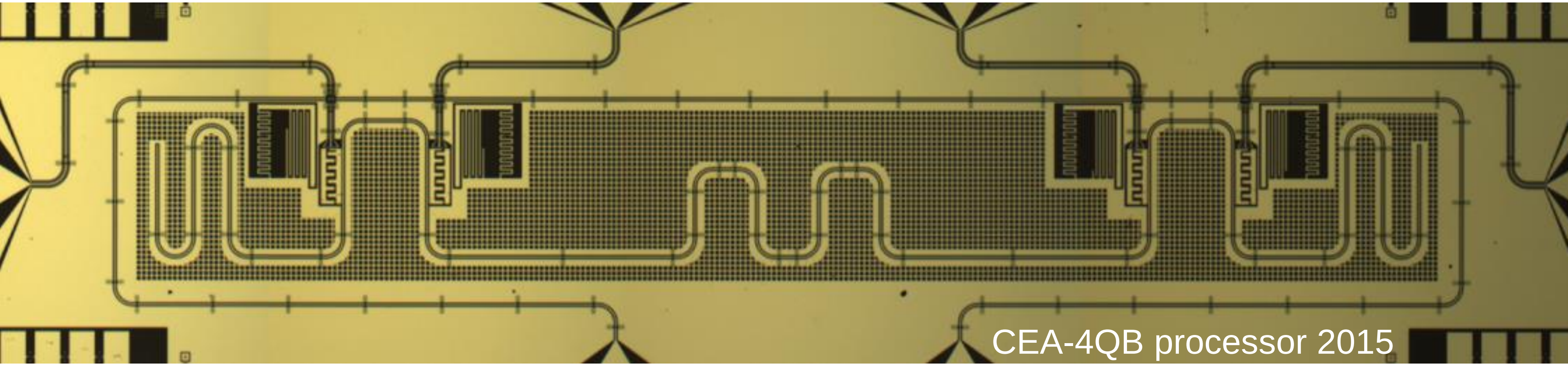
Introduction to Quantum computing

D. Vion QUANTUM ELECTRONICS GROUP



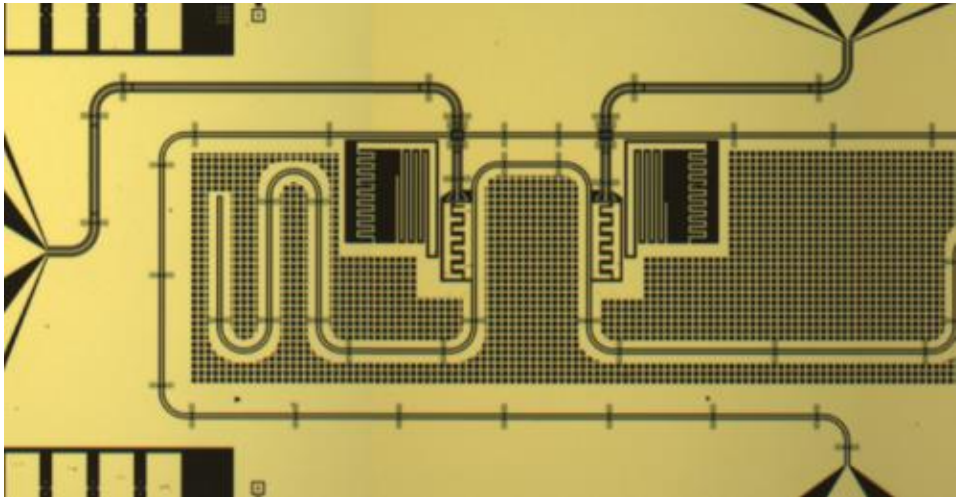
Réinventer l’informatique au-delà des architectures Von Neumann, Paris-Saclay, 6 dec. 2018

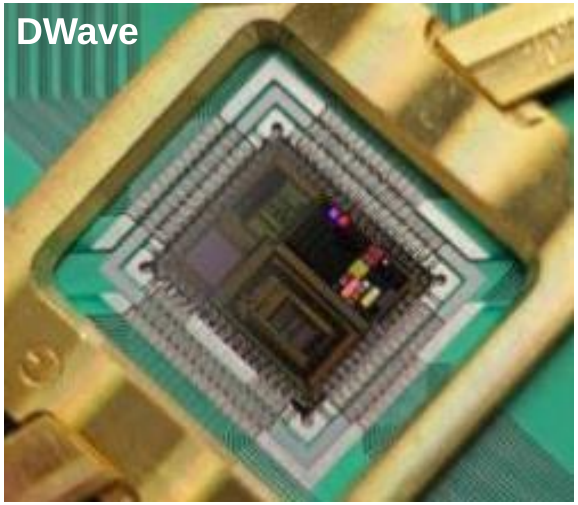
Warning: several types of quantum processors

Logic gate computing

Adiabatic computing

more exotic:
- one way QC
- ...





T. Lanting et al, PRX 4 (2014)

Quantum Turing machine running sequentially gates from a universal set of gates to implement an algorithm

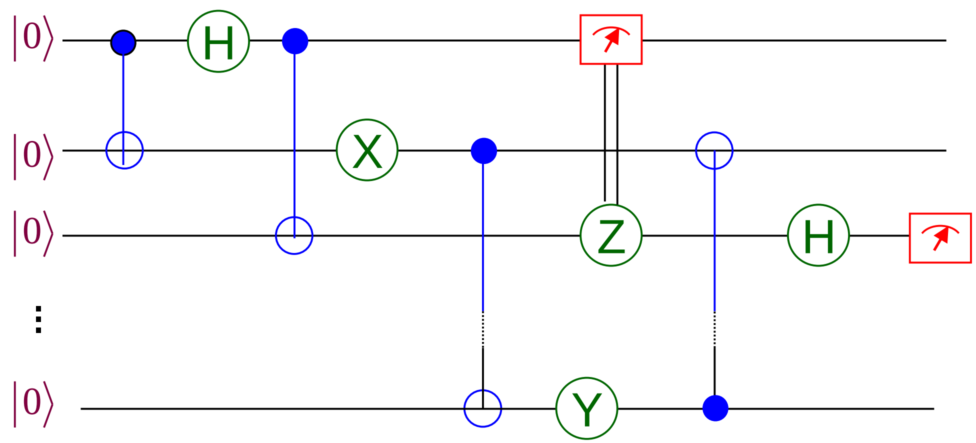
Energy minimization (optimization), by quantum annealing

this introductory talk

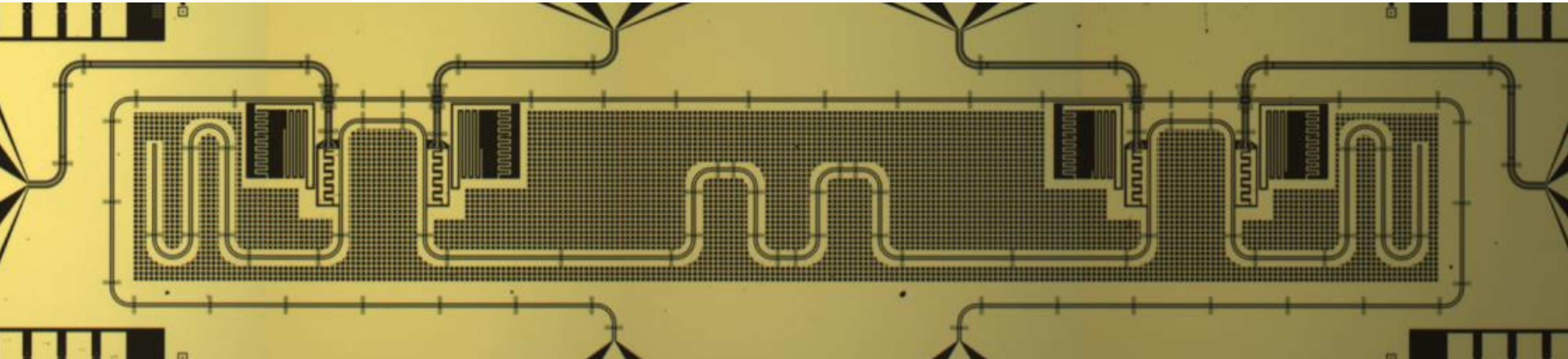
see Witold Kowalczyk's talk?

Outline

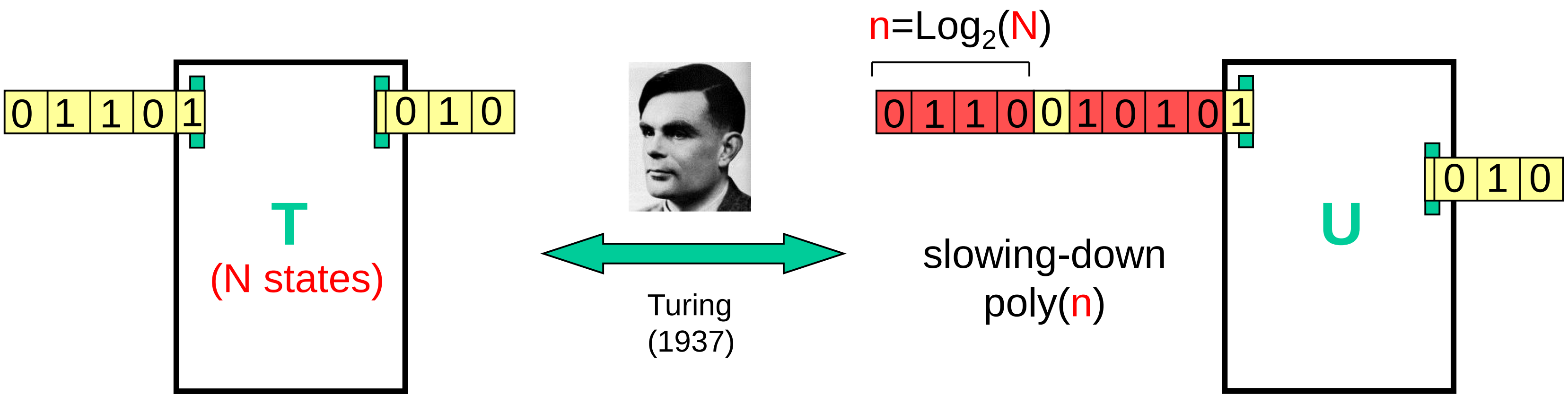
I. Basics of logic gate quantum computing



II. Practical implementations



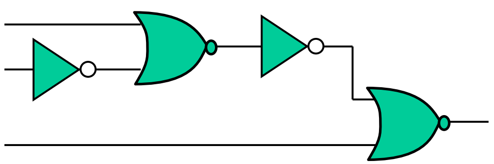
Reminder : the classical gate computer



Elementary information:

bit 0 or 1

Processed with logic gate arrays



NOT and a single 2 bit gate (as **XOR**) are enough : **Universal set**

Imperfections

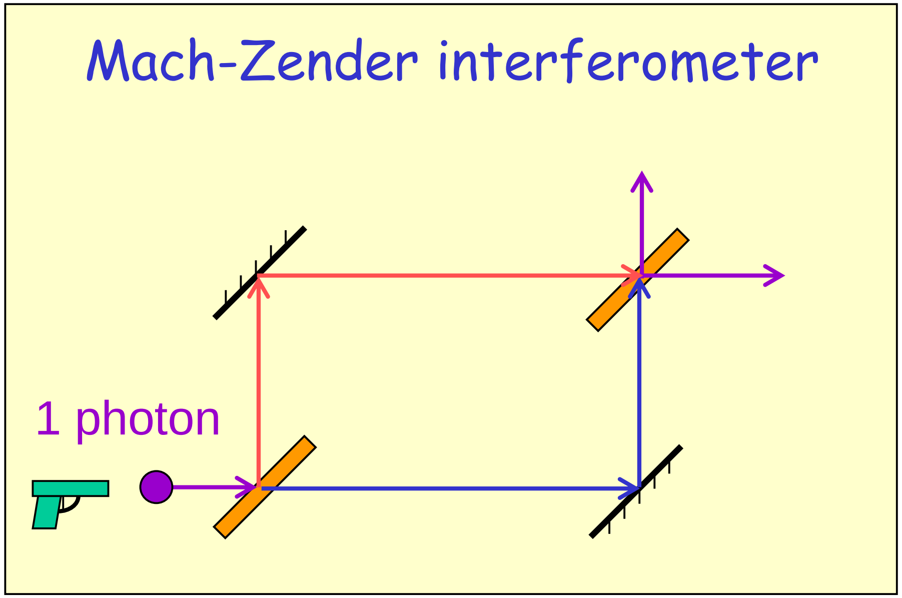
➡ error detection based on redundancy :

