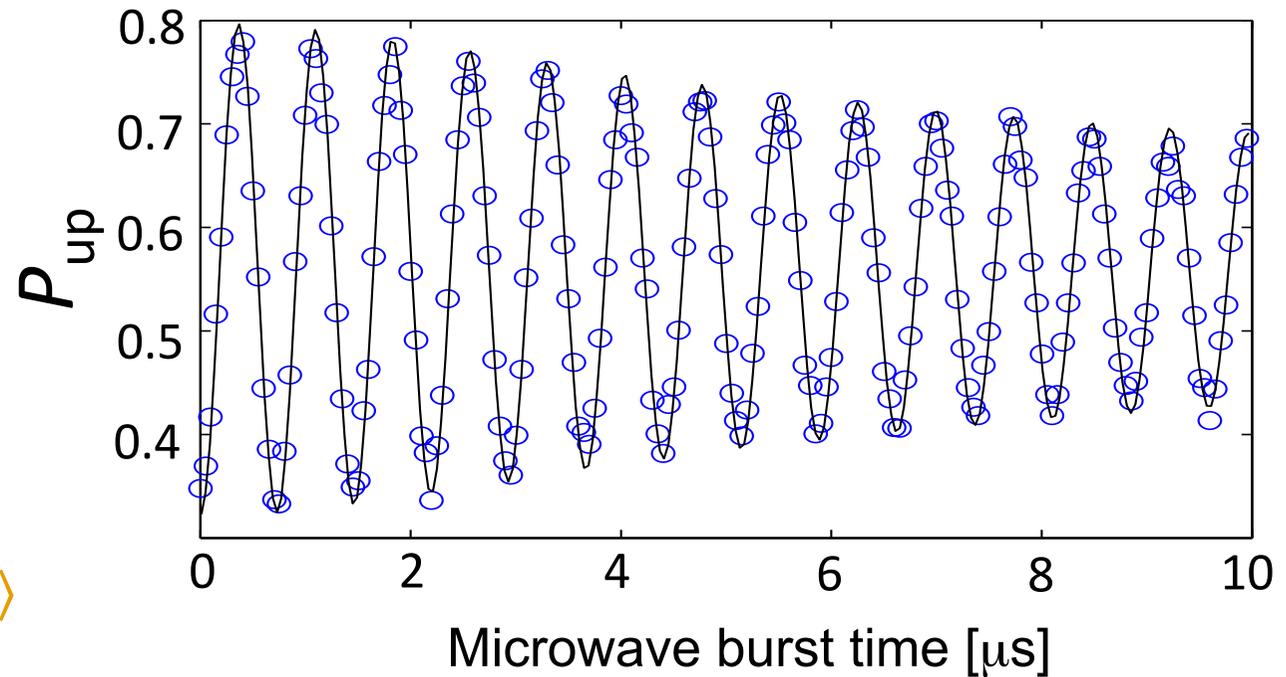
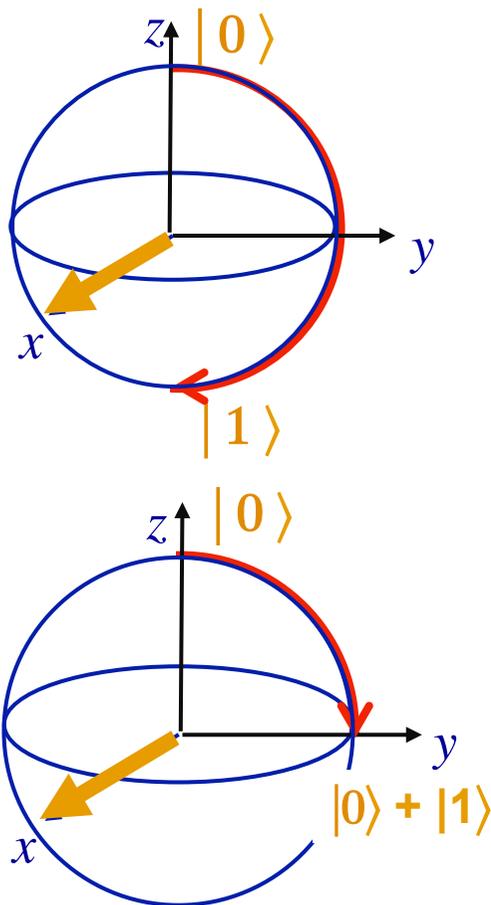
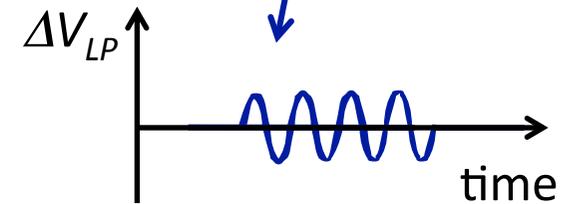
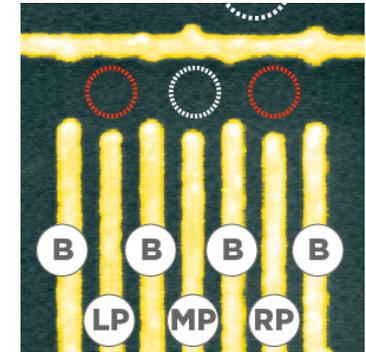
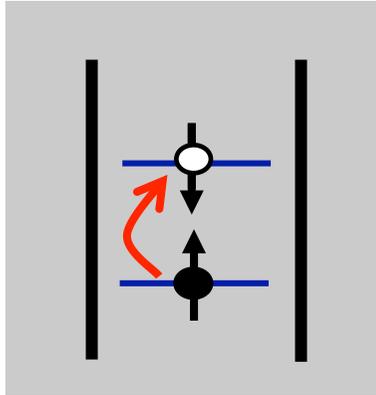
Electrical control and detection

- Tunable # of electrons
- Tunable tunnel barriers
- Electrical contacts



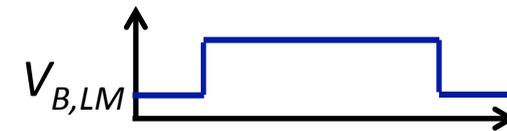
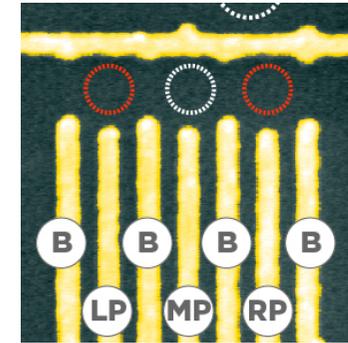
Single-qubit operation

Control individual spins using microwave drive

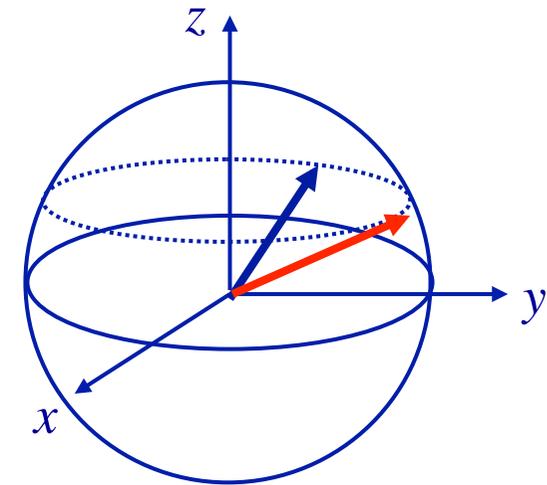
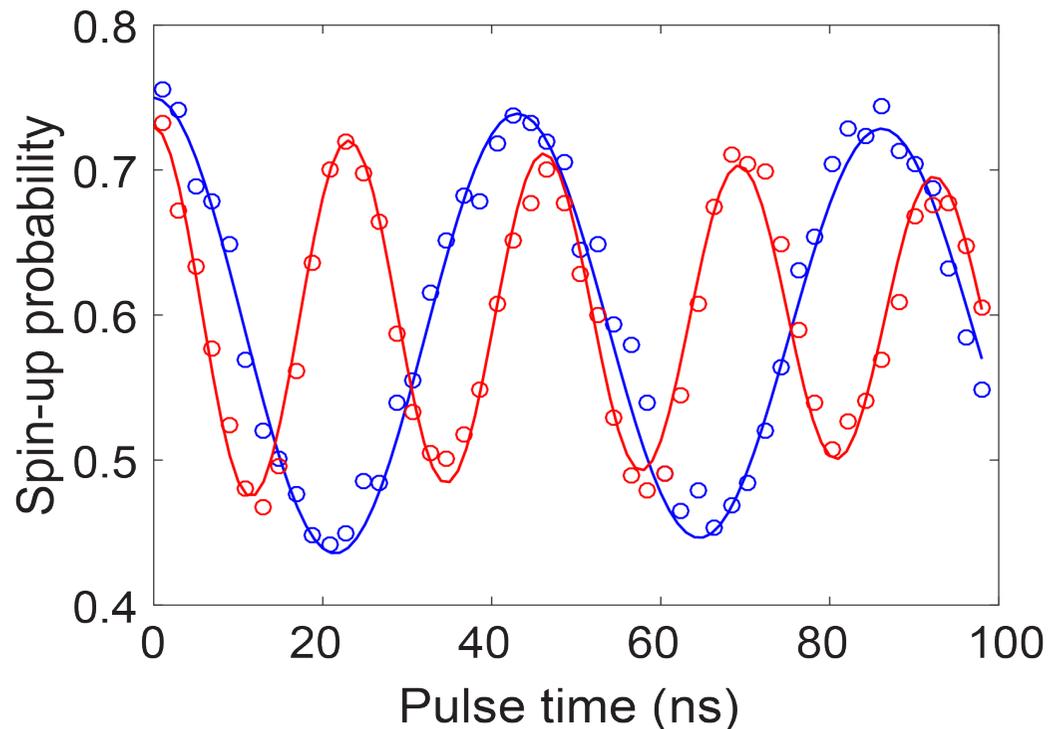


