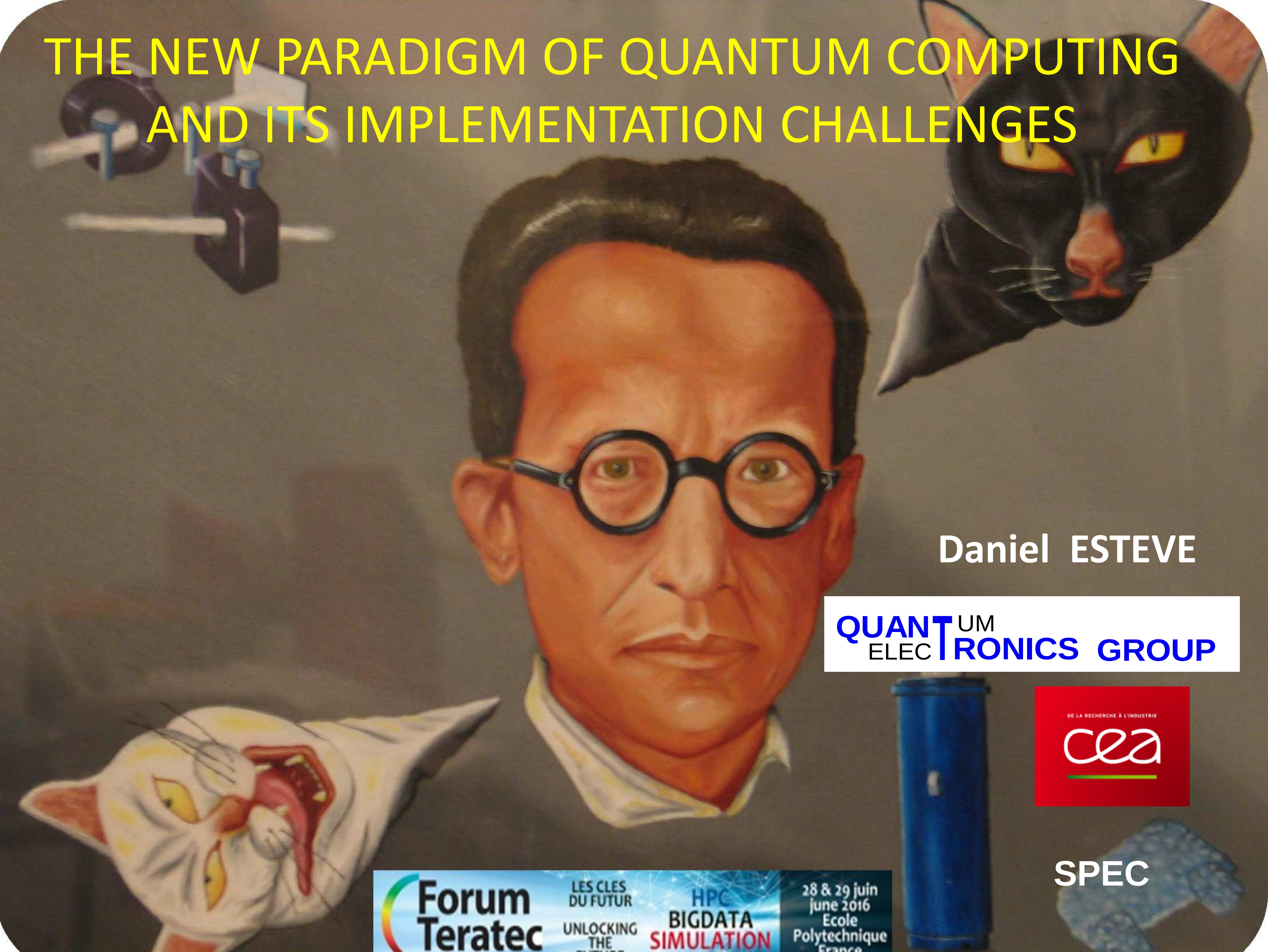
THE NEW PARADIGM OF QUANTUM COMPUTING AND ITS IMPLEMENTATION CHALLENGES



Daniel ESTEVE

QUANTUM ELECTRONICS GROUP

DE LA RECHERCHE À L'INDUSTRIE cea

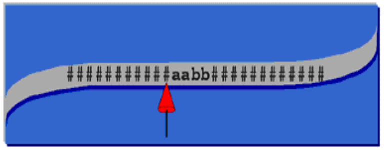
SPEC

Forum Teratec LES CLES DU FUTUR UNLOCKING THE FUTURE HPC BIGDATA SIMULATION 28 & 29 juin june 2016 Ecole Polytechnique France