Ex: parity bit / byte

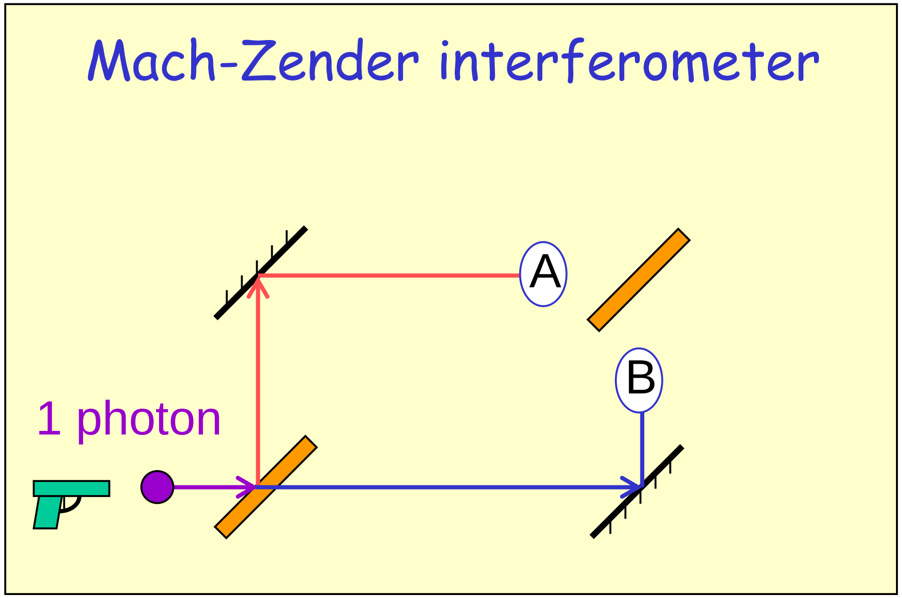
01011001

Do the same with quantum bits to benefit from quantum superposition and entanglement

Quantum objects (bit) and superposition of states

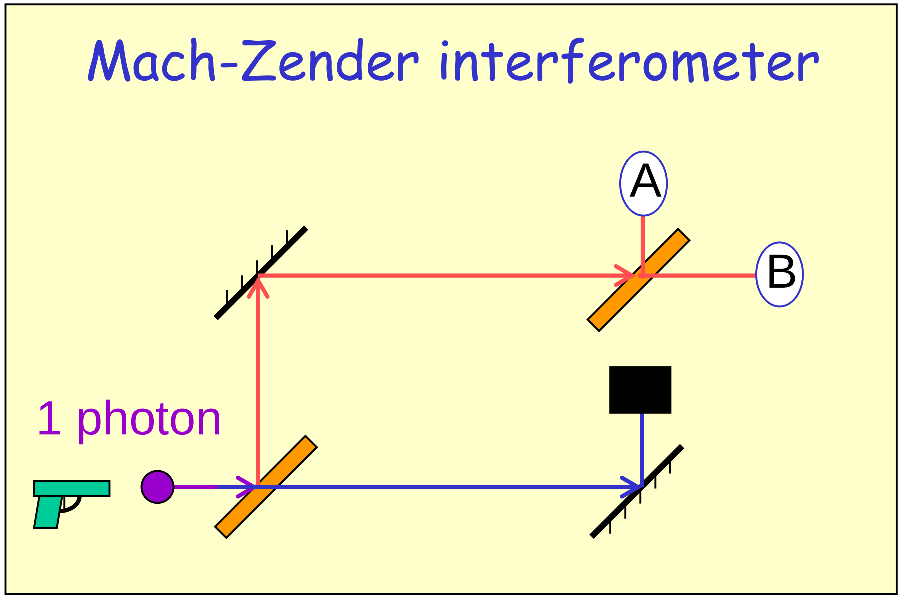


Quantum objects (bit) and superposition of states



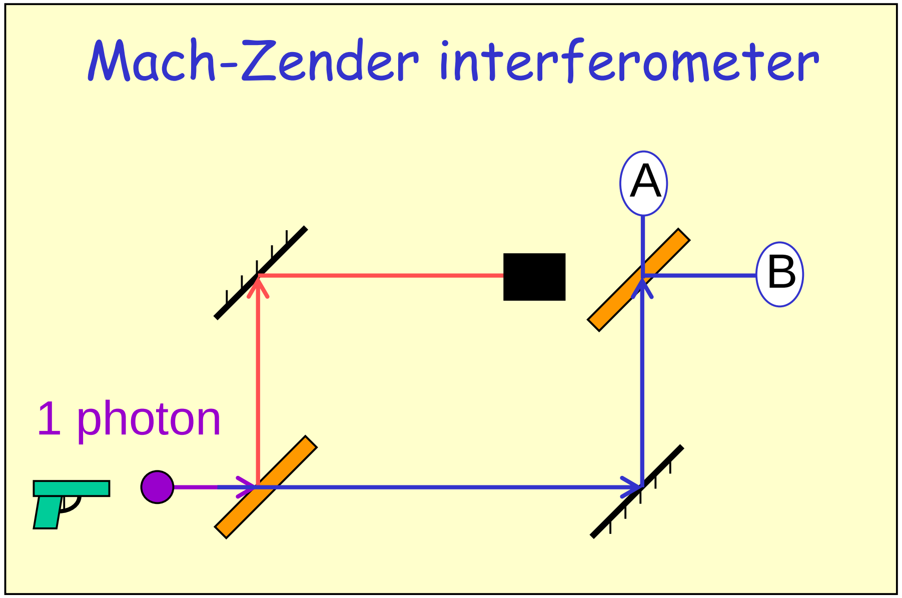
PM A	1	0
PM B	0	1
probability	1/2	1/2

Quantum objects (bit) and superposition of states



PM A	1	0	0
PM B	0	1	0
probability	1/4	1/4	1/2

Quantum objects (bit) and superposition of states



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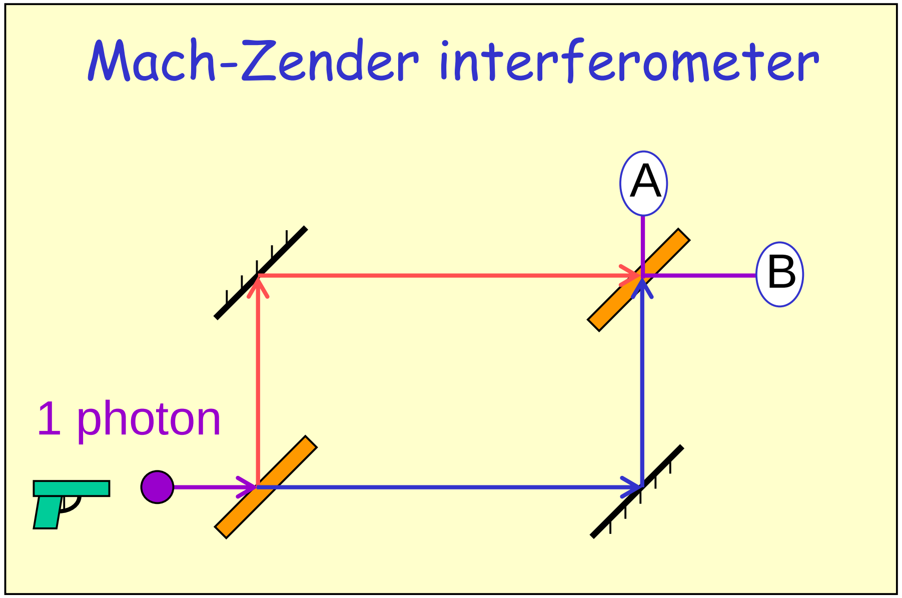
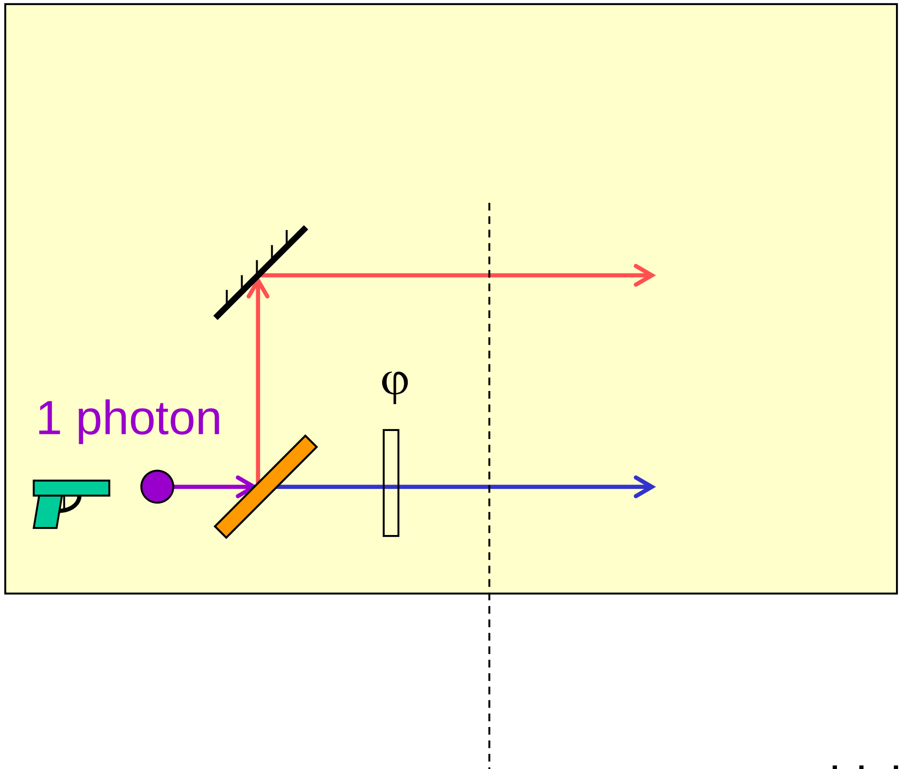
Quantum objects (bit) and superposition of states



PM A	0
PM B	1
probability	**1 !!!**

The photon goes along both paths at the same time… « within the meaning of interference ».

Quantum objects (bit) and superposition of states



The photon goes along both paths
at the same time…

probability

$$|\,photon\rangle = \alpha|0\rangle + \beta|1\rangle \xrightarrow[\text{readout}]{\text{which path measurement}} \begin{cases} |0\rangle & |\alpha|^2 \\ \text{or} & \\ |1\rangle & |\beta|^2 = 1 - |\alpha|^2 \end{cases}$$

copy is impossible !