Two-qubit operation

Electrical control of the coupling between neighbouring spins

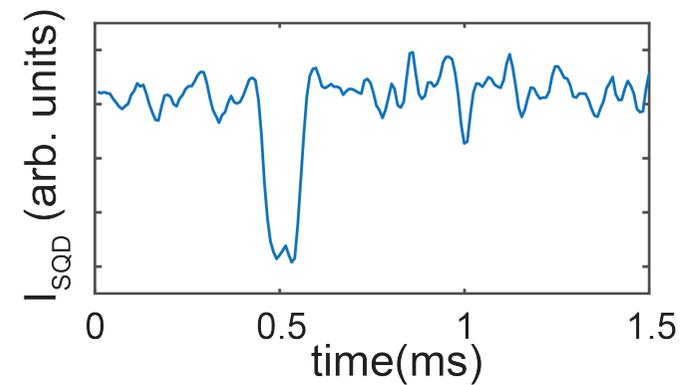
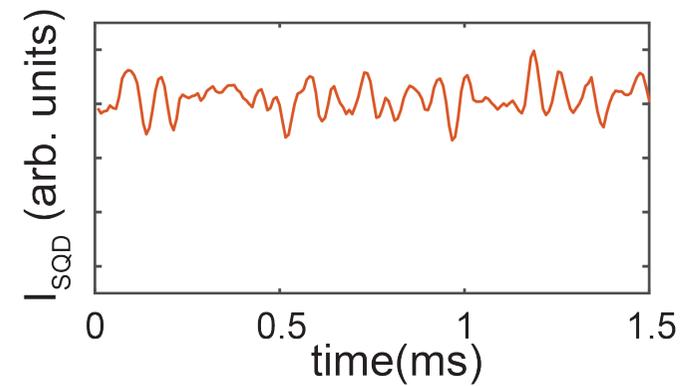
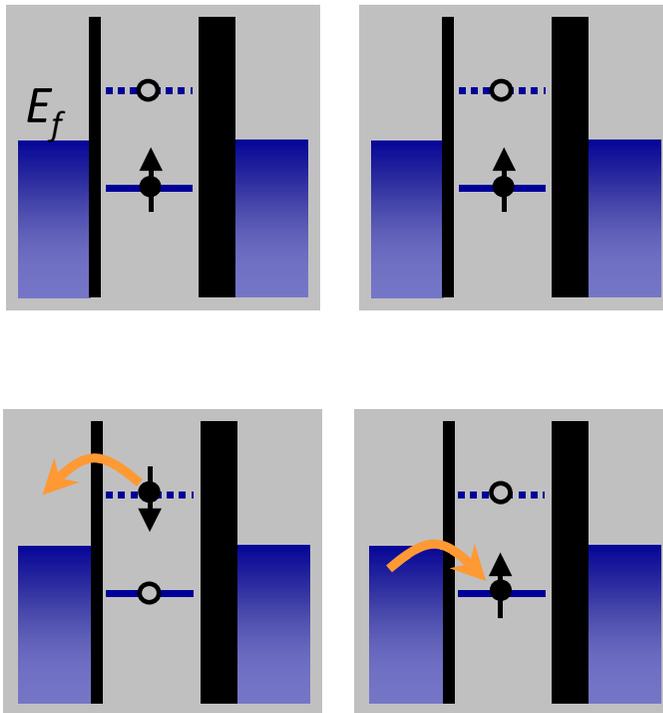
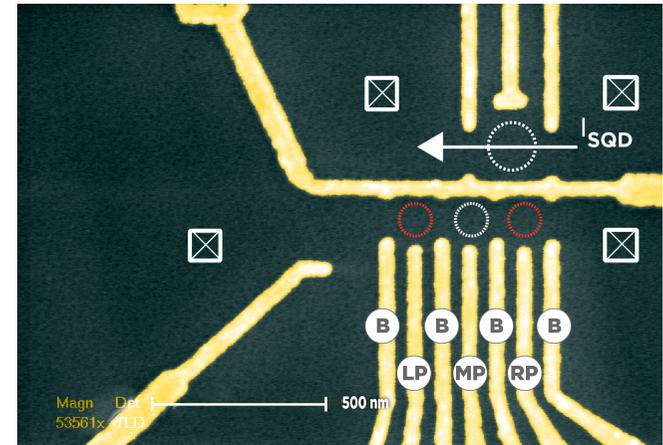


Evolution of spin 2 conditional on spin 1



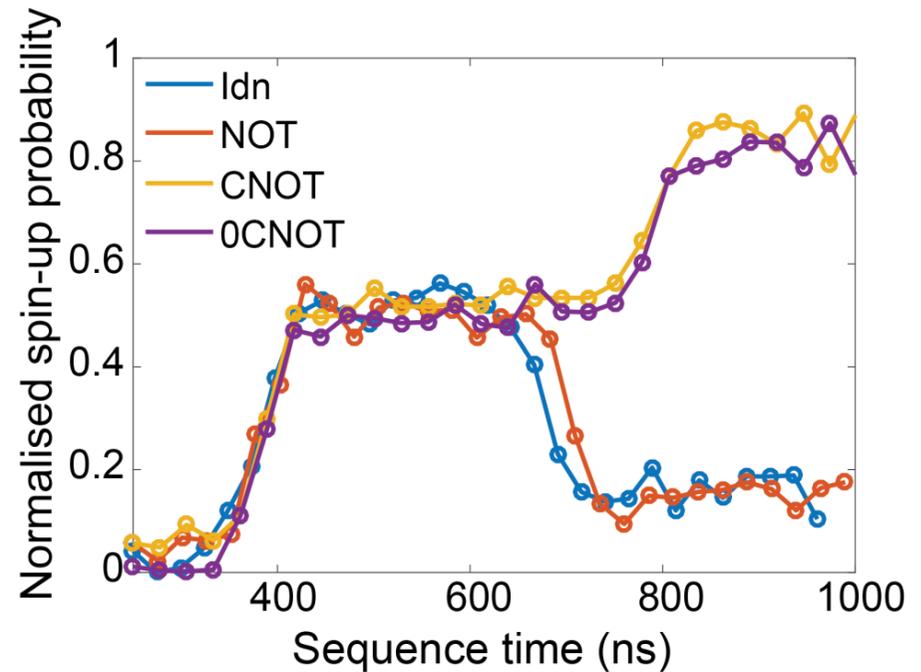
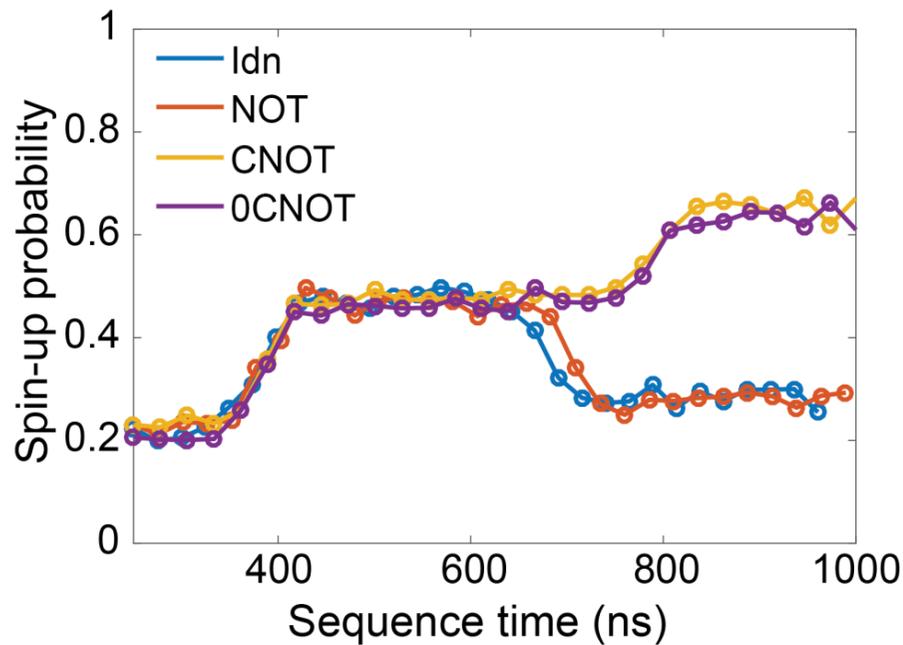
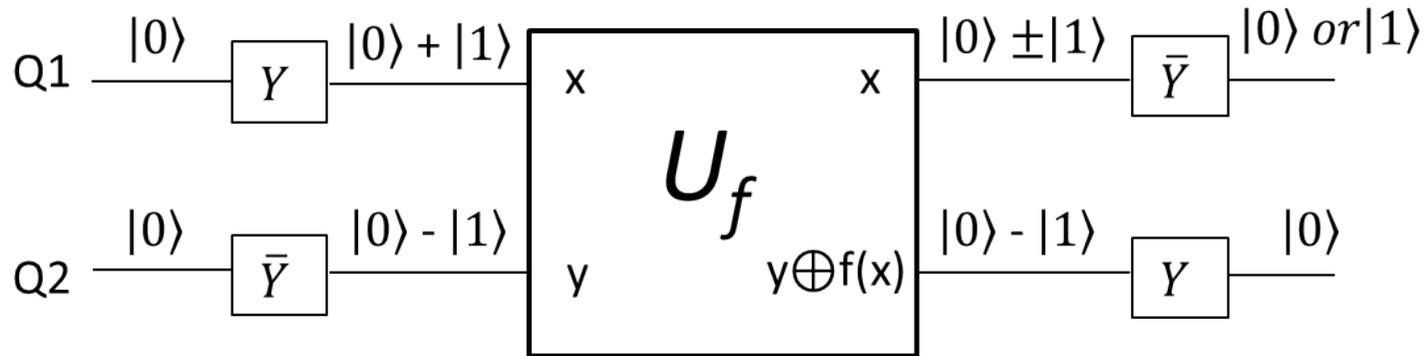
Read-out