A striking discovery: algorithmic complexity is physics, not pure mathematics

A.Turing

the universal Turing machine



Church-Turing thesis

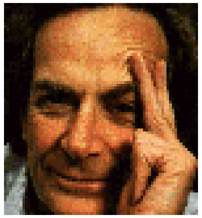
J. v. Neumann

sequential computing

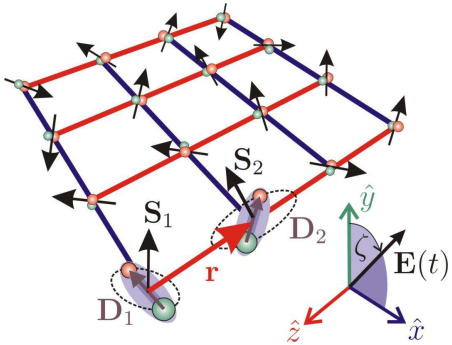
Complexity classes

P, NP

R. Feynman

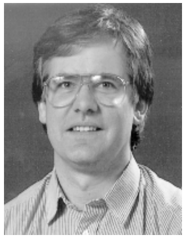


1982:
quantum simulator
needed for simulating
quantum systems



D. Deutsch

R. Jozsa



1985
Quantum algorithms
can be more powerful than
classical algorithms !

Hardware matters!
quantum harware more powerful than classical hardware

Quantum Computing in an nut

quantum bit: two basis states $|0\rangle$ $|1\rangle$

any arb. superposition is a possible state

$$|q_b\rangle = \alpha|0\rangle + \beta|1\rangle$$

quantum register : set of quantum bits

a N qubit register R has 2^N basis states

$$|0,0,0,\ldots 0\rangle, |1,0,0,\ldots 0\rangle, \ldots. |1,1,1,\ldots 1\rangle$$

any arb. superposition of basis states can exist

The register of a quantum processor evolves by applying quantum gates to qubits

QM being linear the evolution can be massively parallel

I X > + I X > + I X> + ... → U → U I X > + U I X > + U I X> + ...

But readout only delivers a N bit answer

Quantum Computing in an nut

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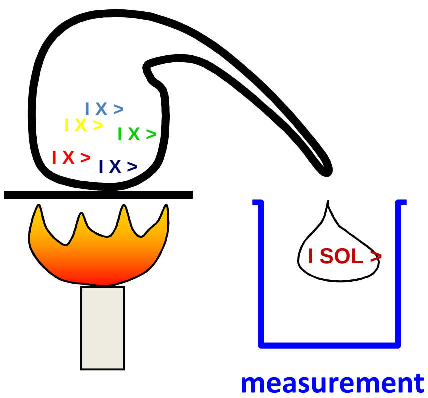
The register of a quantum processor evolves by applying quantum gates to qubits

QM being linear the evolution can be massively parallel

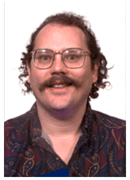
$$|X\rangle + |X\rangle + |X\rangle + \ldots \rightarrow \boxed{U} \rightarrow U|X\rangle + U|X\rangle + U|X\rangle + \ldots$$

But readout only delivers a N bit answer

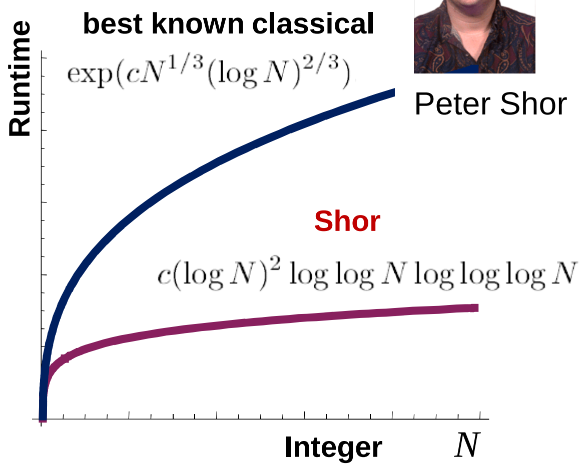
The art of QC:



Factorization algorithm (1994)