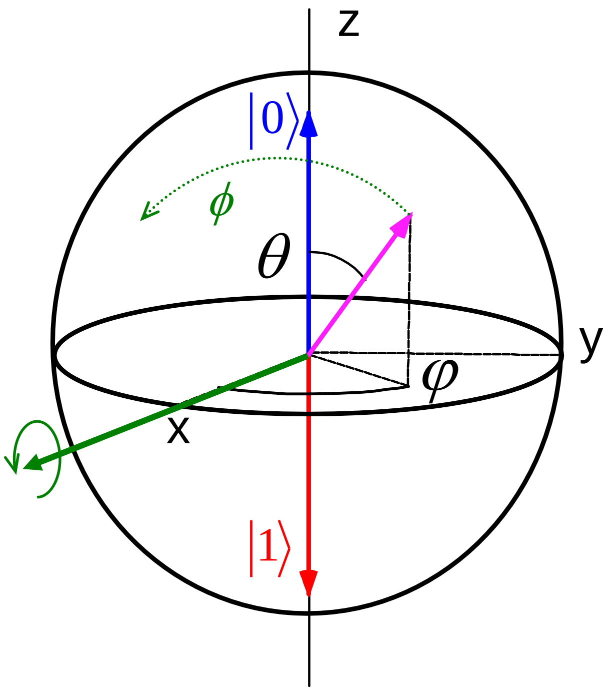
The quantum bit and single qubit gates

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

$$\cos\frac{\theta}{2}e^{-\frac{i\varphi}{2}}|0\rangle + \sin\frac{\theta}{2}e^{+\frac{i\varphi}{2}}|1\rangle$$

projective measurement → $|0\rangle$ ou $|1\rangle$

probability: $|\alpha|^2$ (for $|0\rangle$), $|\beta|^2$ (for $|1\rangle$)



important property: no-cloning
Duplication of unknown state is **impossible**

Single qubit logic gate : all rotations

$$R(\vec{x},\phi) = \begin{bmatrix} \cos(\phi/2) & -i\sin(\phi/2) \\ -i\sin(\phi/2) & \cos(\phi/2) \end{bmatrix}$$

A few gates: $X, Y, Z, H = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

In practice, 180°, 90° and one 45° rotations are enough

But informational content not larger than classical bit:

Power will come from having several qubits and **entanglement**

Quantum register and entangling 2-qubit gate

n qubit register → N = 2^n basis states $\overbrace{|010001...1\rangle}^{n} = |p\rangle$

Most general register state : $|reg\rangle = \sum_{p=0}^{N-1} a_p |p\rangle$

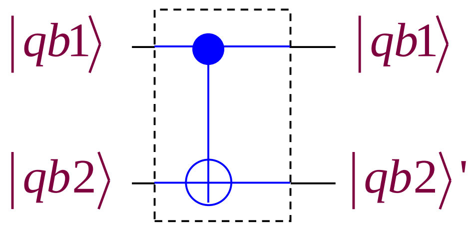
Universal set of gates (any unitary evolutions)

- single qubit gates
- 1 « good » (entangling) 2-qubit gate

CNOT (quantum XOR)

control

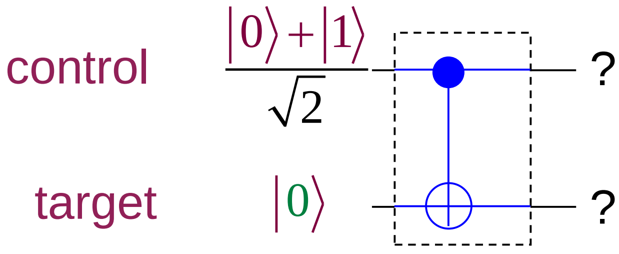
target



$\lvert qb1\rangle$	$\lvert qb2\rangle$	$\lvert qb2\rangle'$
$\lvert 0\rangle$	$\lvert 0\rangle$	$\lvert 0\rangle$
$\lvert 0\rangle$	$\lvert 1\rangle$	$\lvert 1\rangle$
$\lvert 1\rangle$	$\lvert 0\rangle$	$\lvert 1\rangle$
$\lvert 1\rangle$	$\lvert 1\rangle$	$\lvert 0\rangle$

Entanglement is the ressource ! What does it mean ?

CNOT (quantum XOR)



$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

$\|qb1\rangle$	$\|qb2\rangle$	$\|qb2\rangle'$
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|0\rangle$

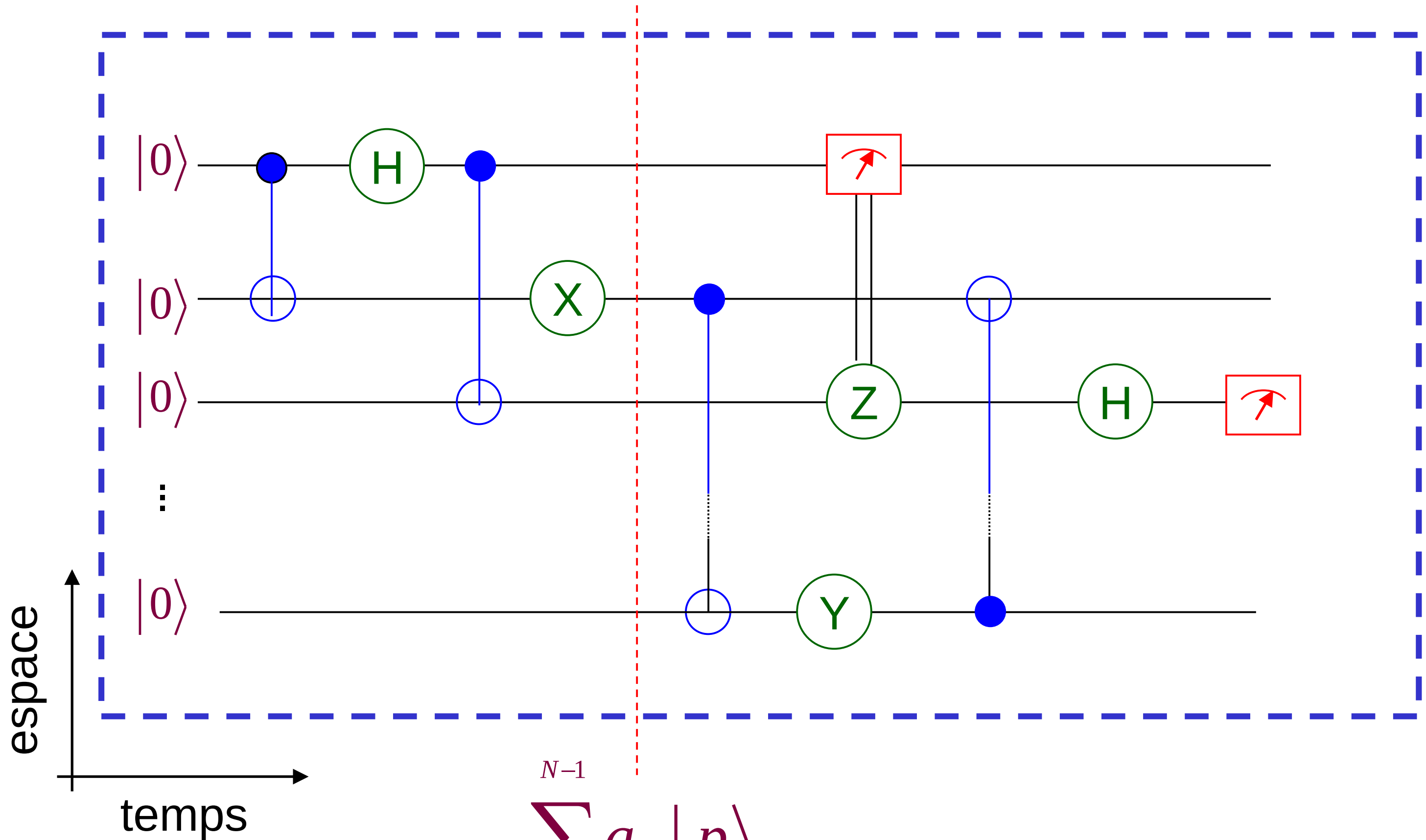
very strong quantum corelations

measure 1 qubit ⟹ projects both !

maximum entanglement

Quantum algorithms

Ensemble de n qubits ➡ N = 2^n états de base $\overbrace{|010001...1\rangle}^{n} = |p\rangle$



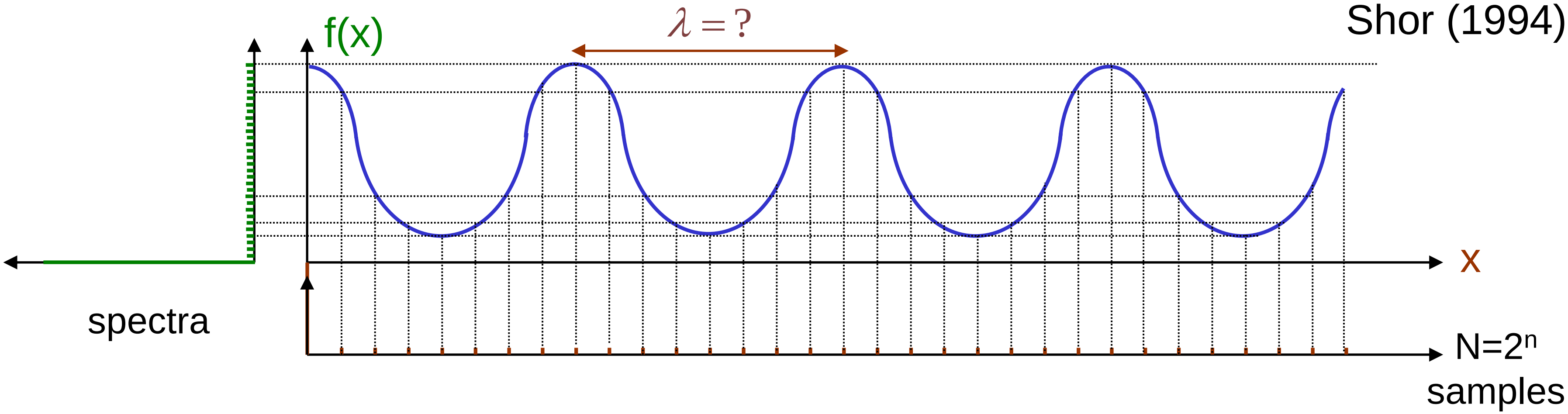
$$\sum_{p=0}^{N-1} a_p |p\rangle$$

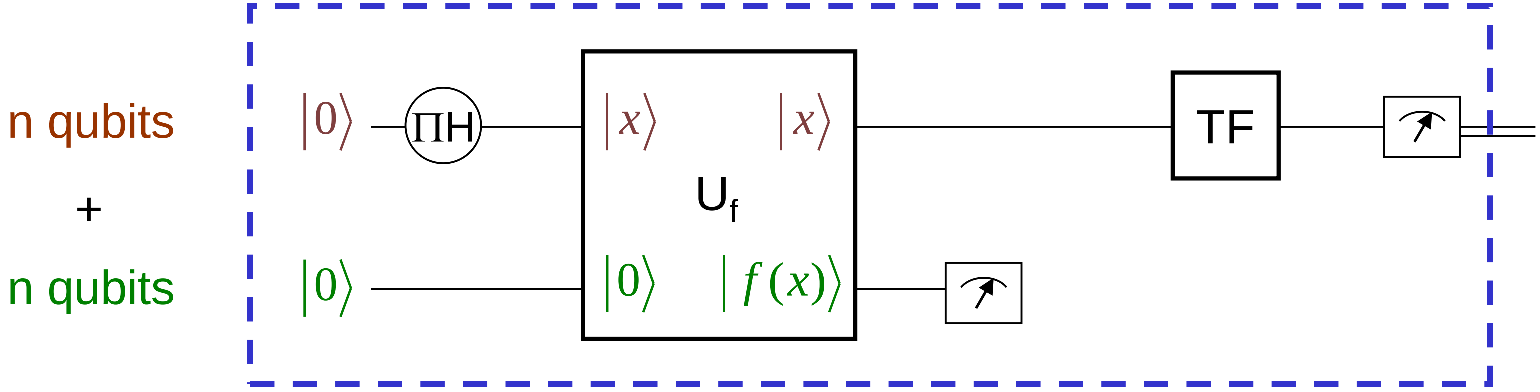
superposition

see Cyril Allouche's talk

Example : find the period of a periodic function

Shor (1994)