Spin-selective tunneling + charge detection



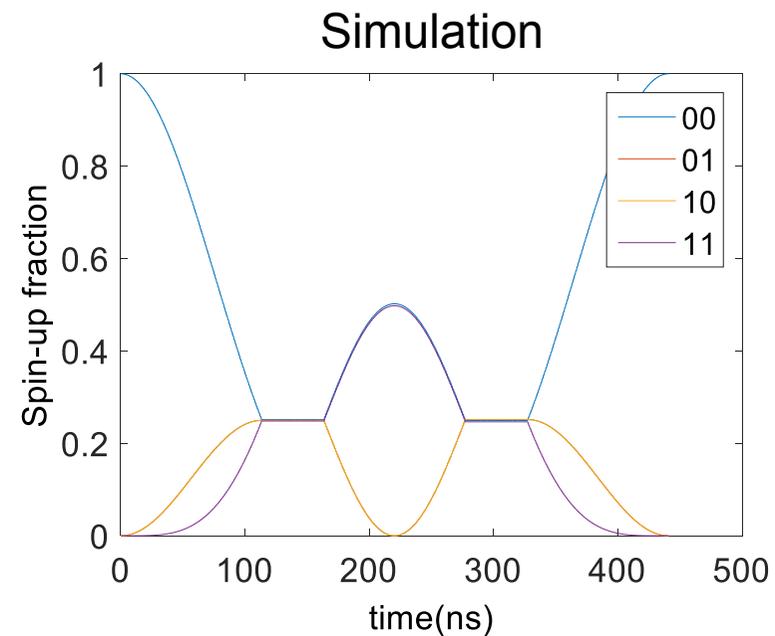
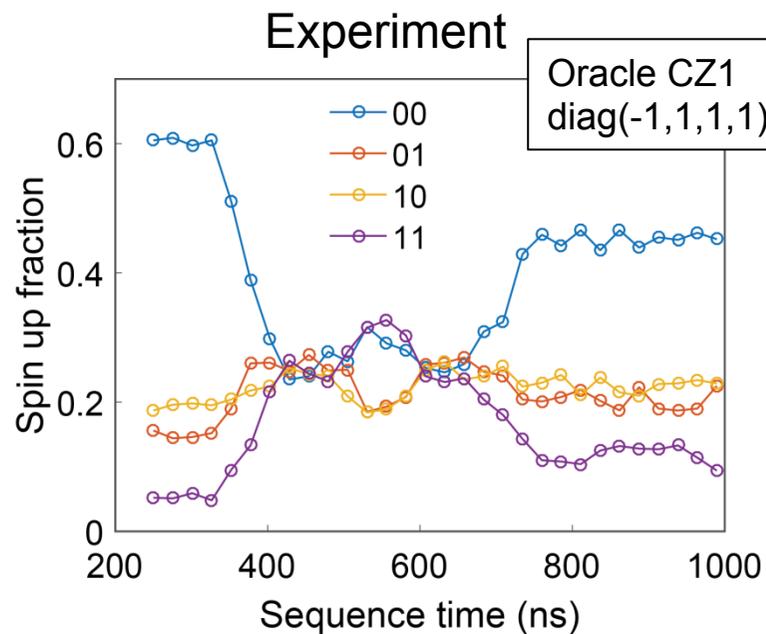
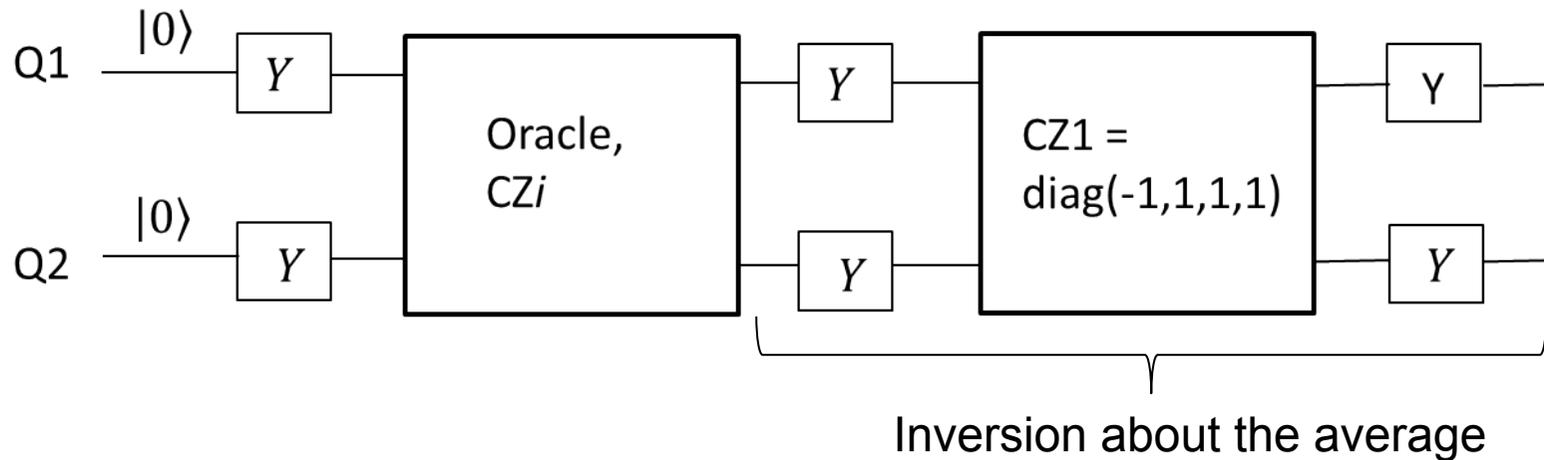
Deutsch-Jozsa algorithm in silicon

T. Watson et al, unpublished

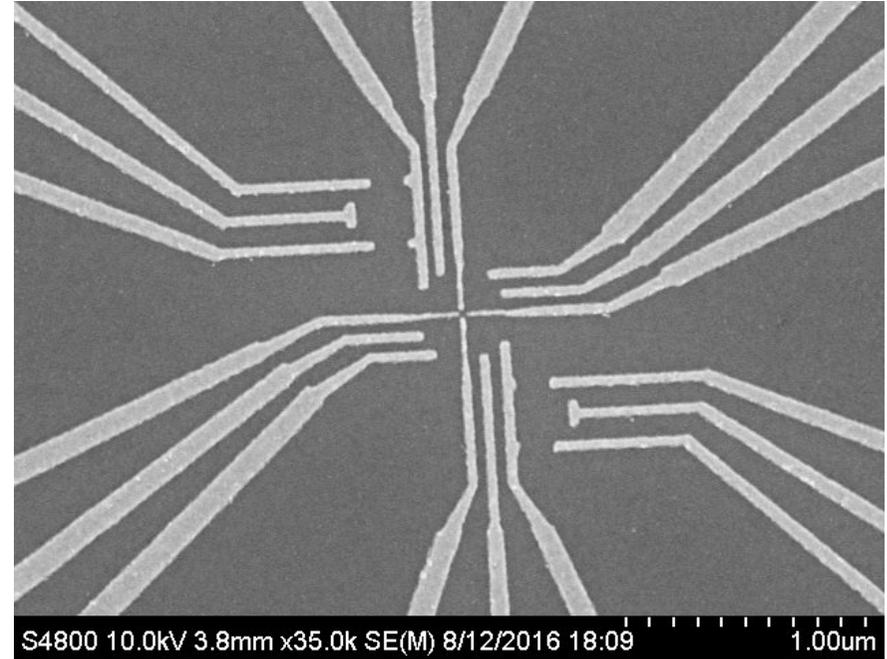
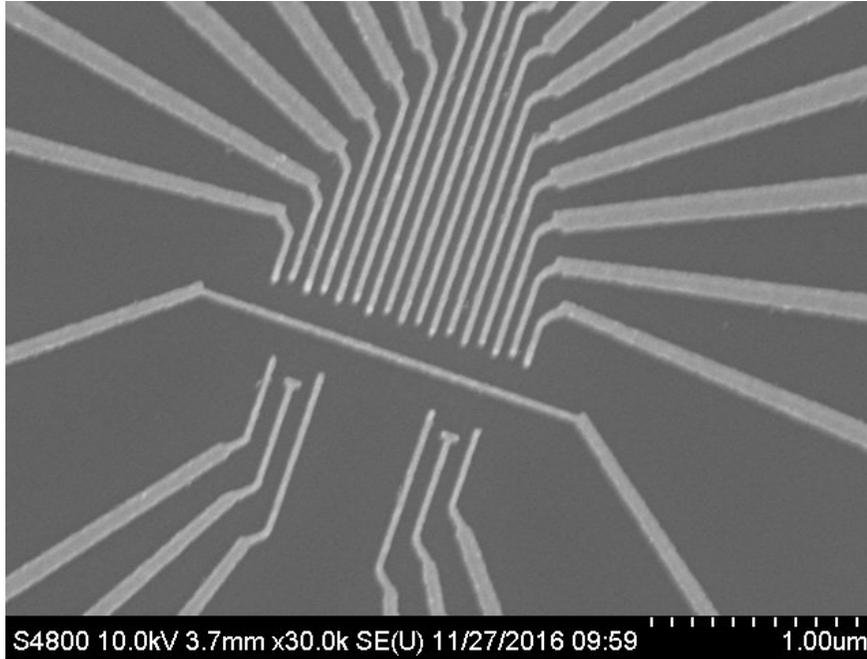