Peter Shor



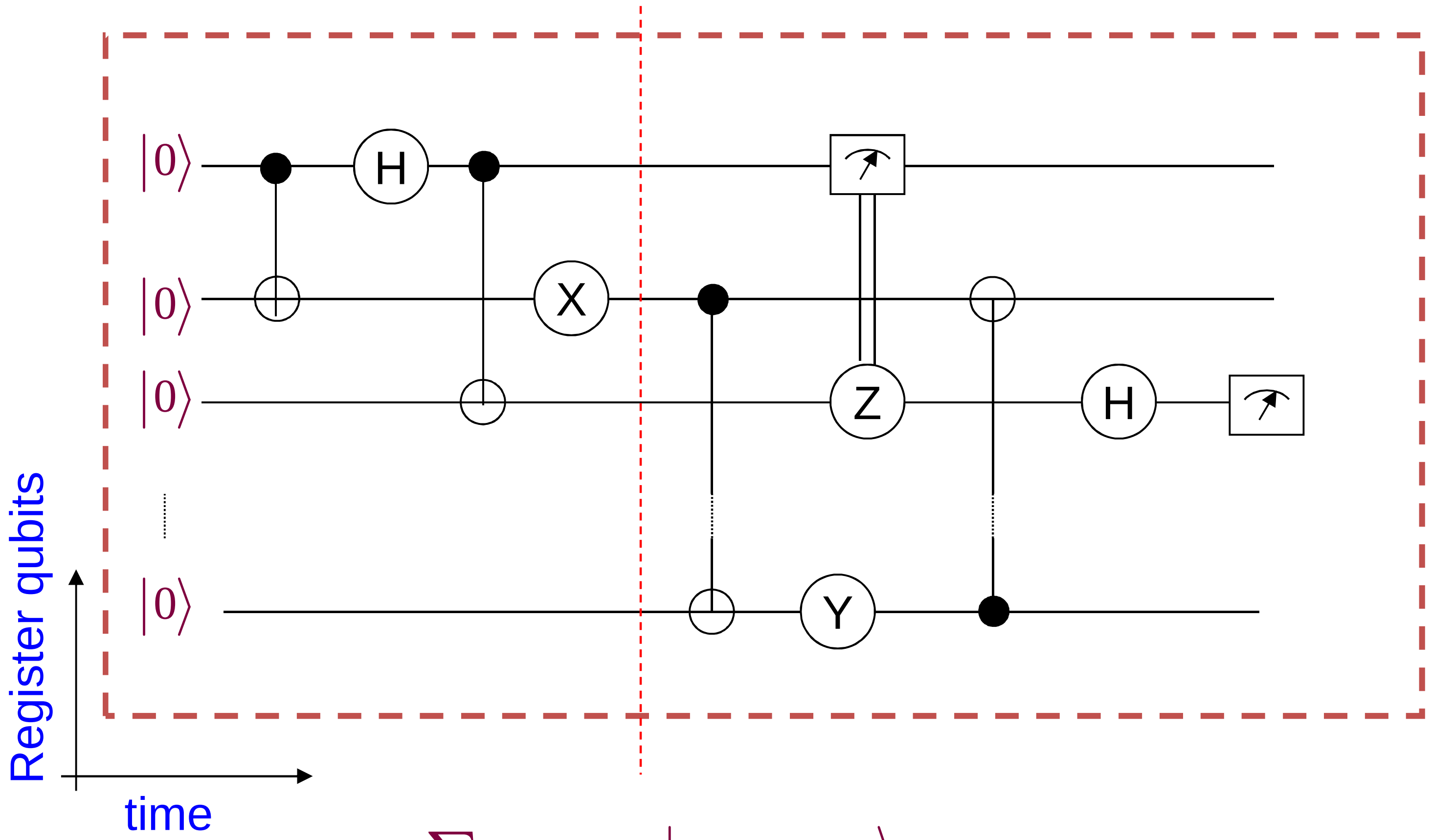
How many qubits for overcoming a classical computer ?

The most advanced classical computers & codes can simulate 45 interacting qubits

A 50-100 ideal qubit qu. computer could overcome classical computers (for some tasks)