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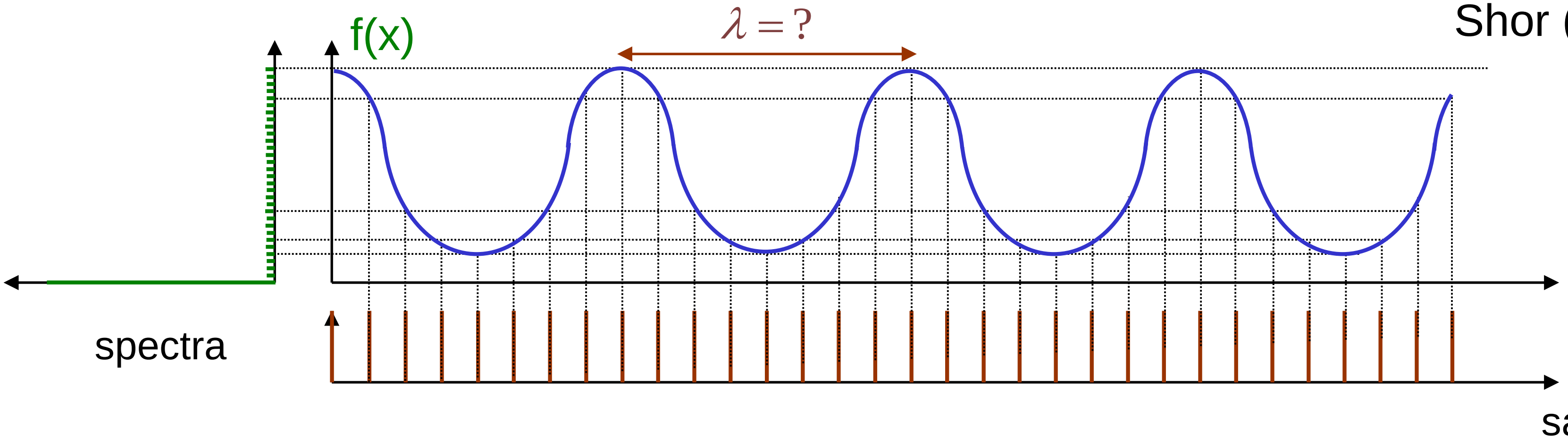

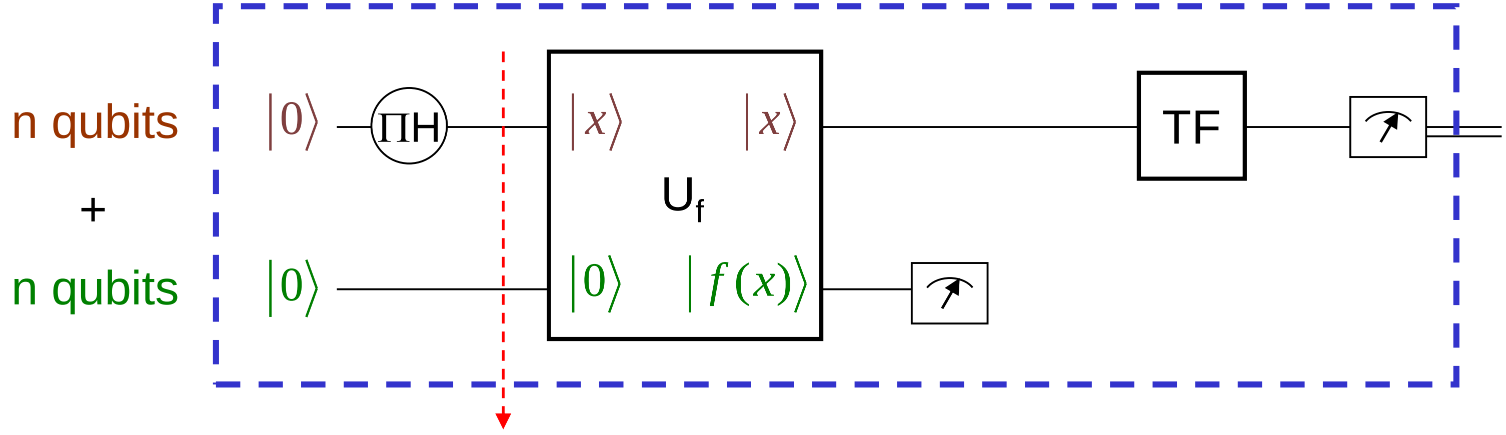

$$\sum_{x=0}^{N-1} |x\rangle \otimes |0\rangle$$

superposition

Example : find the period of a periodic function

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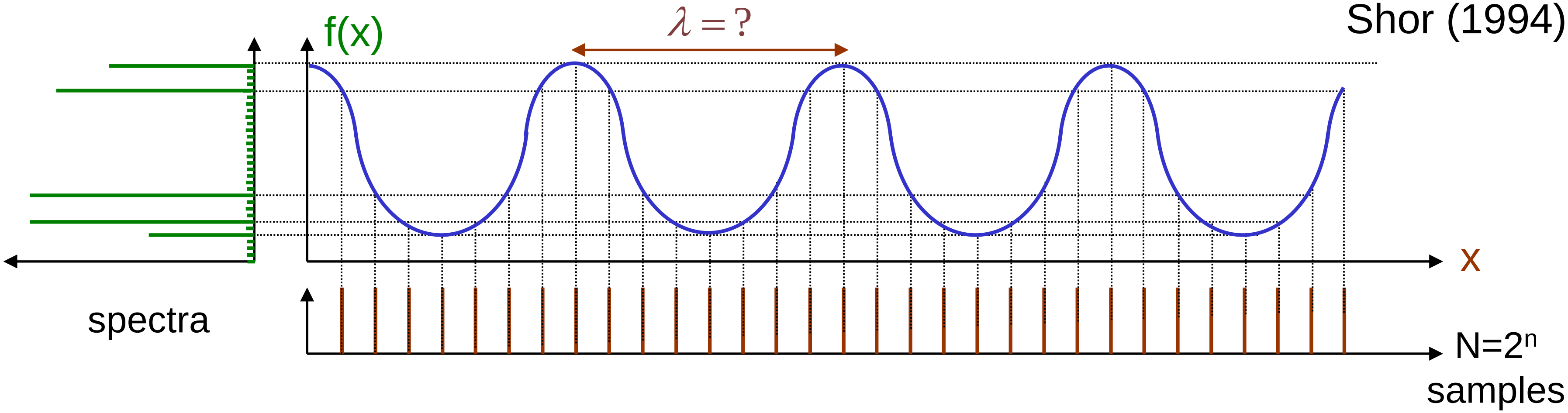
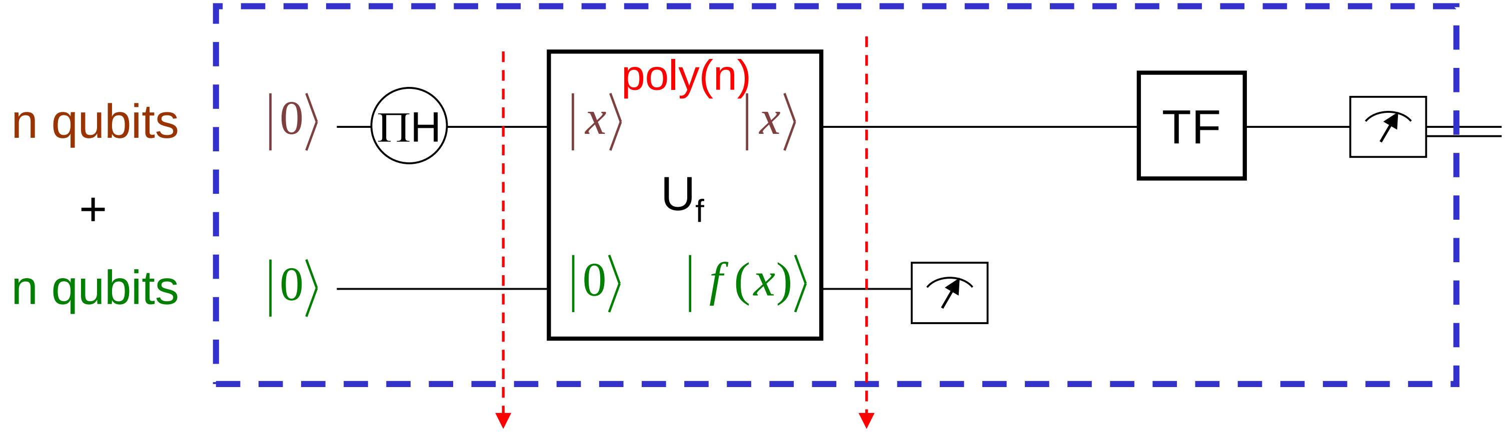
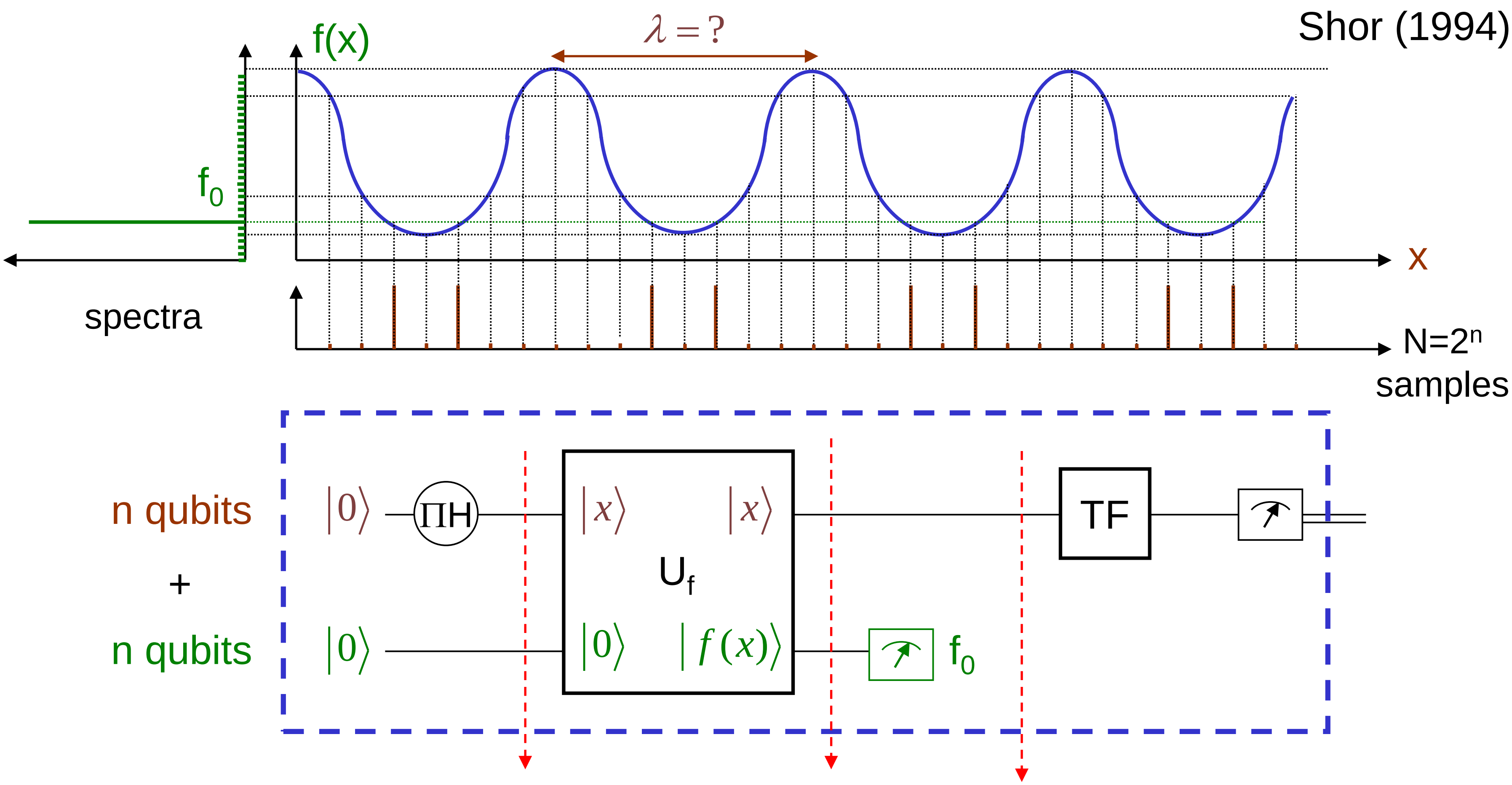




$$\sum_{x=0}^{N-1} |x\rangle \otimes |0\rangle \qquad \sum_{x=0}^{N-1} |x\rangle |f(x)\rangle$$

quantum parallelism
+ entanglement !