Grover's algorithm in silicon

T. Watson et al, unpublished



Ongoing – 1D and beyond

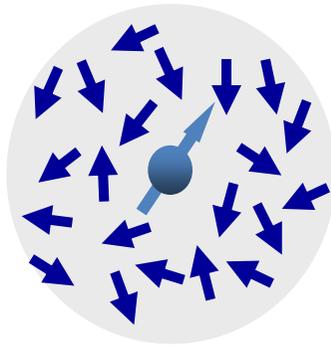


U. Mukhopadhyay, J.P. Dehollain

We can now program and read out
electron spin qubits
in silicon all-electrically

Advance 2: Extending quantum coherence

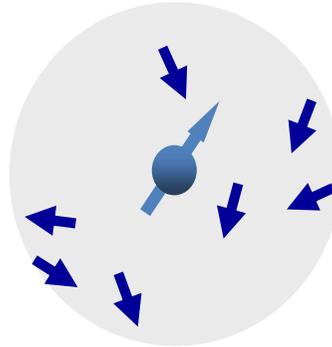
GaAs



$$T_2^* \sim 0.01 \mu\text{s}$$
$$T_2^{\text{DD}} < 0.2 \text{ ms}$$

Petta et al,
Science 2005

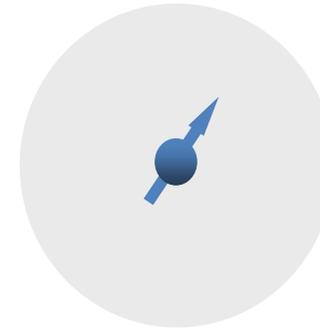
Si



$$T_2^* \sim 1 \mu\text{s}$$
$$T_2^{\text{DD}} > 0.5 \text{ ms}$$

Kawakami, Scarlino, et al,
Nature Nano 2014

^{28}Si

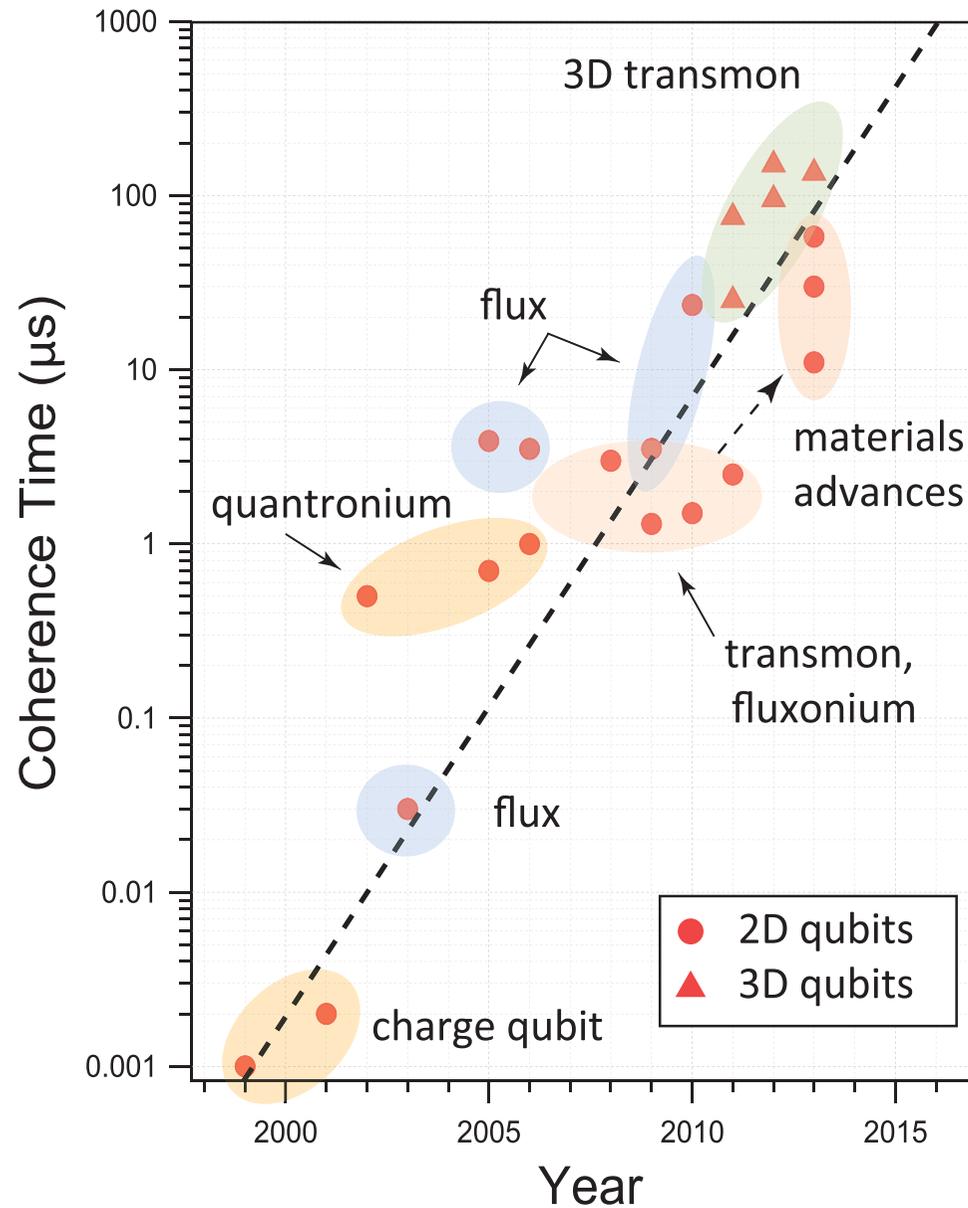


$$T_2^* \sim 100 \mu\text{s}$$
$$T_2^{\text{DD}} \sim 28 \text{ ms}$$

Veldhorst, et al,
Nature Nano 2014

Quantum state lifetimes boosted by four orders of magnitude

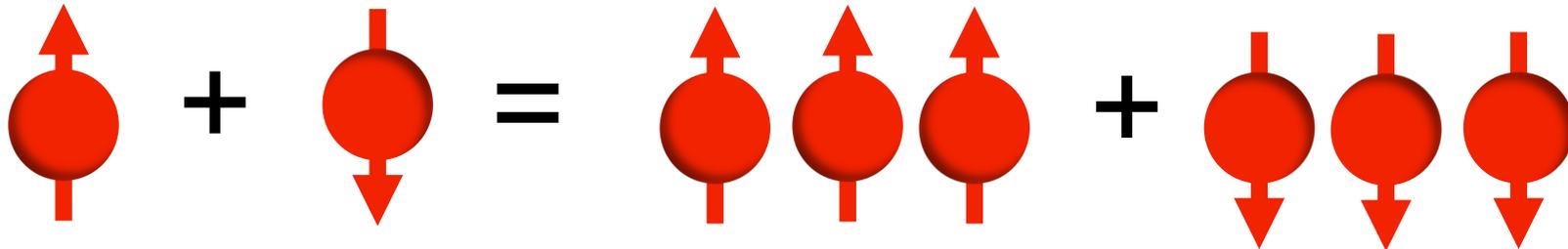
Coherence for superconducting qubits



Oliver and Welander,
MRS Bulletin 2013

Advance 3: Quantum error correction

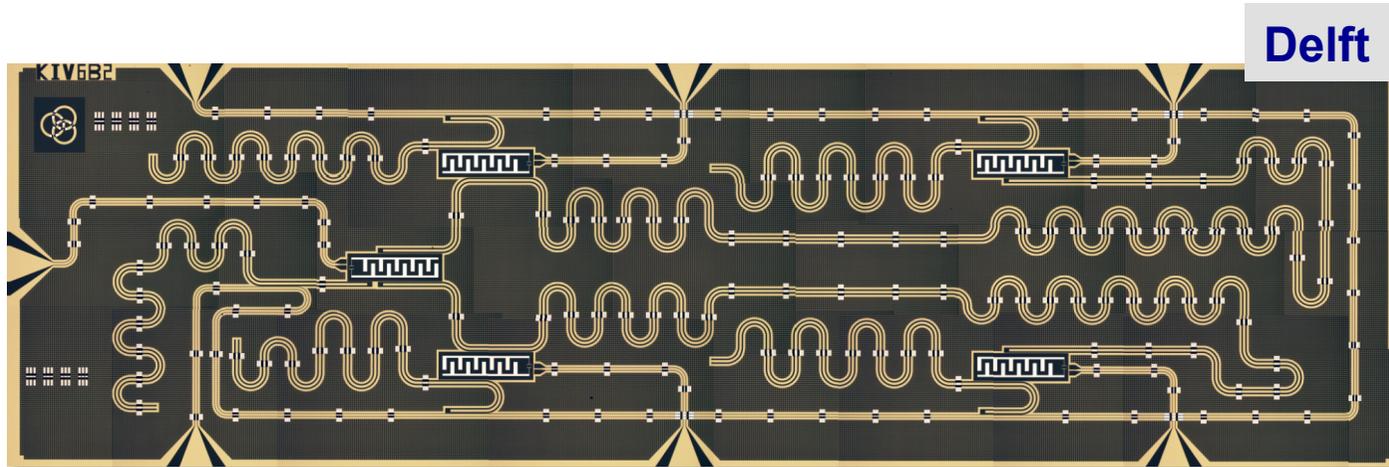
Use redundancy to remove errors faster than they occur



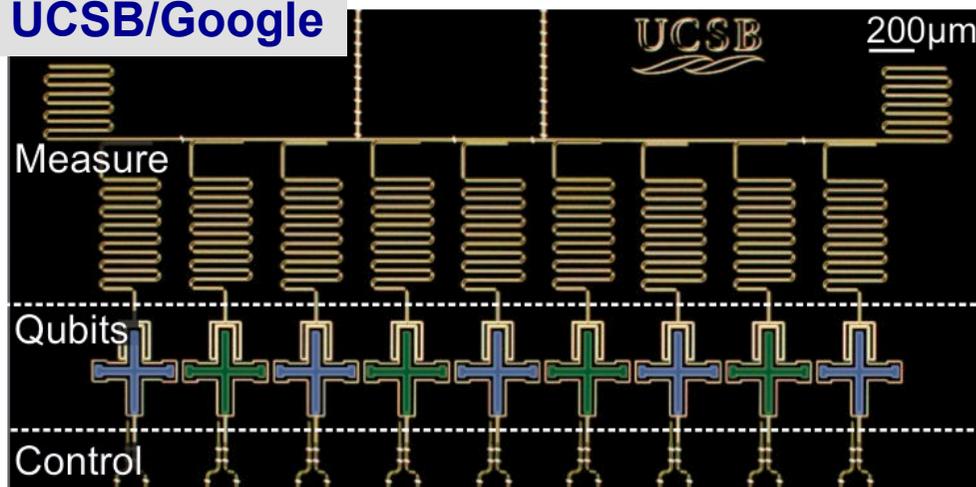
Requires: error probability per step below 1% (previously below 0.01%)
large redundancy (100x to 10,000x)

Can preserve quantum states for as long as is needed!

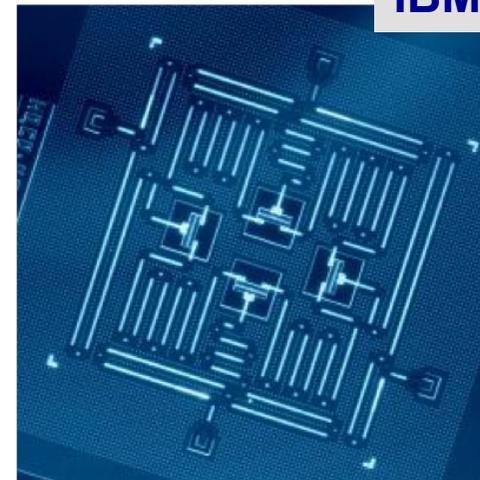
Quantum error correction demonstrated using superconducting qubits



UCSB/Google

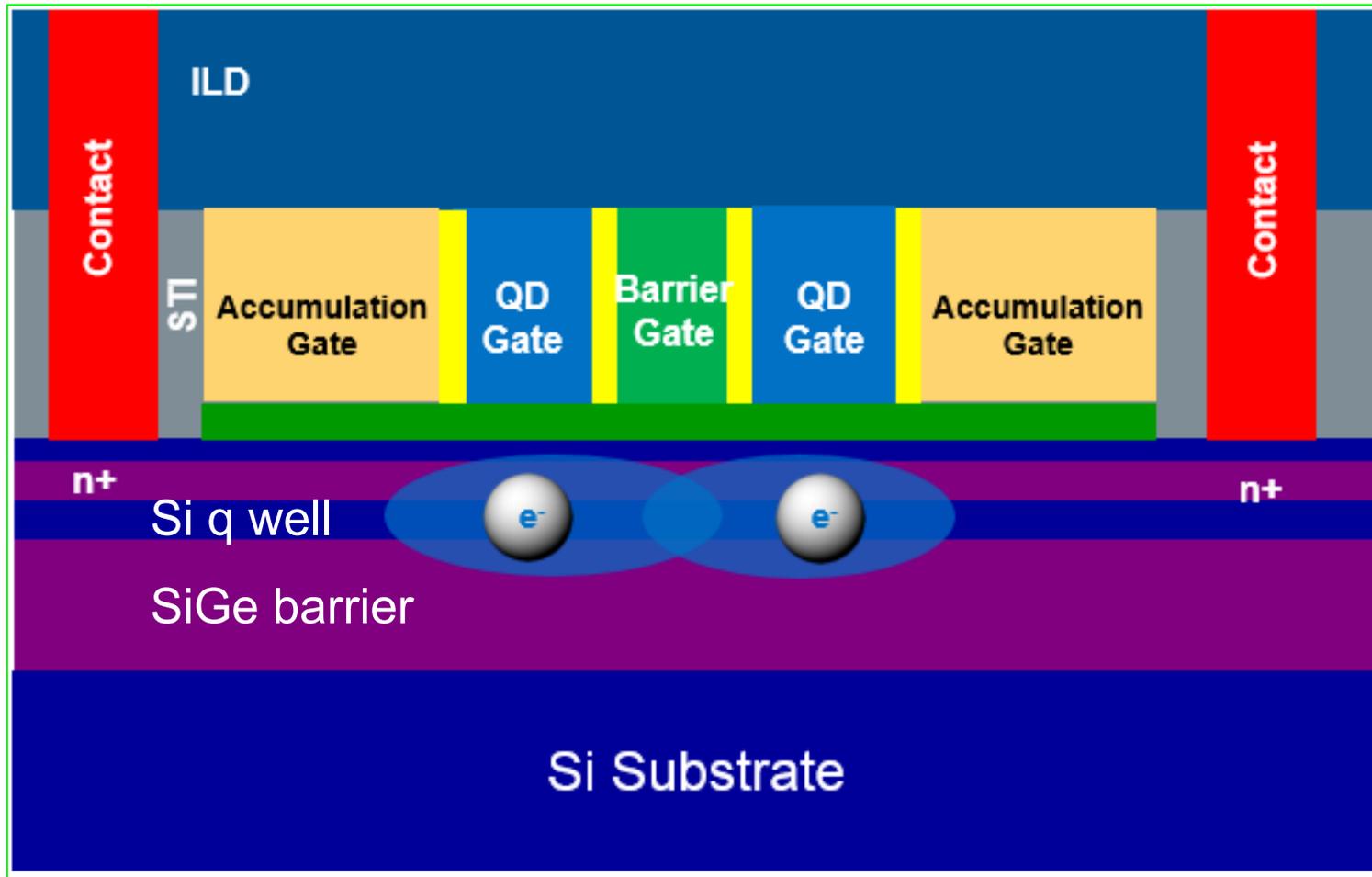


IBM



What stops us from having
a quantum computer today?