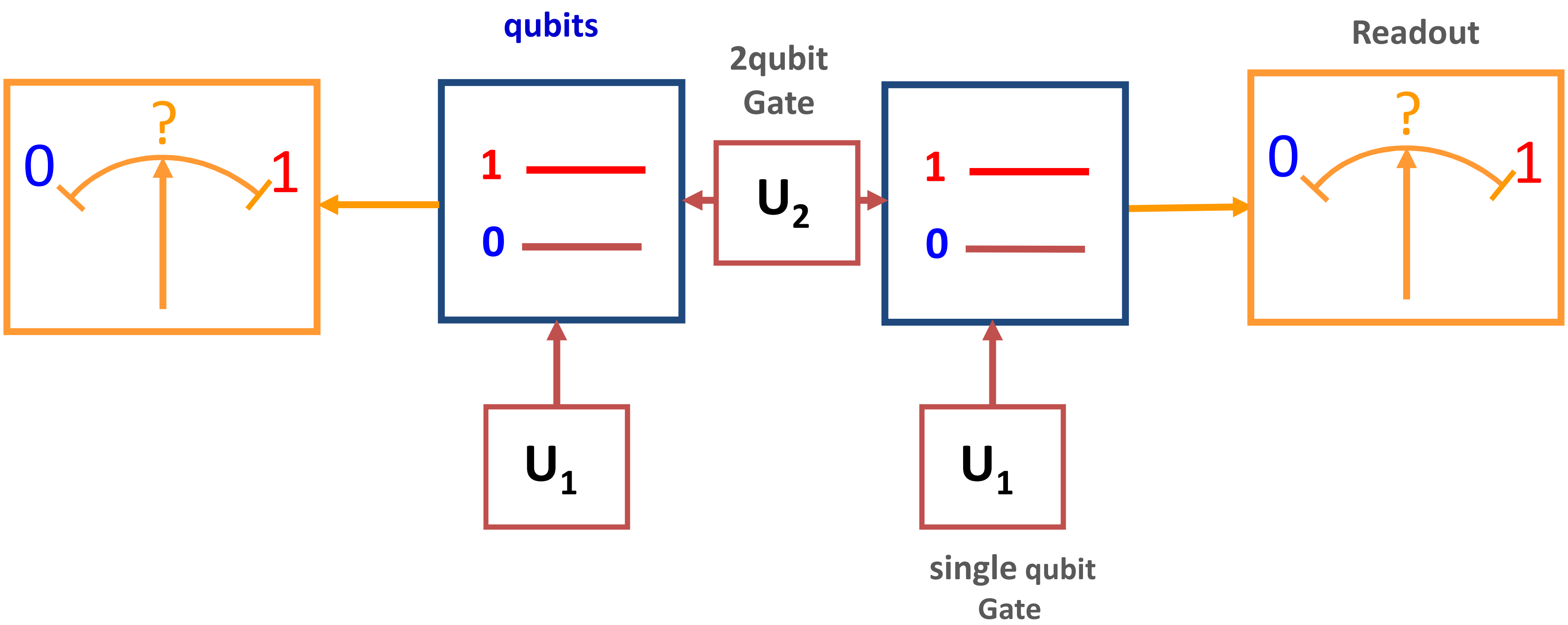
Running a quantum algorithm

- coherent evolution of a quantum register + readouts



$$\sum_{i_k=0,1} a_{i_1 i_2 i_3 i_{4....} i_{2^N}} \left| i_1, i_2, i_3 ... i_{2^N} \right\rangle$$

Blueprint of a quantum processor based on quantum gates



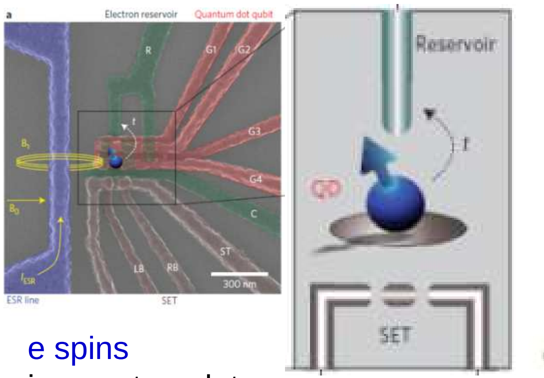
Huge Scalability challenges:

Hifi readout, hifi gates, quantum error correction

Electrical qubit circuits **(in a nut)**

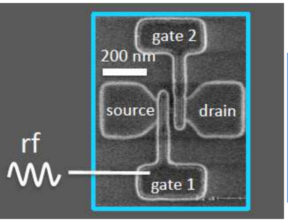
Electron spin states in semiconductor structures

recent breakthrough at U. Of New South Wales (Sydney)

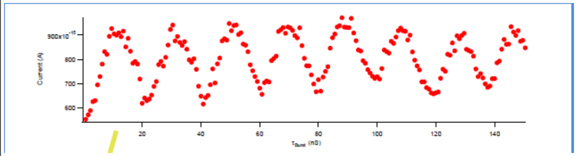


e spins
in quantum dots

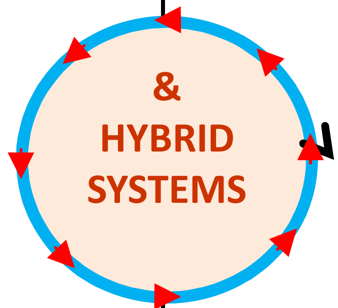
UNSW, TUDelft (+Intel), Harvard,…
And **CEA** (Grenoble)



Ultra-small
CMOS technology



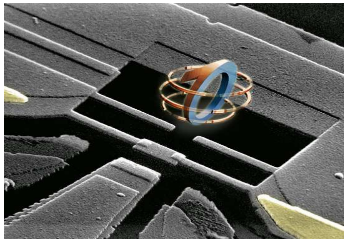
First qubit fabricated on
an **industrial** platform



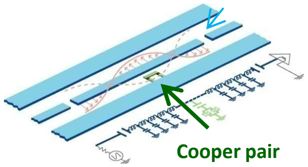
quantum states of superconducting Josephson circuits

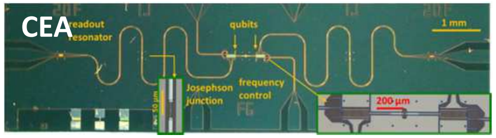
First SC 'Cooper pair box' qubit
(NEC 1999)

functional SC qubit
(CEA 2002)