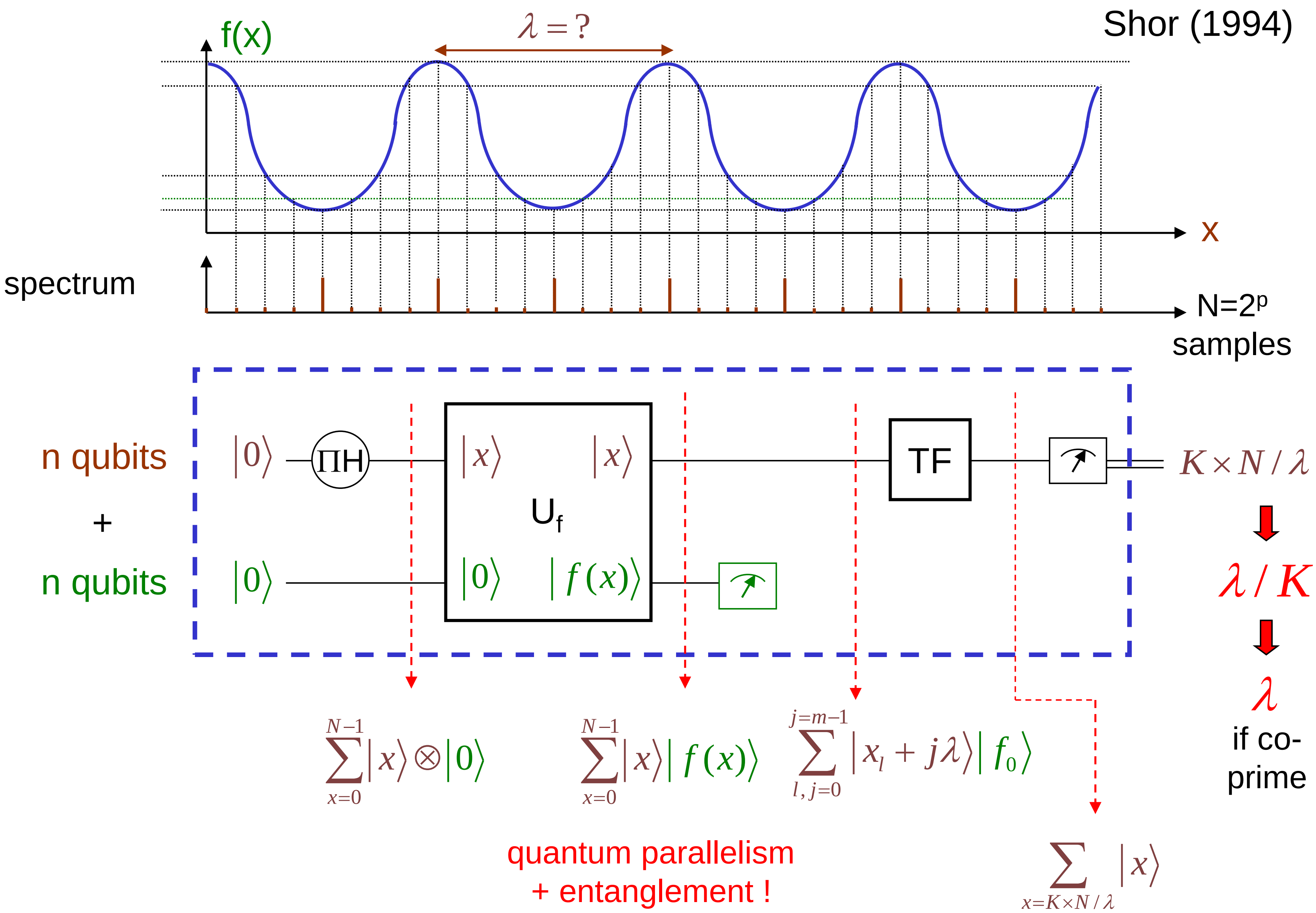
Example : find the period of a periodic function



$$\sum_{x=0}^{N-1} |x\rangle \otimes |0\rangle \qquad \sum_{x=0}^{N-1} |x\rangle |f(x)\rangle \qquad \sum_{l,j=0}^{j=m-1} |x_l + j\lambda\rangle |f_0\rangle$$

quantum parallelism
+ entanglement !

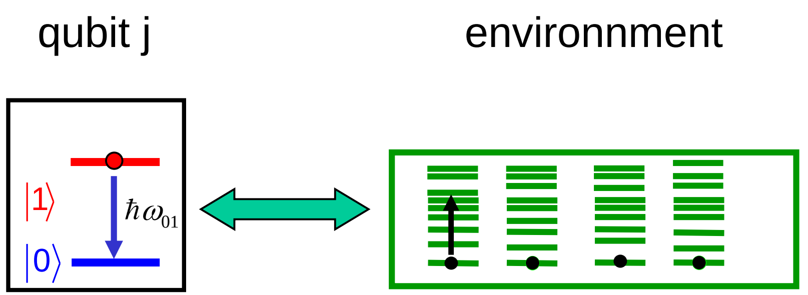
Example : find the period of a periodic function



Fragility of quantum superpositions: decoherence…

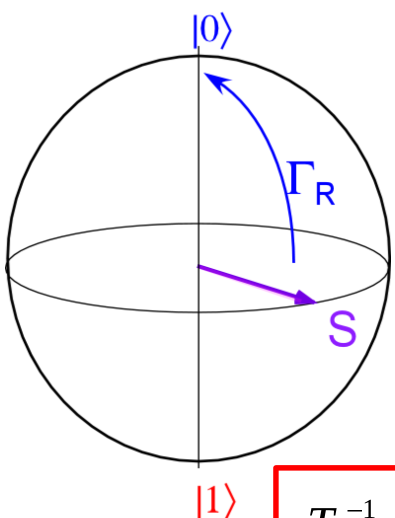
$$|reg\rangle = \alpha_0 e^{i\varphi_0}|0,0,...,0\rangle + \alpha_1 e^{i\varphi_1}|1,0,...,0\rangle + ... + \alpha_{N-1} e^{i\varphi_{N-1}}|1,1,...,1\rangle$$

Sudden death: relaxation

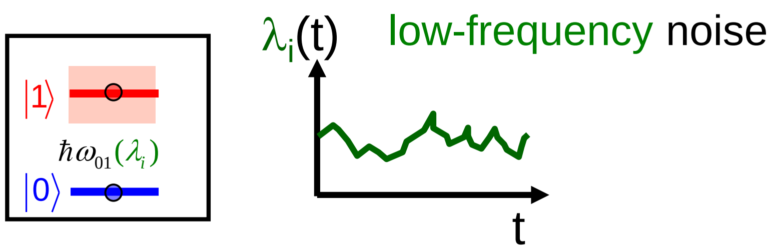


$|1\rangle_j$

$$T_1^{-1} = \Gamma_1$$



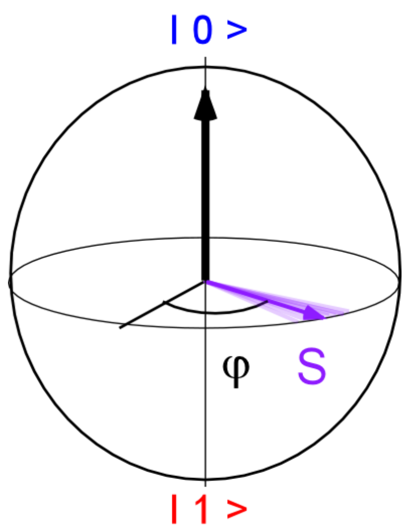
Disease: pure dephasing



$a|0\rangle_j + be^{i\varphi(t)}|1\rangle_j$

$$\langle e^{i\varphi(t)}\rangle \approx e^{-\Gamma_\varphi t}$$

$$\Gamma_\varphi$$



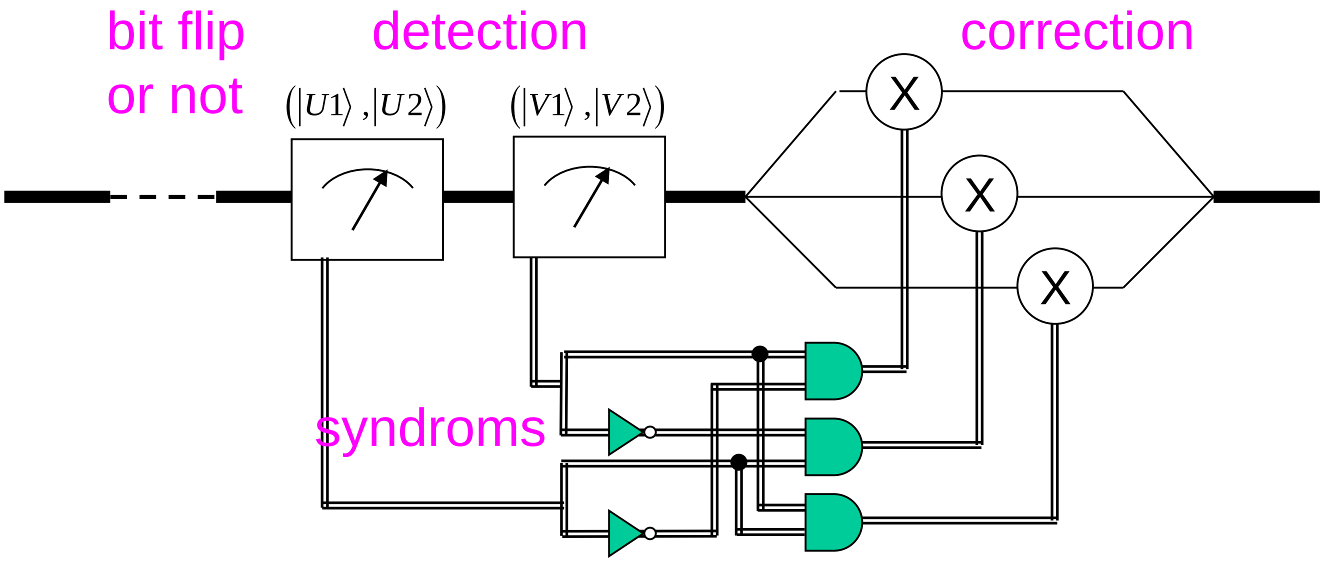
$$T_2^{-1} = \Gamma_2 = \Gamma_\varphi + \frac{\Gamma_1}{2}$$