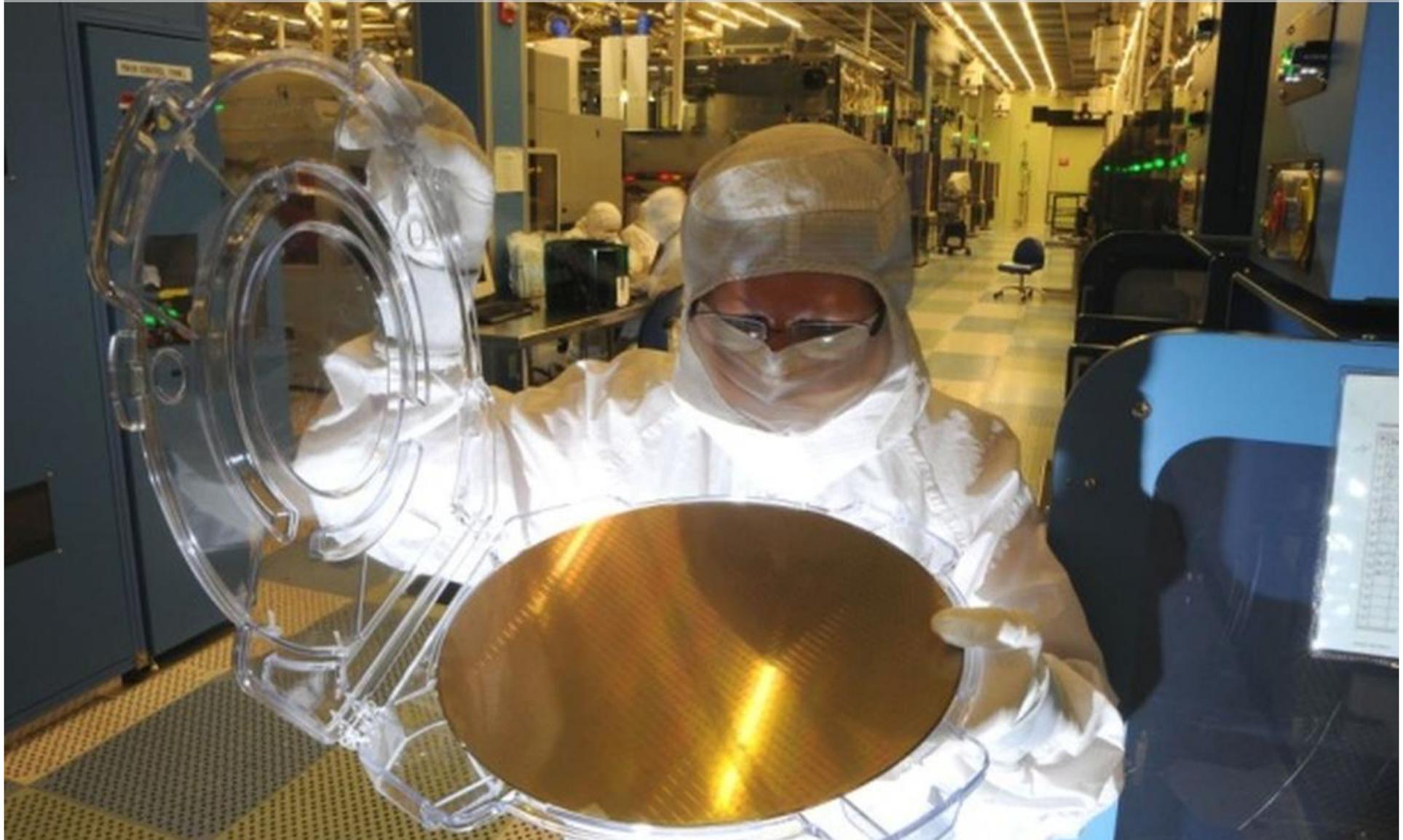
Challenge 1: Qubits have personalities



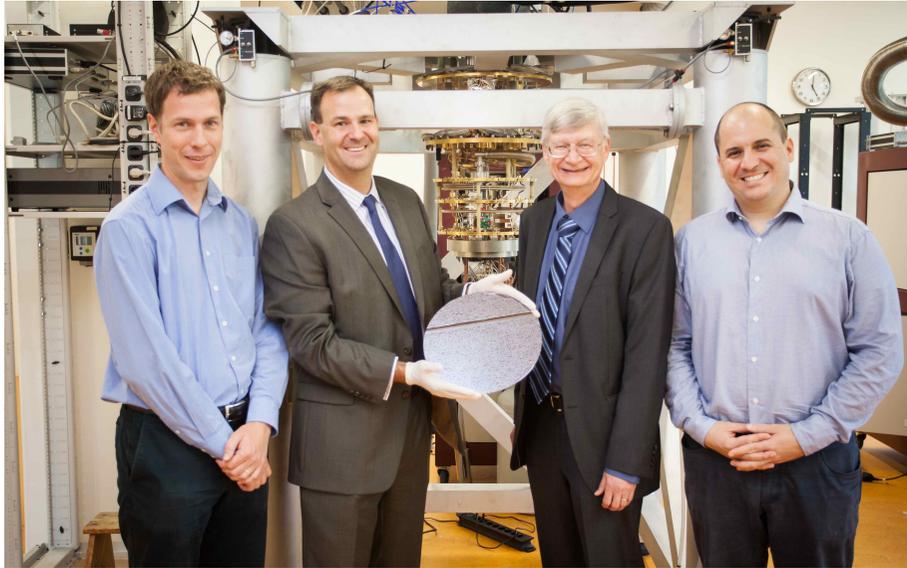
Qubit is much more sensitive to CD variations, scattering, defects, charge noise and even nuclear spins