Modern « in resonator » version (Yale, 2006) :

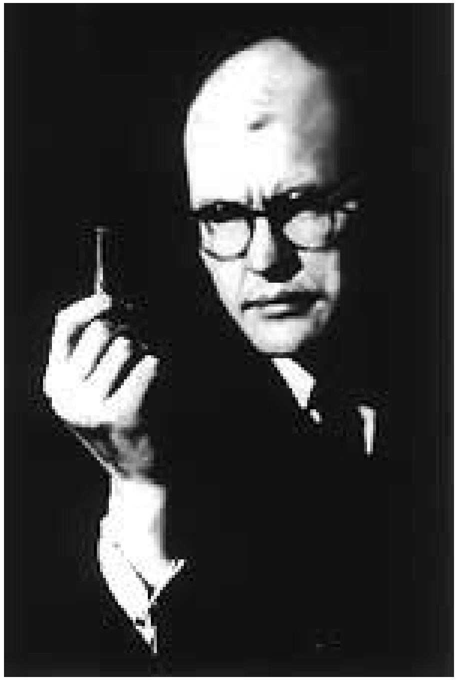




But electrical circuits
are (usually) not quantum !

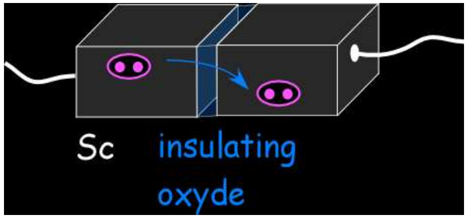
A simple quantum circuit based on the Josephson junction

Jack S. Kilby handling
the first integrated circuit



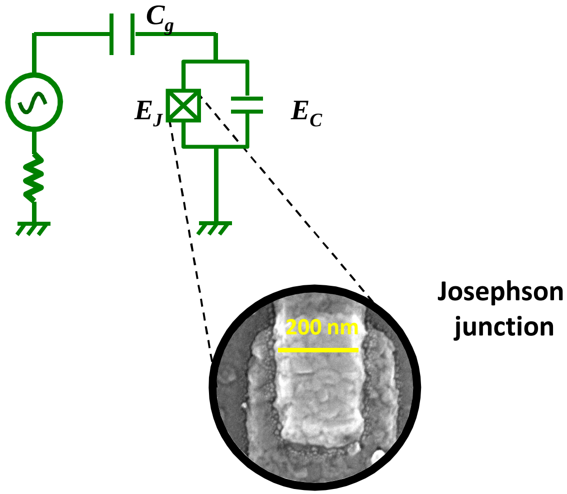
Large # degrees of freedom
and dissipation make electrical
variables classical

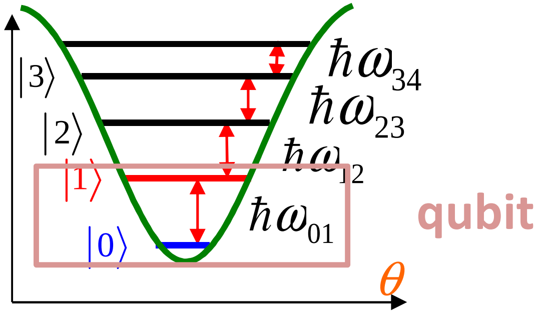
A non dissipative
quantum component:
the **Josephson junction**



A **non-linear inductor**
That can make an
anharmonic resonator

Cooper pair box **qubit** circuit

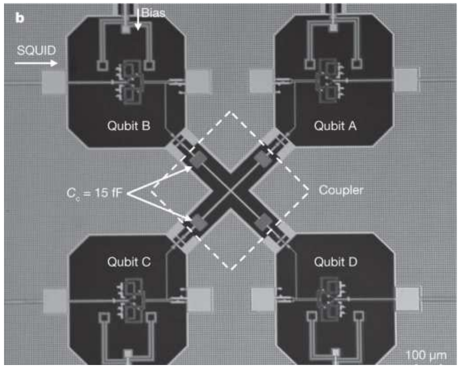




SC quantum processors ?

Elementary **universal** SC quantum processors

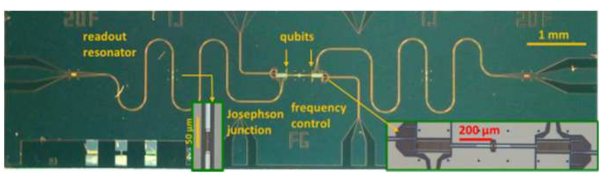
Martinis Lab, UC Santa Barbara
Yamamoto et.al. , PRB 82 2010 , Nat Phys 2012



Shor factorization algorithm
(of 15)

Running the Grover Search algorithm
(on 4 items)

Quantronics, CEA
Dewes et. al., PRL & PRB 2012
Grover Search algorithm
(on 4 items)