Fragility of quantum superpositions: error correction

Use redundancy (despite non-cloning)

Example: relaxation (bit-flip) correction $\left(|0_L\rangle, |1_L\rangle\right) = \left(|000\rangle, |111\rangle\right)$

$|\psi\rangle = a|0_L\rangle + b|1_L\rangle$



Generalization to all 3 possible errors: 7-bit Steane code

Works if error < 0.01% per gate ! **Surface code: 1%, but huge overhead !**

In the meantime, run short-depth small algorithm see Ivano Tavernelli's talk

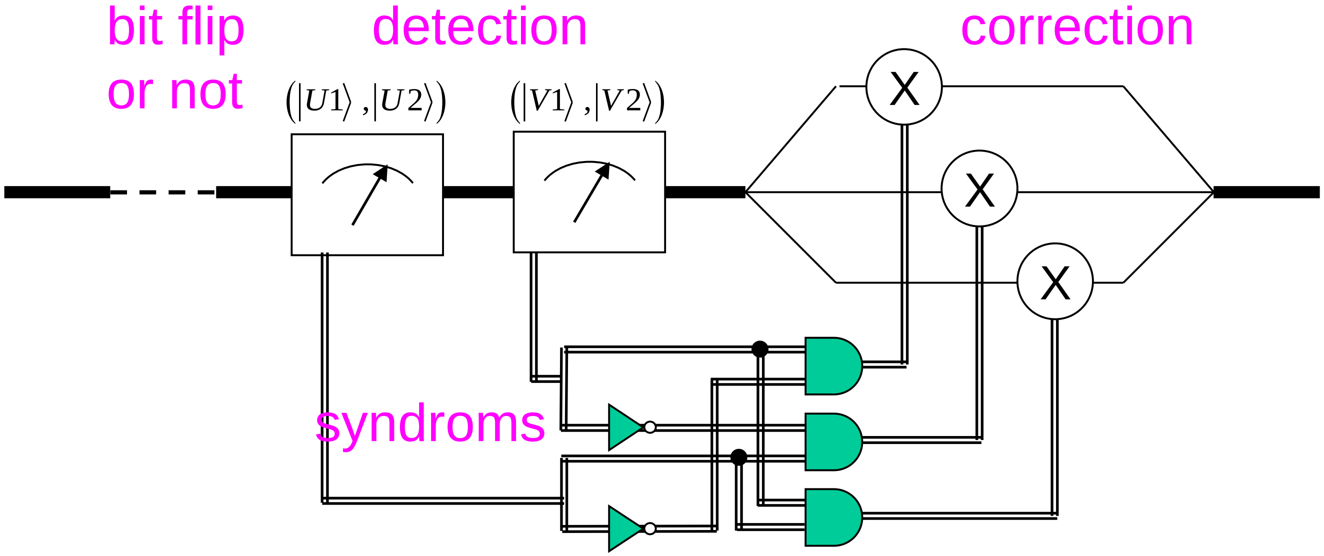
Fragility of quantum superpositions: error correction

Example: relaxation (bit-flip) correction $\quad (|0_L\rangle, |1_L\rangle) = (|000\rangle, |111\rangle)$

$$(|U1\rangle \;,\; |U2\rangle) = (|000\rangle + |111\rangle + |001\rangle + |110\rangle \;,\; |010\rangle + |101\rangle + |100\rangle + |011\rangle)$$

$$(|V1\rangle \;,\; |V2\rangle) = (|000\rangle + |111\rangle + |010\rangle + |101\rangle \;,\; |001\rangle + |100\rangle + |100\rangle + |011\rangle)$$

$$|\psi\rangle = a|0_L\rangle + b|1_L\rangle$$



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Outline

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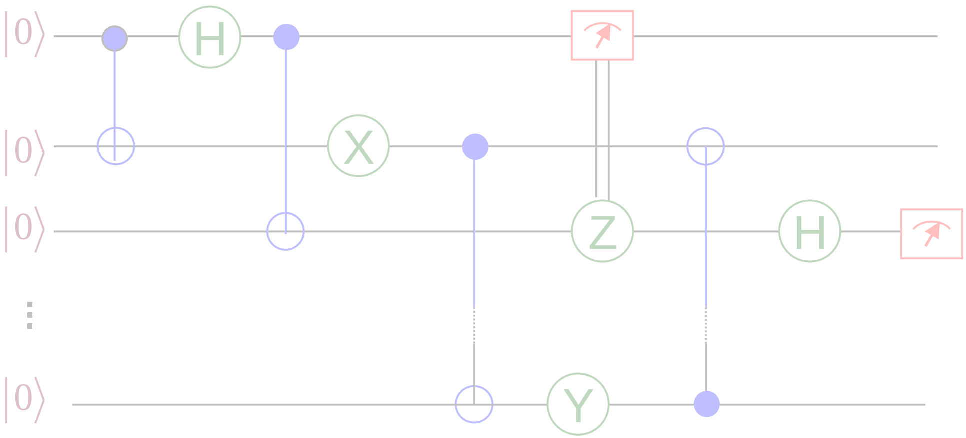
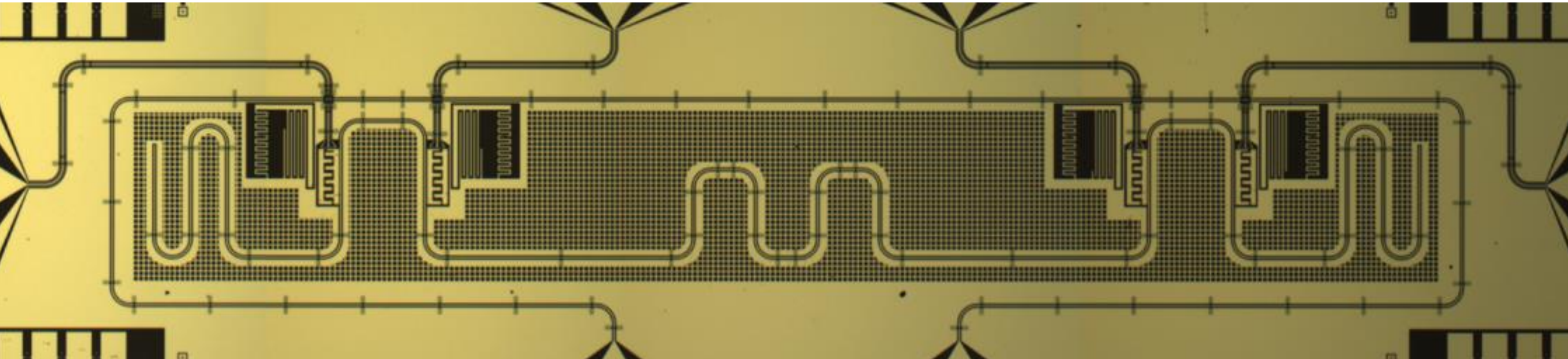
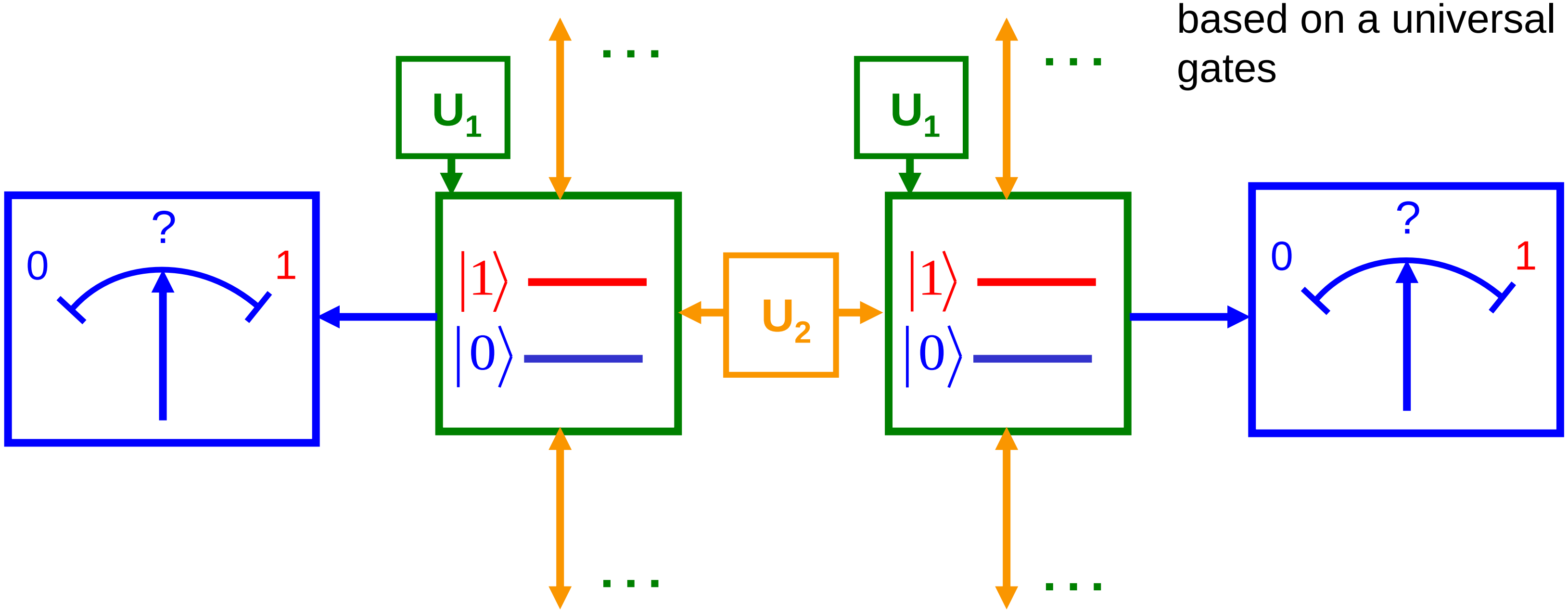


II. Practical implementations



The gate quantum processor

A quantum Turing machine based on a universal set of gates



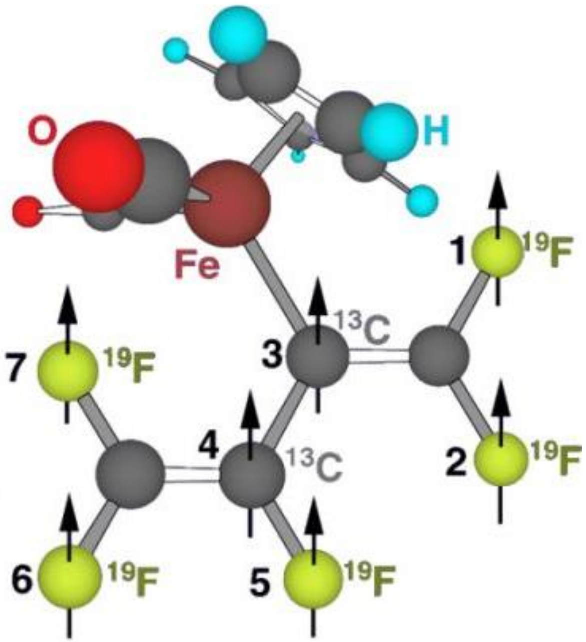
- qubit: 2-level-system $|\psi\rangle = a|0\rangle + b|1\rangle$ resetable to $|0\rangle$
- A few single qubit gates $U_1|\psi\rangle$
- a 2-qubit entangling gate $U_2|\alpha_0, \alpha_1, \alpha_2, \alpha_3\rangle_{00,01,10,11}$