Way forward 1: Use industry cleanrooms

Tailor-made devices and circuits. Leverage known processes



QuTech-Intel collaboration



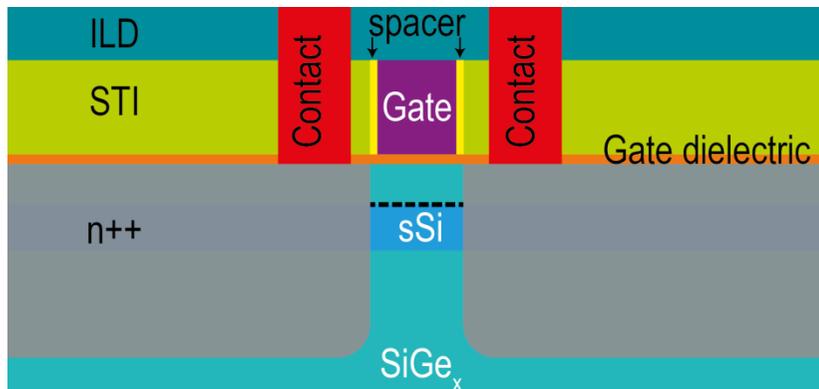
10 years, 50 M\$

Silicon spin qubits
Transmon qubits

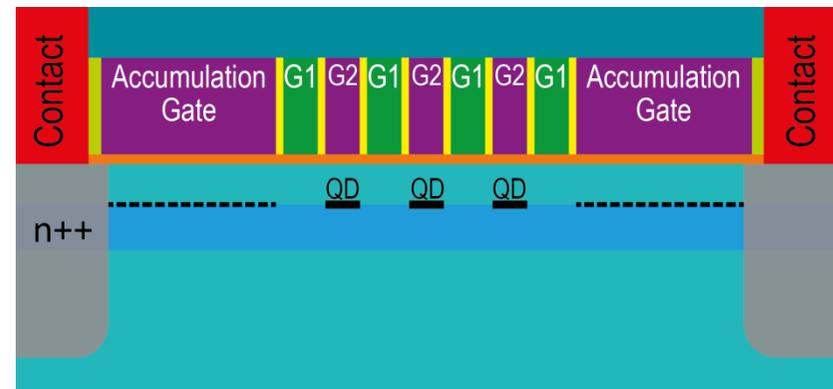
Architecture, Cryo-CMOS,
interconnects

Coming this year: quantum dot arrays made @ Intel 300 mm cl

Transistor: 1 gate / 1 device

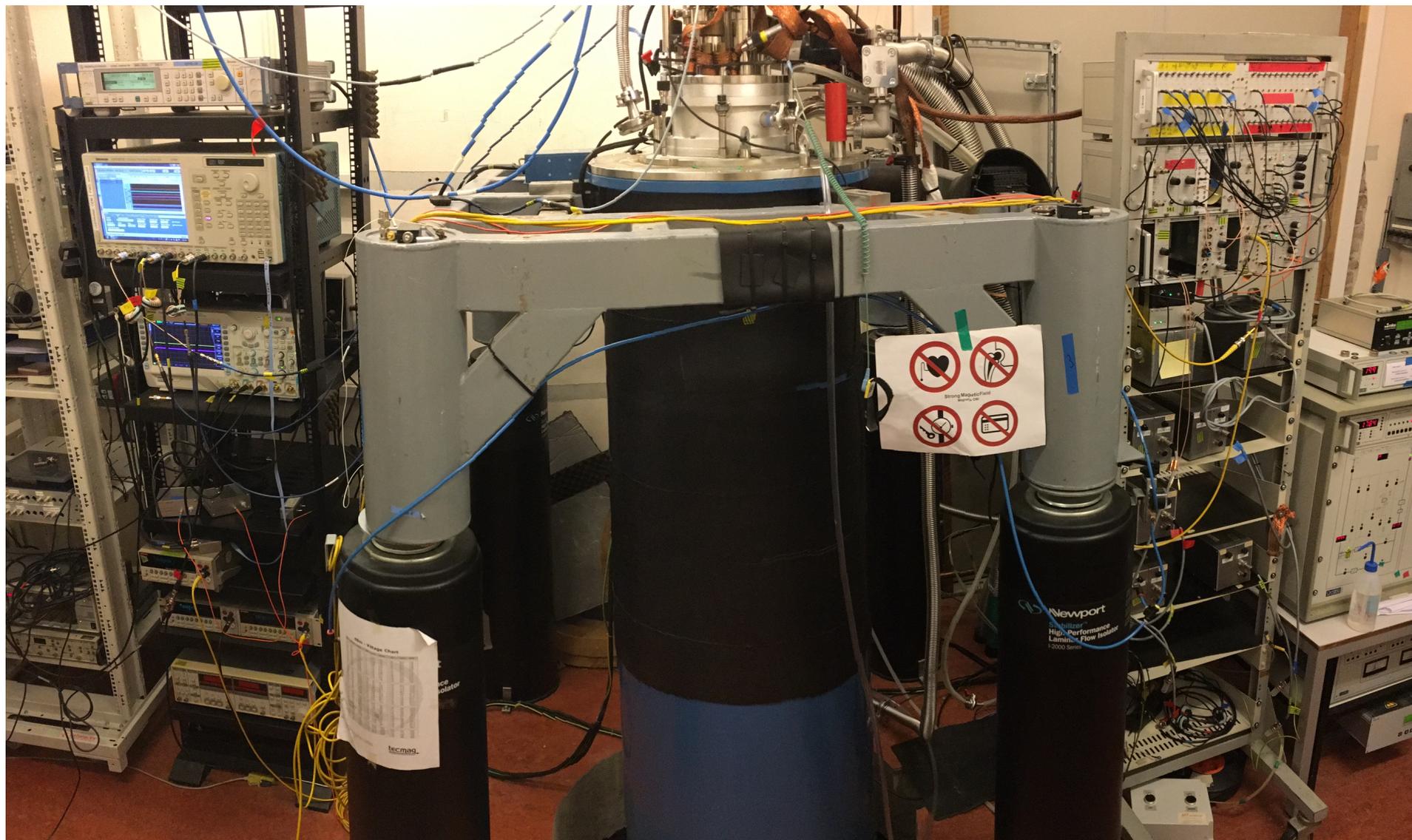


QDots: $2N+3$ gates / N devices



Challenge 2: Scalable control circuits

Today: bulky, expensive equipment



Way forward 2 : Tailored (cryo-)electronics

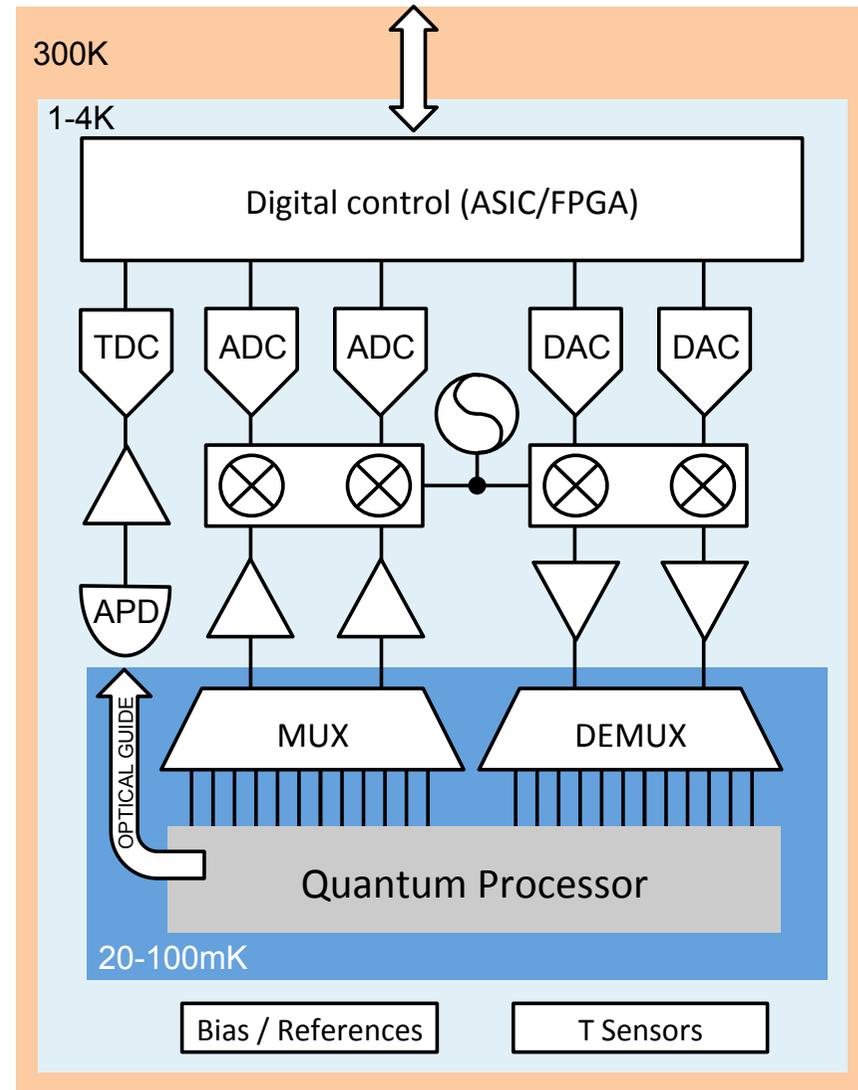
Integrated electronics
1% accuracy in all parameters