Finding the coin by lifting a cup once only

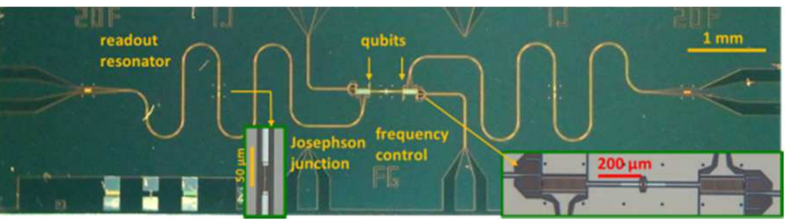
Classical query&check alg. ¼ success / run

Elementary **universal** SC quantum processors

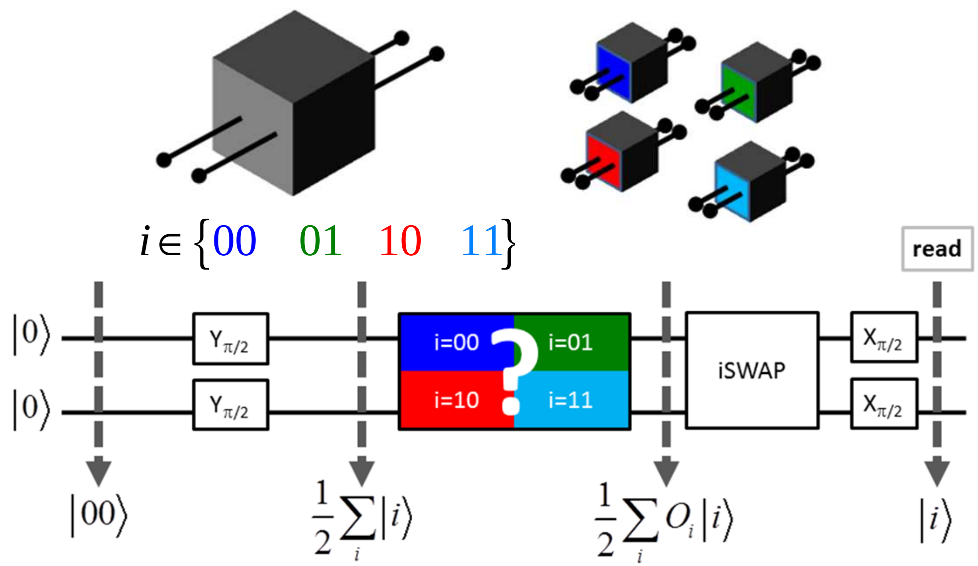
Quantronics, CEA

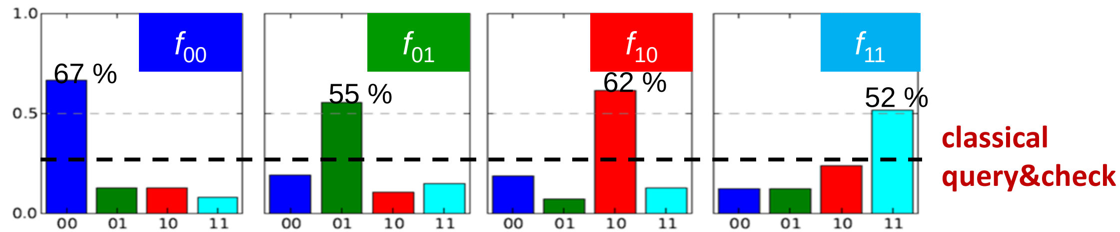
Dewes et. al., PRL & PRB 2012

Grover Search algorithm
(on 4 items)