} universal set

- qubit readout with high fidelity

Physical implementations

NMR



Physical implementations

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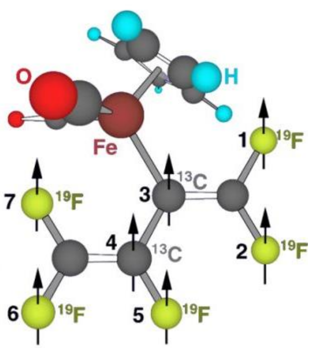
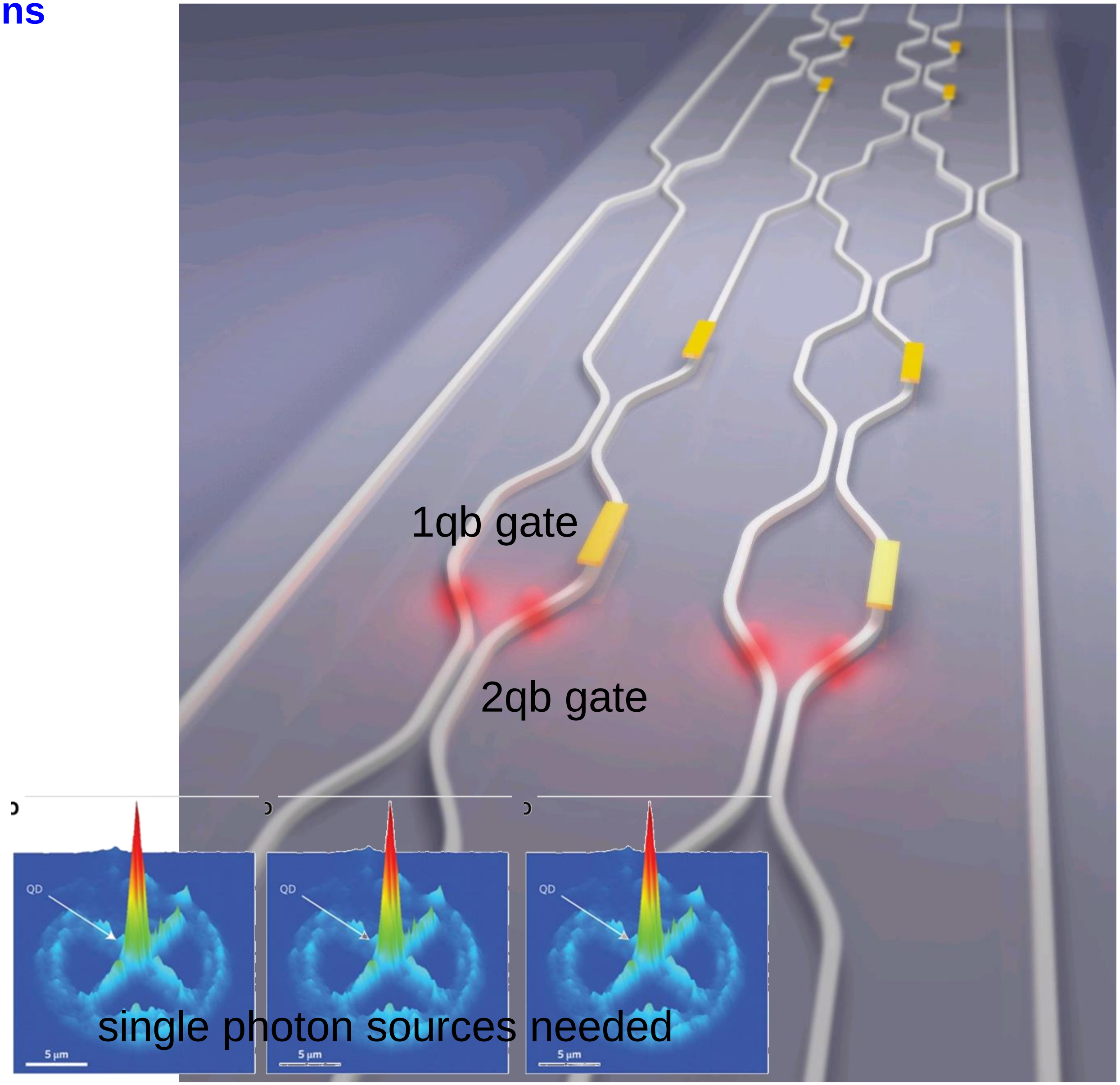


non scalable

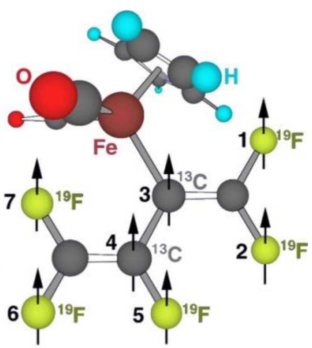
Photons



single photon sources needed

Physical implementations

NMR



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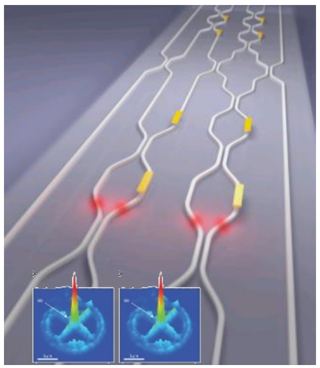
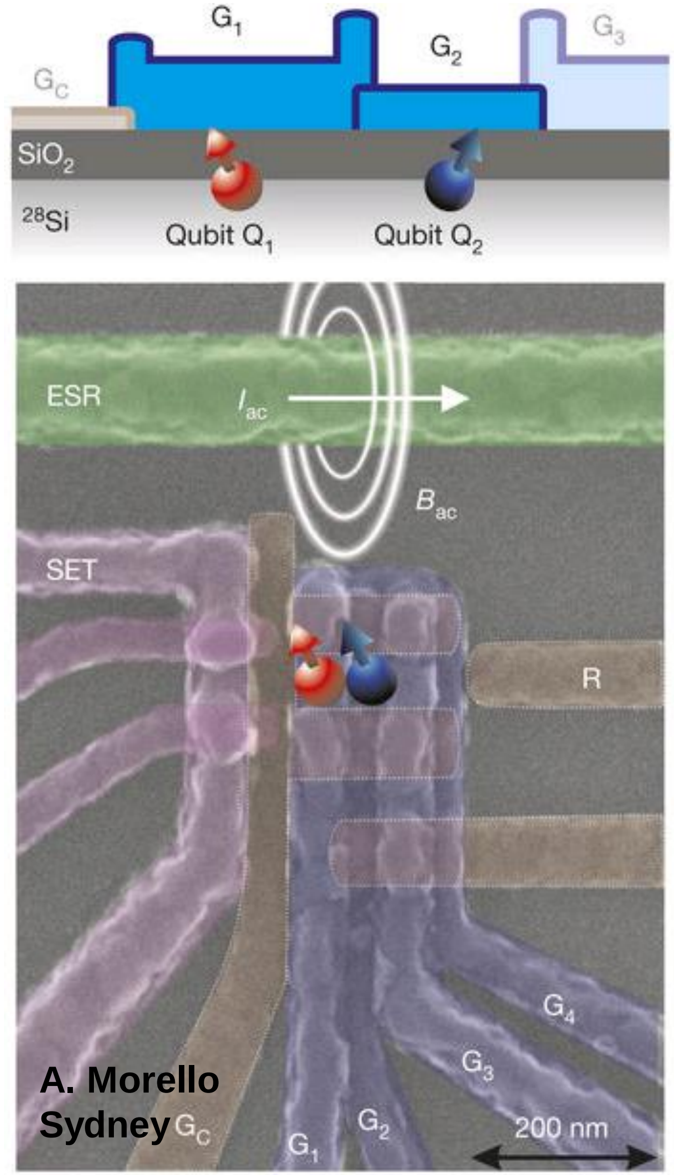


non deterministic
yet (in progress)

Spins in solid

- Implanted
- Quantum dots

- electronic
- nuclear

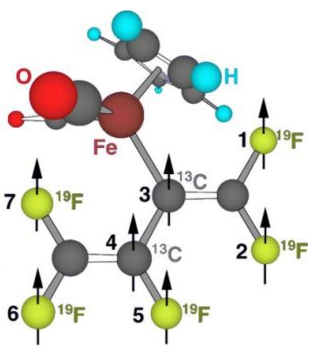


A. Morello
Sydney

see Tristan Meunier's talk

Physical implementations

NMR



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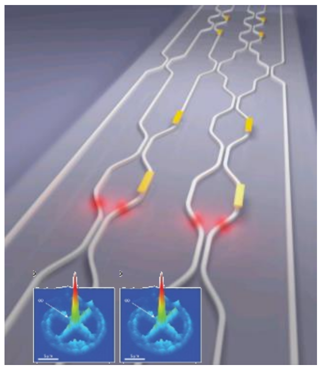
Photons



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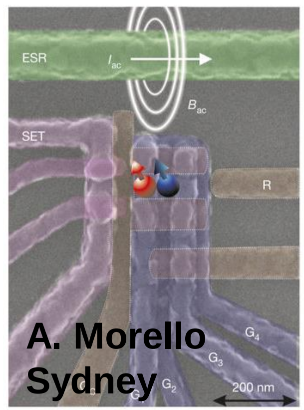
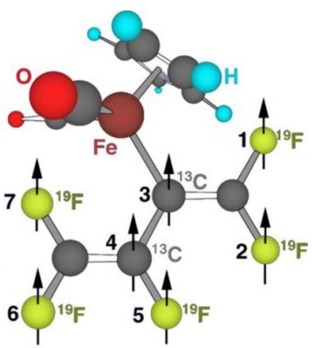