60 K



4 K
2 W

100 mK
0.5 mW



E. Charbon et al., "Cryo-CMOS for Quantum Computing", IEDM 2016.
See ISSCC 2017, Paper 15.5 (Tuesday)

Challenge 3: Wiring up qubits



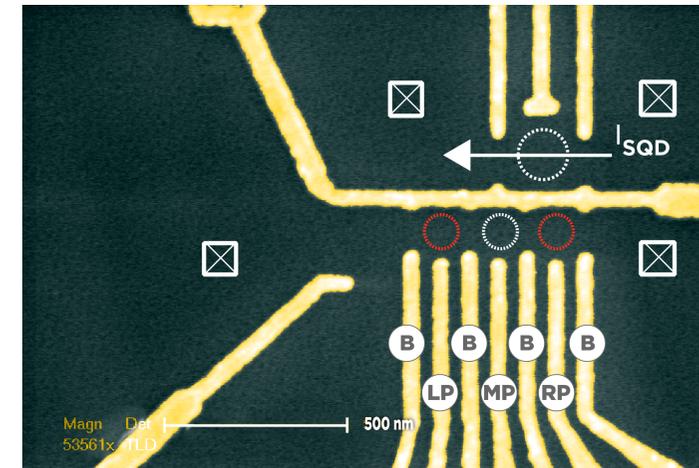
Processor

- 10^9 transistors
- 10^3 pins



Memory

- 10^{12} bytes
- 10^2 pins

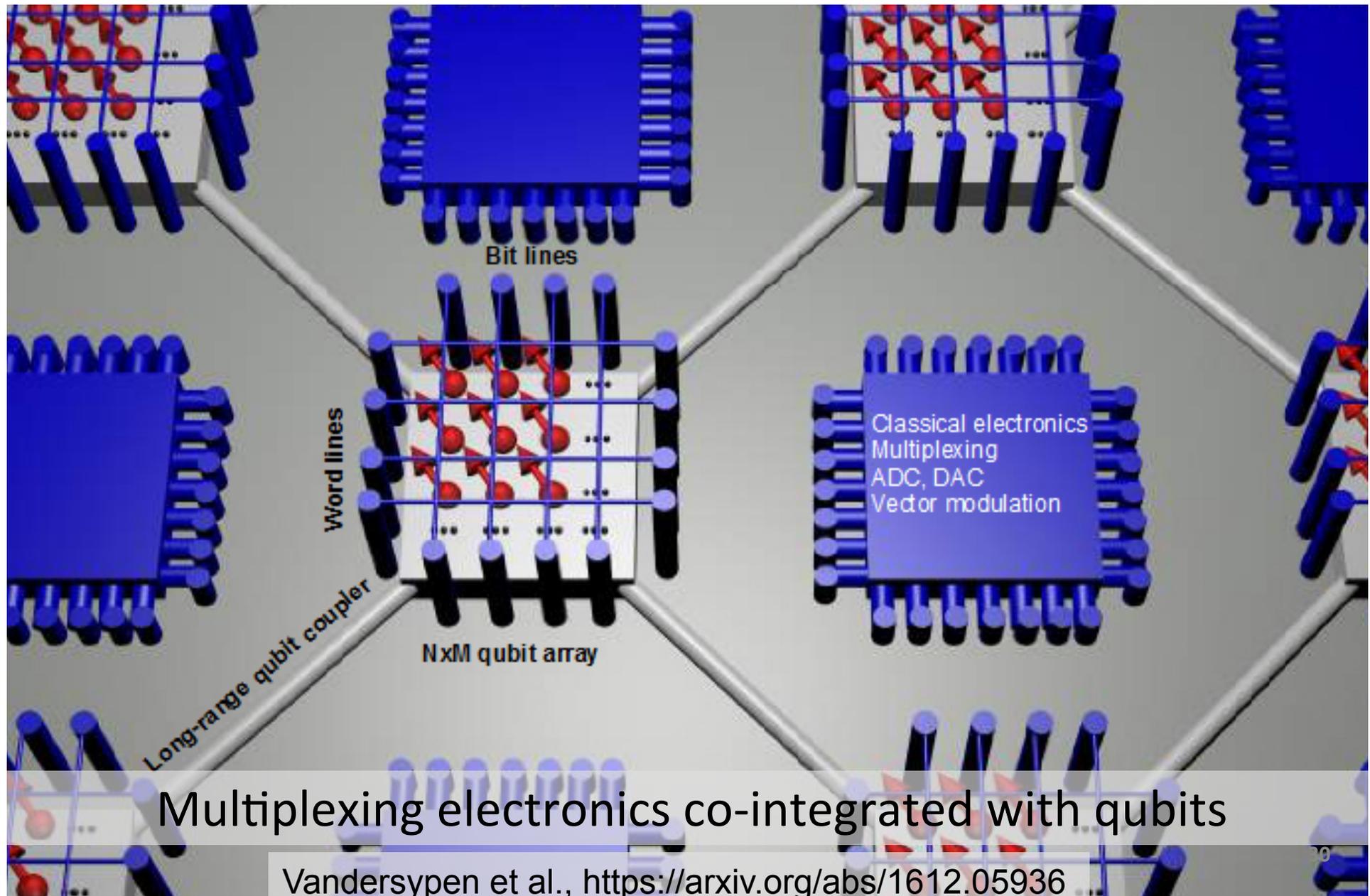


Quantum dots

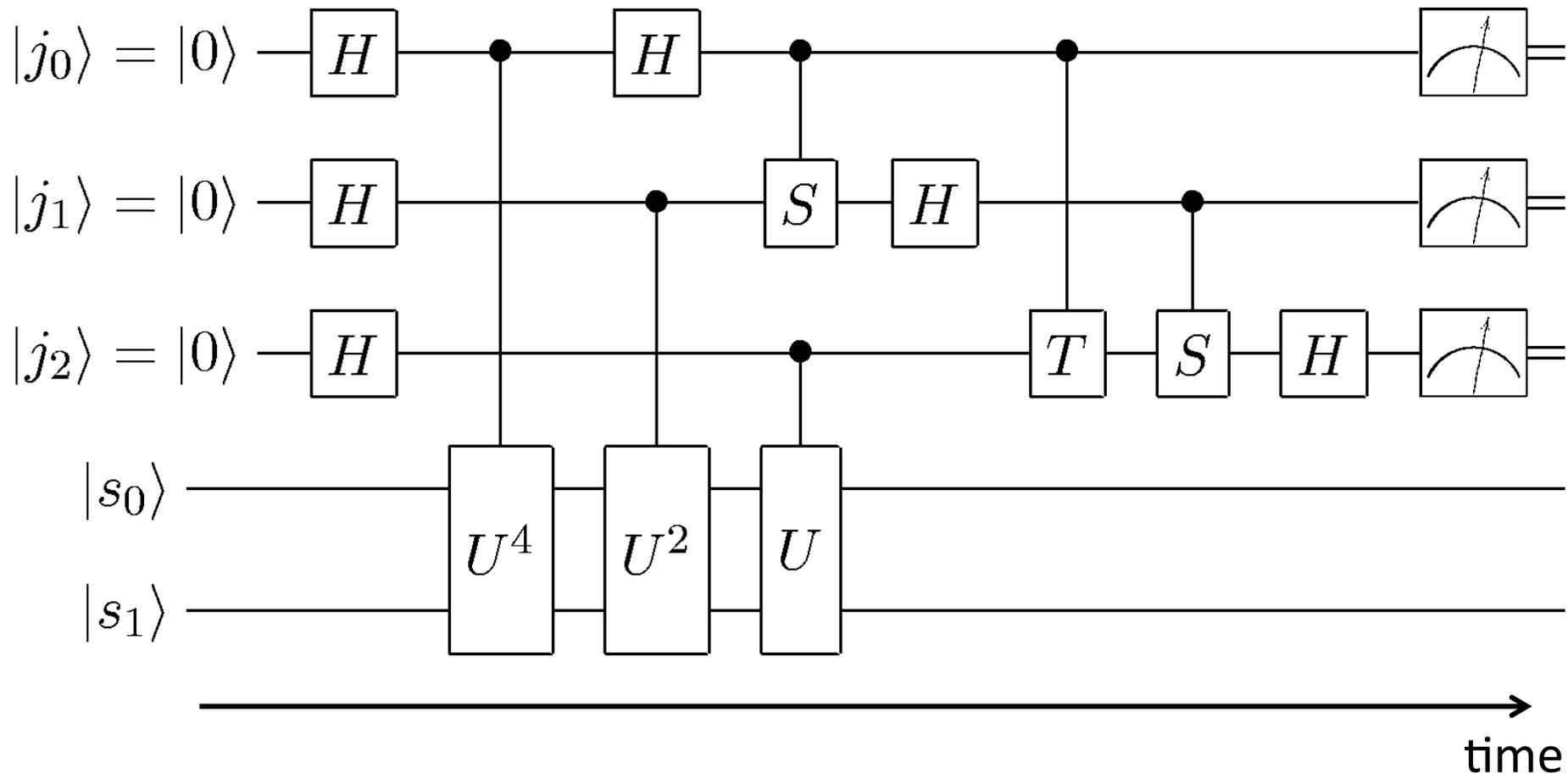
- 3 qubits
- 16 pins

Require signals to/from every single qubit

Way forward 3: Quantum version of Rent's rule



Challenge 4: Architecture



Does not map to any established architecture

Way forward 4: Quantum architecture

The screenshot displays three overlapping windows from a quantum programming interface:

- Open QL Code:** Contains C++-style code for building a Clifford circuit. Key lines include:

```
* build rb circuit
*/
void build_rb(int num_cliffords,
ql::quantum_kernel& k)
{
  assert((num_cliffords%2)
  int n = num_cliffords/2,

  cliffords_t cl;
  cliffords_t inv_cl;

  // add the clifford and its reverse
  for (int i=0; i<n; ++i)
```
- QASM:** Shows the intermediate assembly code, including instructions like `prepz q0`, `rx90 q0`, `ry90 q0`, `mr90 q0`, and `display`. A file selection dialog is visible at the bottom with the text "Choose File No file chose".
- QuMIS:** Shows the final low-level instructions, such as `trigger 10010000, 2`, `wait 2`, and `trigger 00100000, 2`. Another file selection dialog is visible at the bottom with the text "Choose File No file chosen".

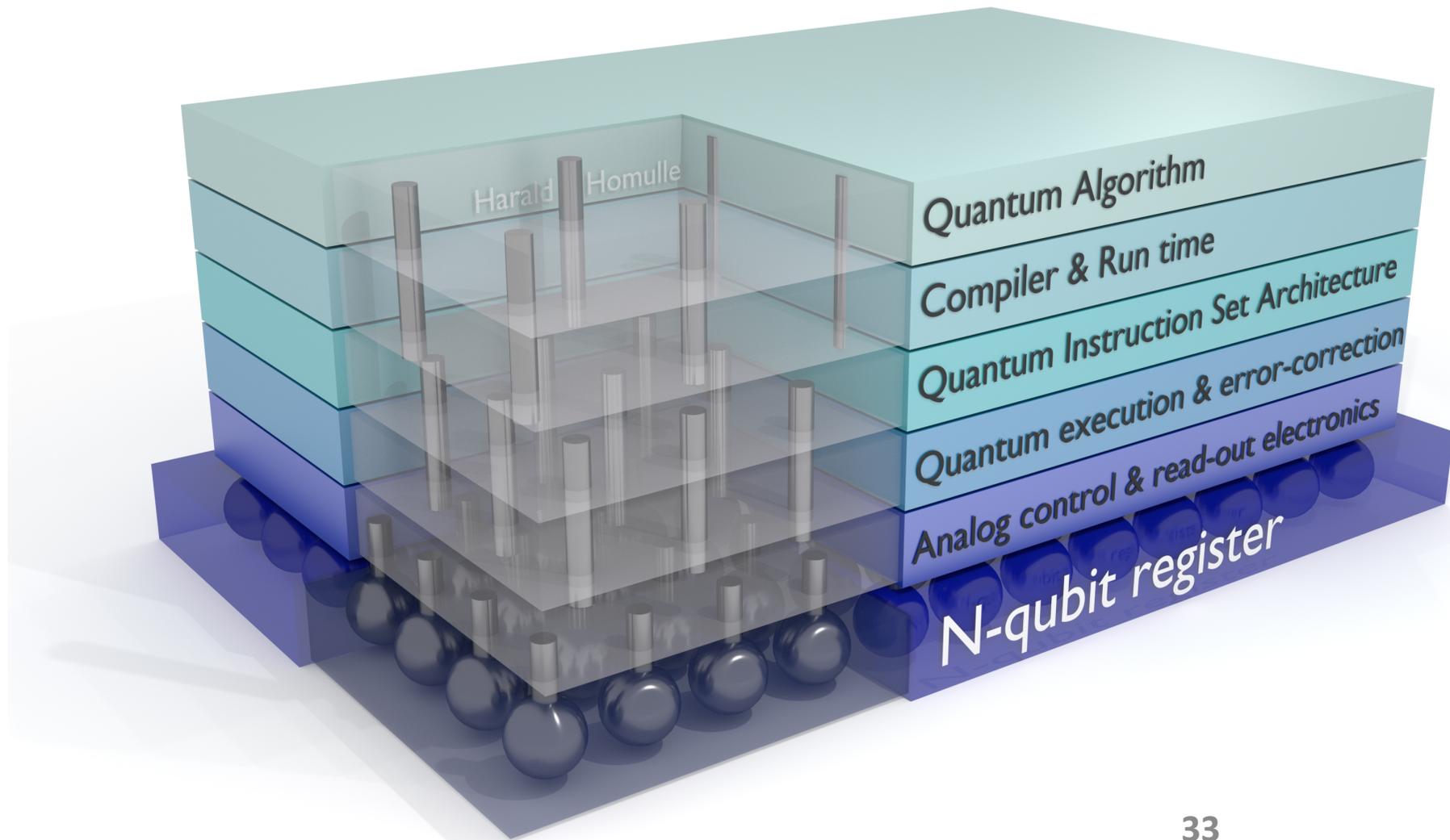
A blue arrow points from the OpenQL code window to the QuMIS window, with the text "Compile to low-level instructions" written along it.

Recycle ideas where possible
Rethink where needed

Systems approach needed

Challenges in each layer

Layers are highly interrelated

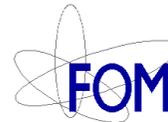


QuTech partnership @ Delft

Quantum technology will not be built by physicists alone



With support from:



5 engineering faculty, 5 physics faculty

20 senior scientists

20 technicians

10 administrative staff

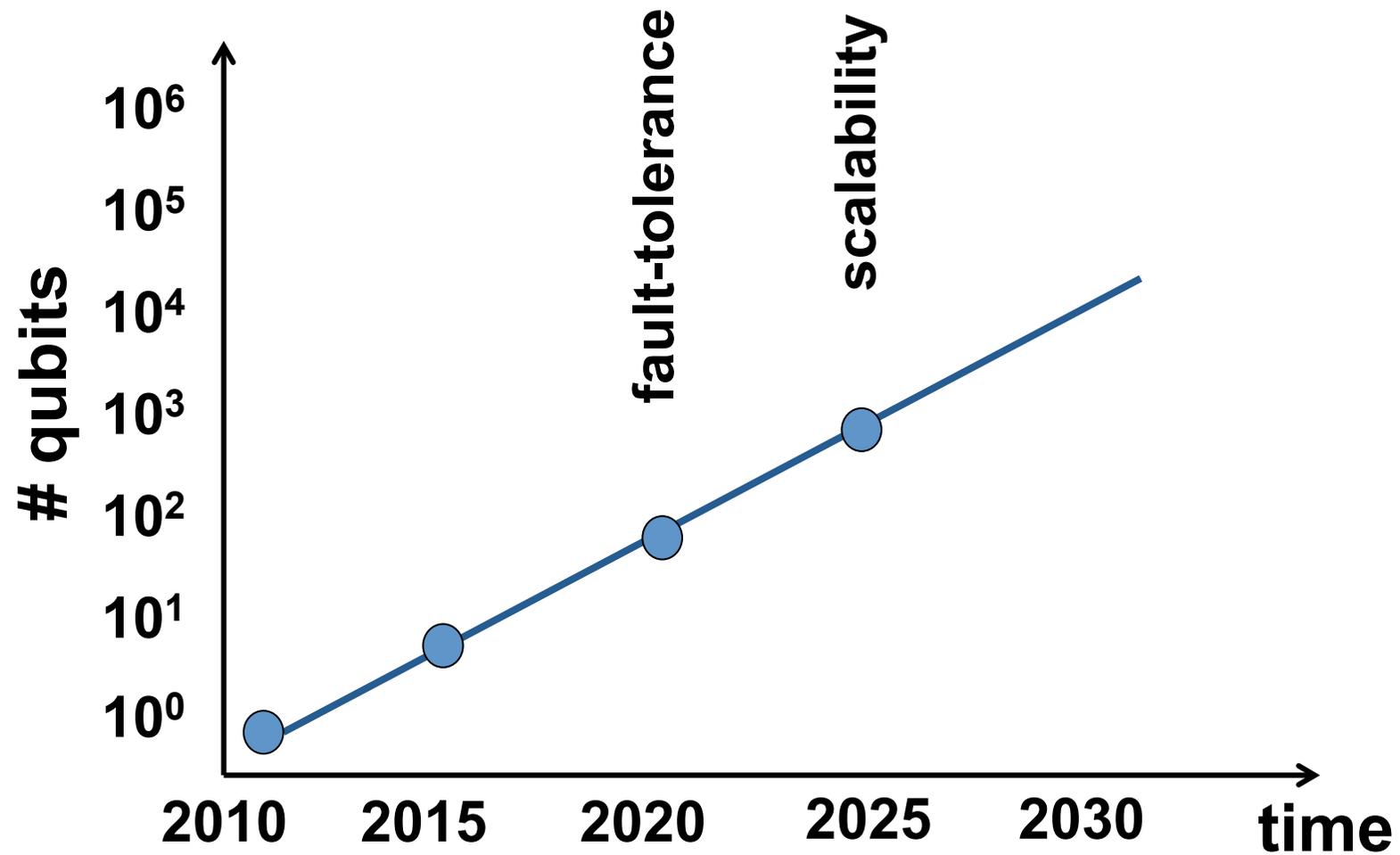
building renovation, nanofab facilities, equipment