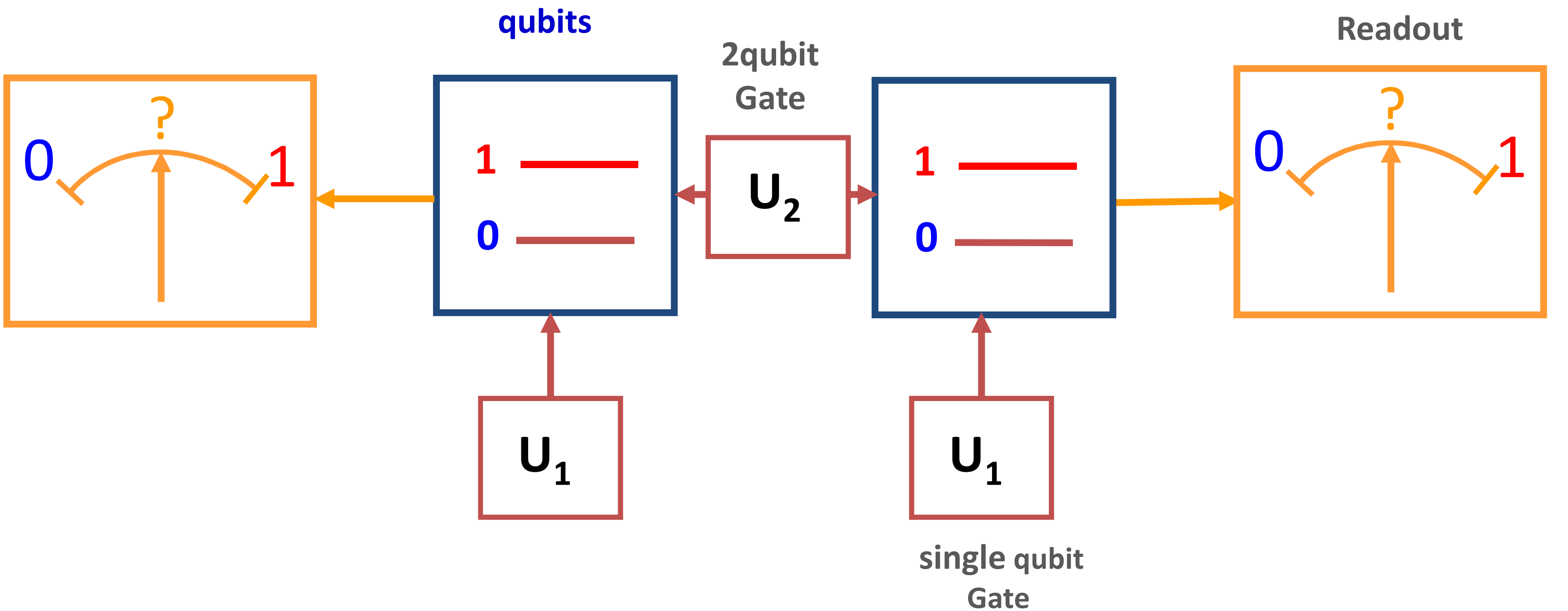
Running the Grover Search algorithm
(on 4 items)





Proof-of-principle for **quantum speed-up**
on elementary cases
(Quantronics 2012)

Blueprint of a quantum processor based on quantum gates



Huge Scalability challenges:

Hifi readout, hifi gates, quantum error correction

The overall quantum processor landscape in QC

Error-corrected (surface code) Josephson qubit processors

IBM,
Google,
TUDelft (QuTech)
(NL , Kavli & Intel support)
UCSB
...start-ups

More robust qubit architectures

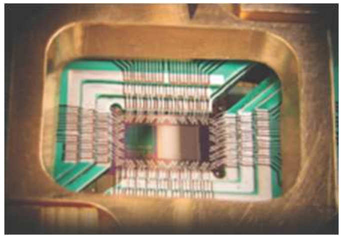
Yale
(IARPA support)

Quantronics
(CEA, Fr & Eu support)

Robust
spin based qubits

Quantum assisted annealing machines

D-Wave The Quantum Computing Company™   Google

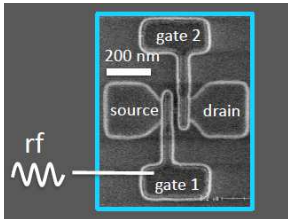


A challenger catching up ?

Electron spin states
in **semiconductor** structures

UNSW, TUDelft (+Intel), Harvard,...
And **CEA** (Grenoble)

No architecture yet



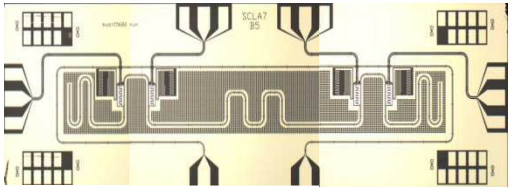
Ultra-small
CMOS technology

First qubit fabricated on
an **industrial** platform

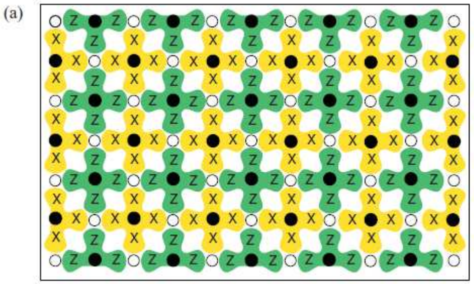
Recent progress towards universal QC processors :

Quantum register readout

Simultaneous hifi **readout** of a 4 qubit register (only!)
UCSB-Google, CEA, 2014



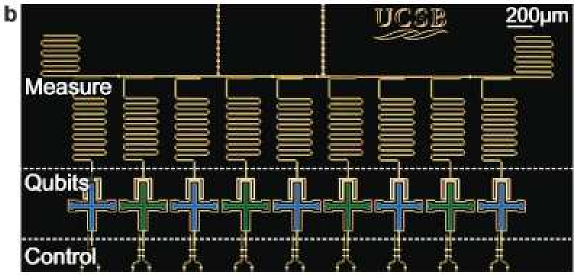
○ Data ● measurement



a less demanding fault-tolerant architecture, But with a huge qubit resource overhead

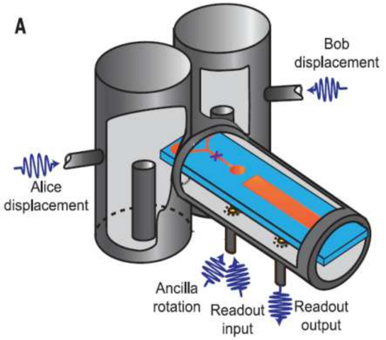
the **surface code architecture** (realistic ?)