PhD students and postdocs to be funded through external sources

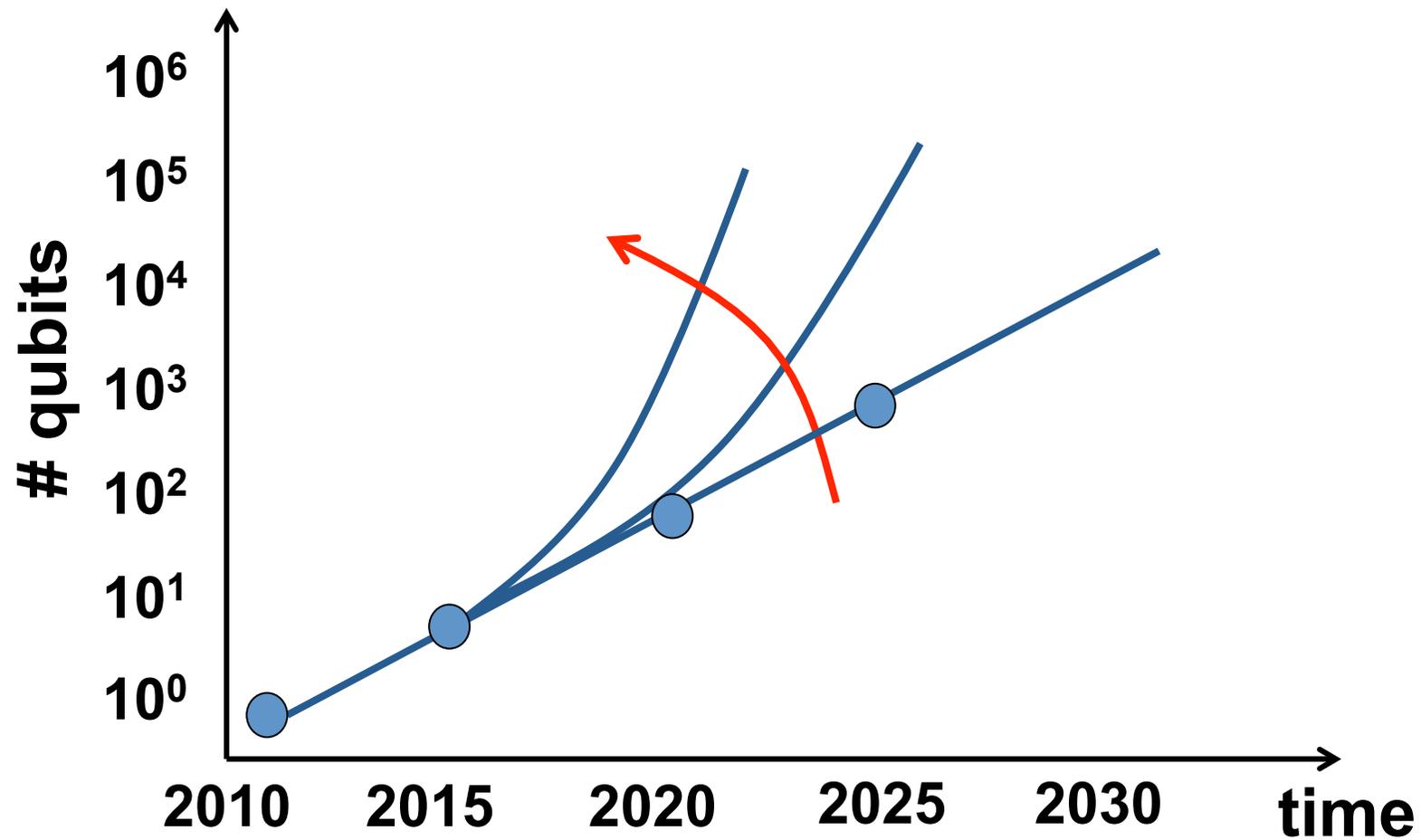


Requires a team effort

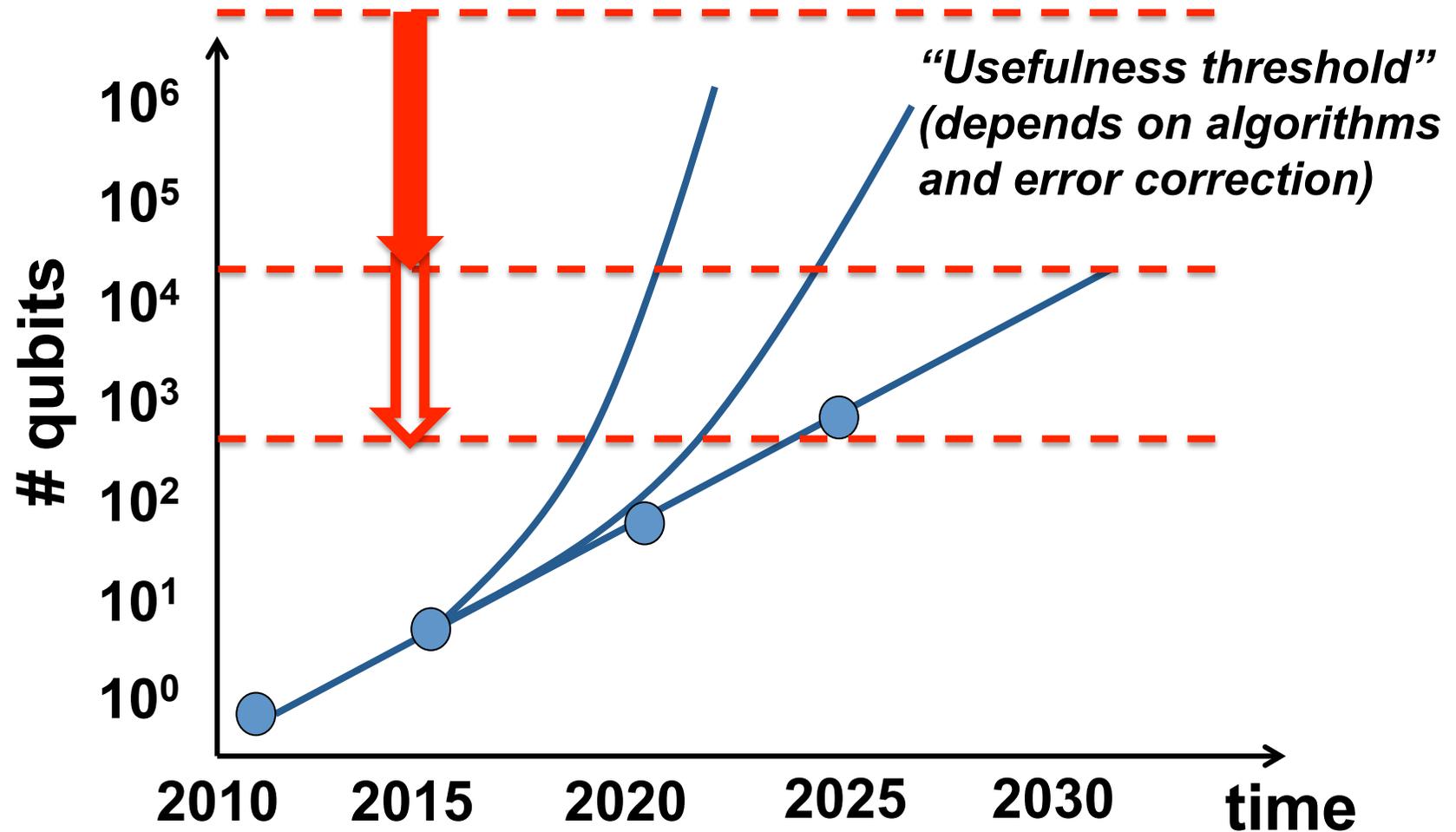
Projecting quantum progress



Can we accelerate hardware development?



Can we accelerate software development?



IBM Quantum Experience

Accessible to anyone through the cloud

The screenshot displays the IBM Quantum Experience interface. At the top, there are navigation tabs: "er Guide", "Composer", and "My Scores". The "Composer" tab is active. In the top right corner, it says "Standard User, Units: 76".

The main area shows a quantum circuit titled "Name: 'Hash cracking with Grover's Algorithm'" and "Real Quantum Processor". The circuit has five qubits, labeled Q_0 through Q_4 , all initialized to $|0\rangle$. The circuit is as follows:

- Q_0 : No operations.
- Q_1 : H gate, S gate, CNOT (control on Q_1 , target on Q_2), S gate, H gate, X gate, CNOT (control on Q_1 , target on Q_2), X gate, H gate, MEASURE.
- Q_2 : H gate, S gate, H gate, CNOT (control on Q_2 , target on Q_1), H gate, S gate, H gate, X gate, H gate, CNOT (control on Q_2 , target on Q_1), H gate, X gate, H gate, MEASURE.
- Q_3 : No operations.
- Q_4 : No operations.

At the bottom, there is a "GATES" palette with the following options: Id (orange), X (green), Z (green), Y (green), H (blue), S (blue), S^\dagger (blue), CNOT (blue circle with +), T (orange), T^\dagger (orange), MEASURE (pink), and another MEASURE (pink).

The quantum computer – Coming to stores near you (soon?)





<http://qutech.nl/vandersypenlab>