First 1D test circuits
For quantum error correction :
UCSB-Google, TU Delft
2015



towards robust qubits with hing Q resonators

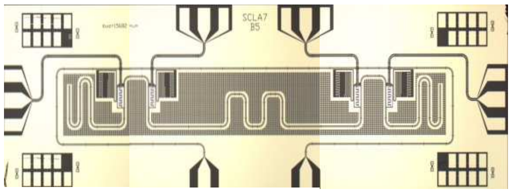
Yale,
With M. Mirrahimi (INRIA)
2014-16

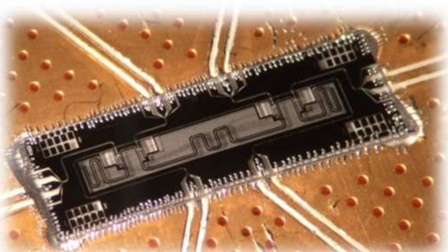


Quantronics research directions on QIP

larger universal processors ?
4 to 10 qubits
without error correction

2015:

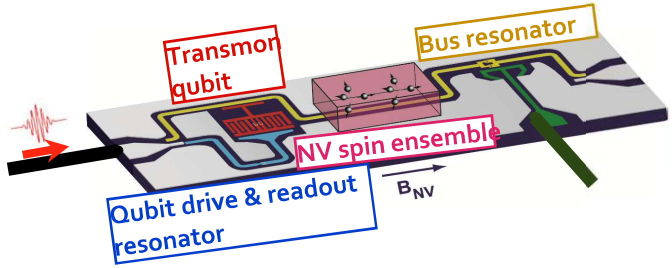


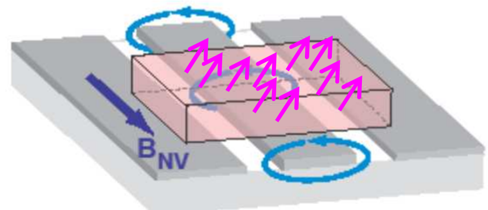


4 qubit processor
2 qubit gate operated, but
processor not functional

not scalable,
& too tech. demanding

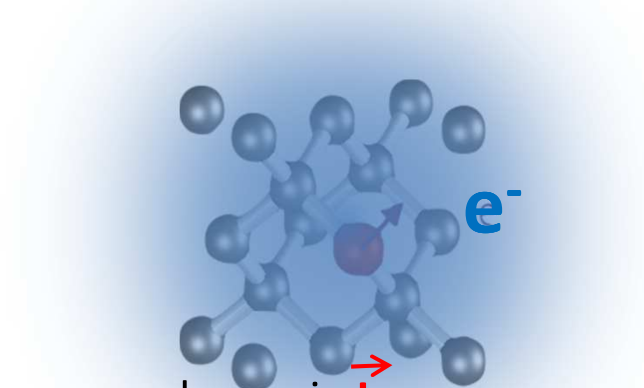
A multimode
hybrid memory



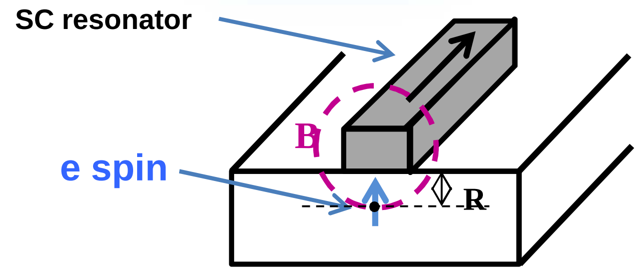


hybrid structures

A new architecture
spins & electrical circuits



nuclear spin **I**
coupled to electron spin



Electron spin coupled to
μw photons that can be measured

Towards a robust qubit architecture
based on nuclear spins

THE NEW PARADIGM OF QUANTUM COMPUTING AND ITS IMPLEMENTATION CHALLENGES

-A POTENTIAL GAME-CHANGER THAT FACES MAJOR ROADBLOCKS

-DIFFERENT ROUTES

-MAJOR PLAYERS ENTER

- YIELDS TO APPEALING QUANTUM TECHNOLOGIES

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2015