in progress

see Tristan Meunier's talk

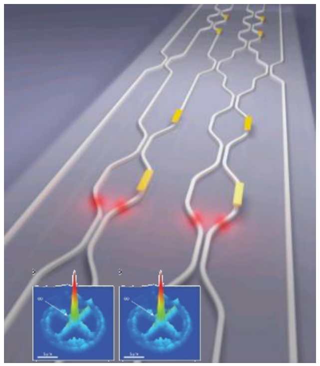
Physical implementations

NMR



non scalable

Photons



non deterministic yet

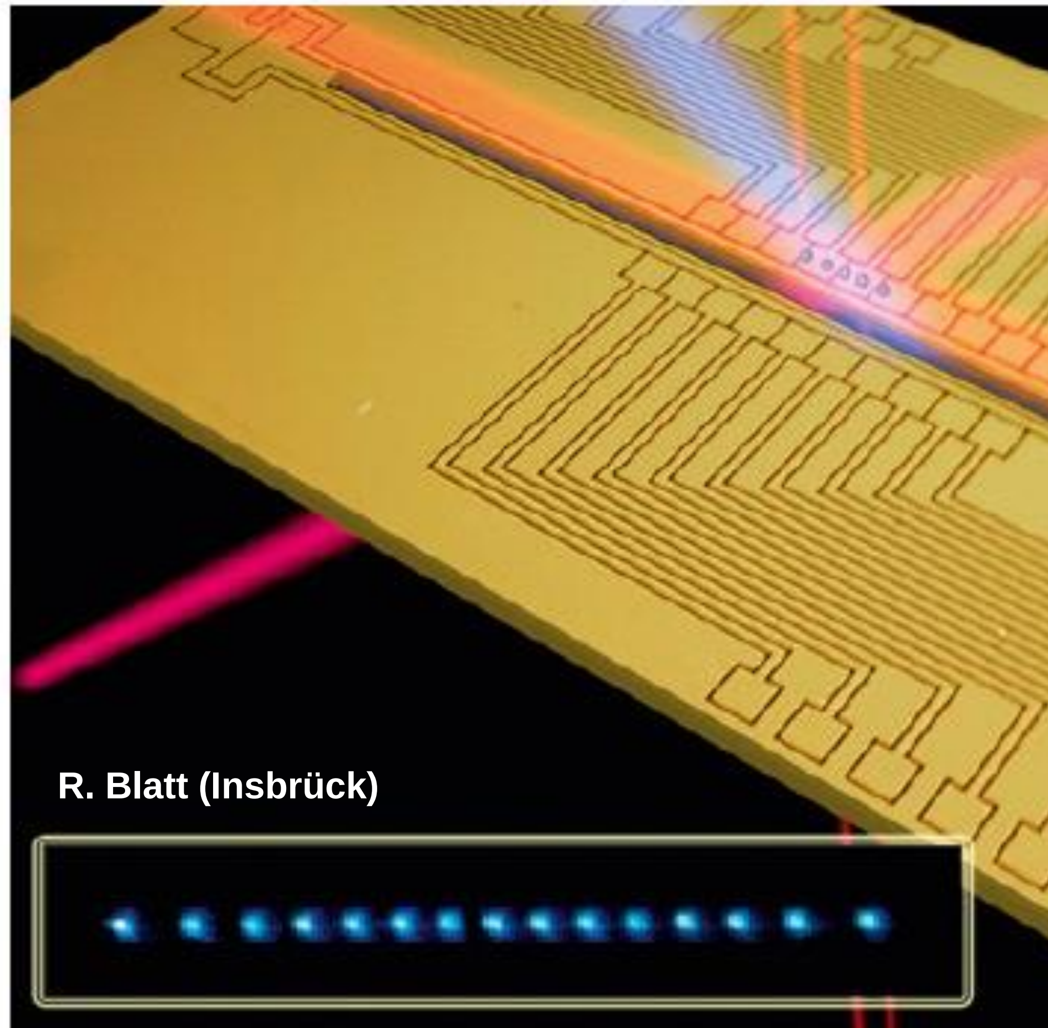
Spins in solid

- Implanted
- Qua
- elec
- nuc

in pr

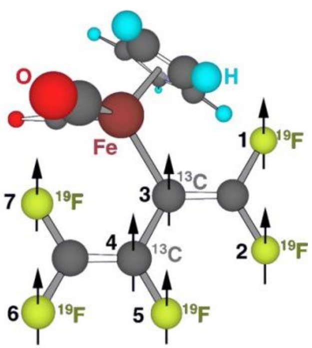
DRF

Trapped ions (or atoms)



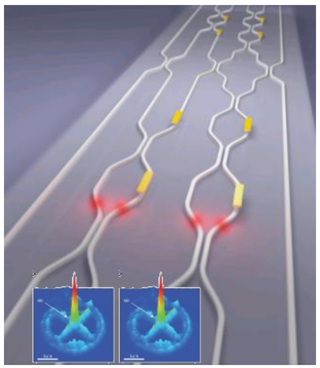
Physical implementations

NMR



non scalable

Photons

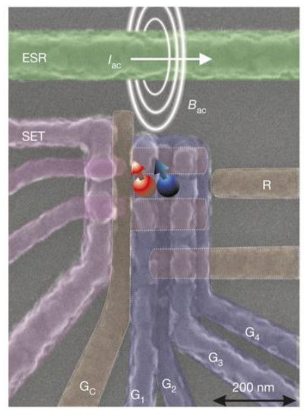


non deterministic yet

Spins in solid

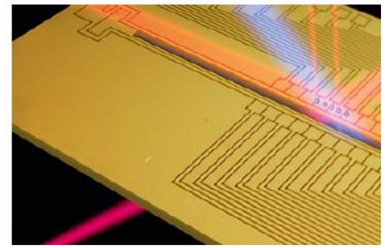
- Implanted
- Quantum dots

- electronic
- nuclear

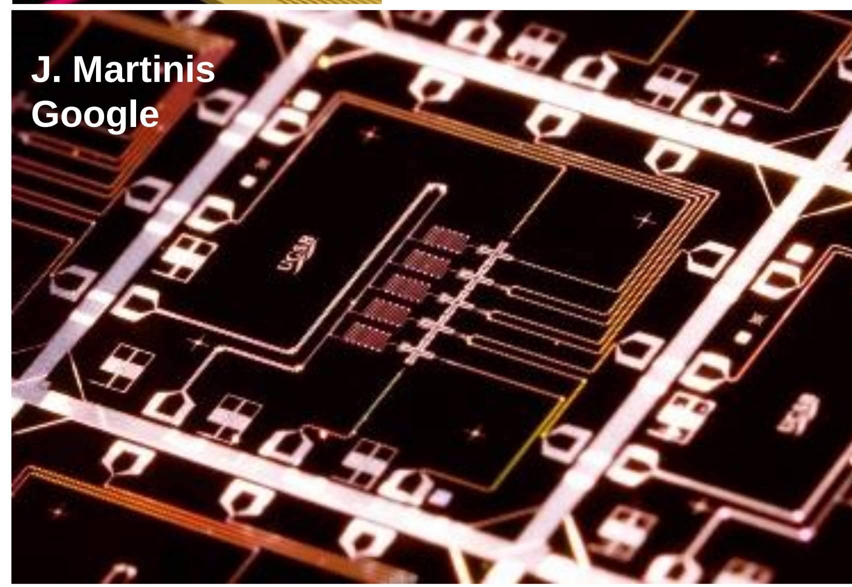


in progress

Trapped ions (or atoms)

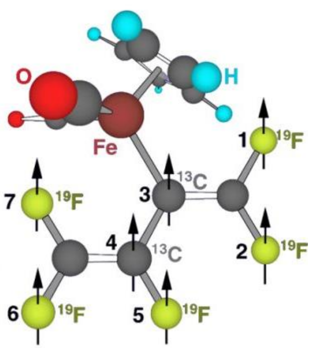


Superconducting circuits



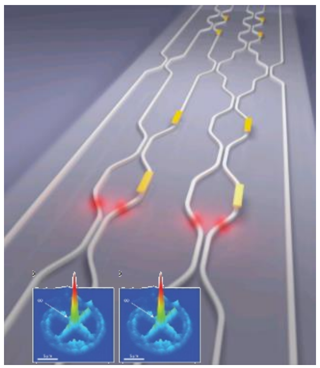
Physical implementations (non exhaustive)

NMR



non scalable

Photons

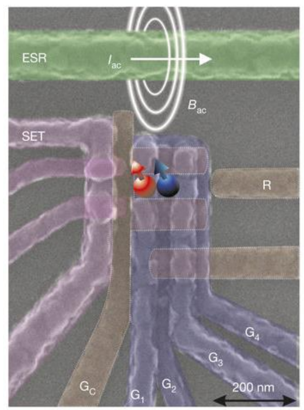


non deterministic yet

Spins in solid

- Implanted
- Quantum dots

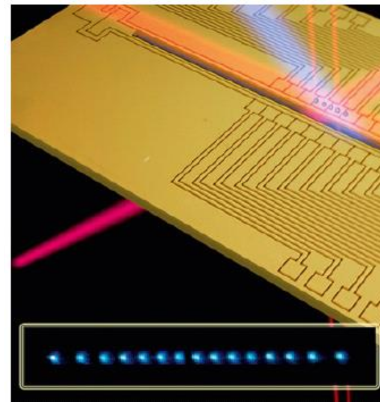
- electronic
- nuclear



in progress

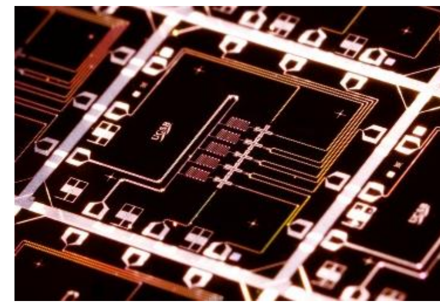
see Tristan Meunier's talk

Trapped ions (or atoms)



Most advanced
not easily scalable

Superconducting circuits



Most advanced

see Ivano Tavernelli's talk

Actors in quantum computing (not exhaustive)

ACADEMIC WORLD

NATIONAL LABS:
Lincoln Lab, JET, CEA LETI, …

BIG COMPANIES:

- IBM => gate QC (17 qbits , > 50 ?) — see Christophe Jurczak's talk
- GOOGLE + UCSB: gate QC (> 50 ?) — see Ivano Tavernelli's talk
- INTEL + QTECH: gate QC (17 qbits, 49 ?)
- MICROSOFT + QTECH : soft
- ATOS: 40-qubit emulator + compilers — see Cyril Allouche's talk

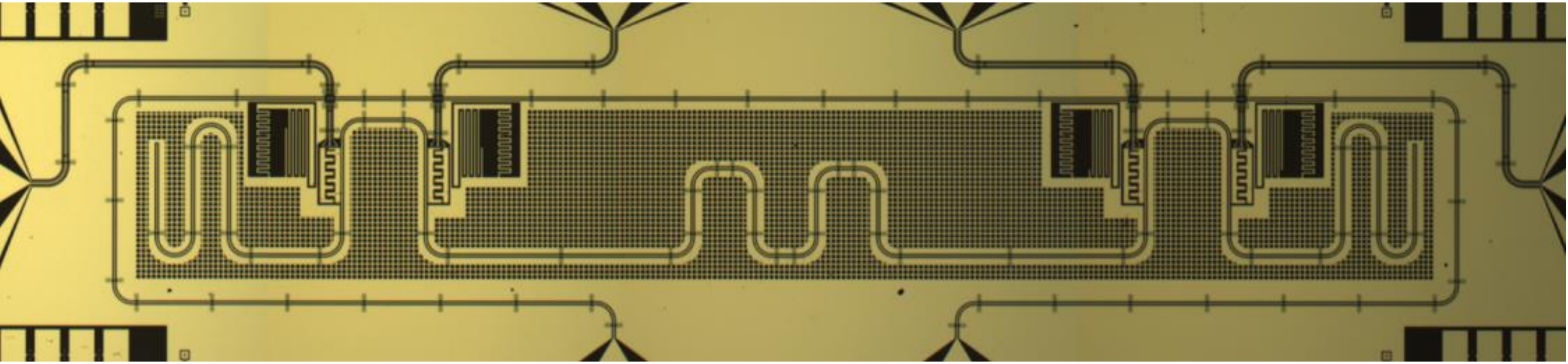
…

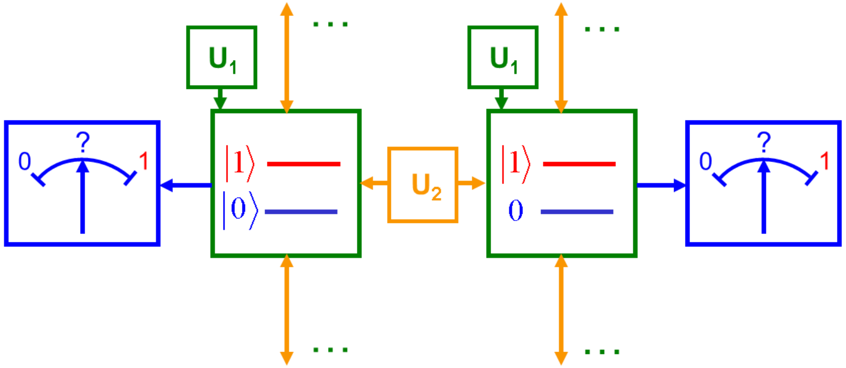
SMALLER COMPANIES:

- DWAVE: Adiabatic QC, annealing with 2000 qubits
- RIGETTI Computing: Hard + soft
- HYPRES: fabrication

….

II. Practical implementation with superconducting qubits

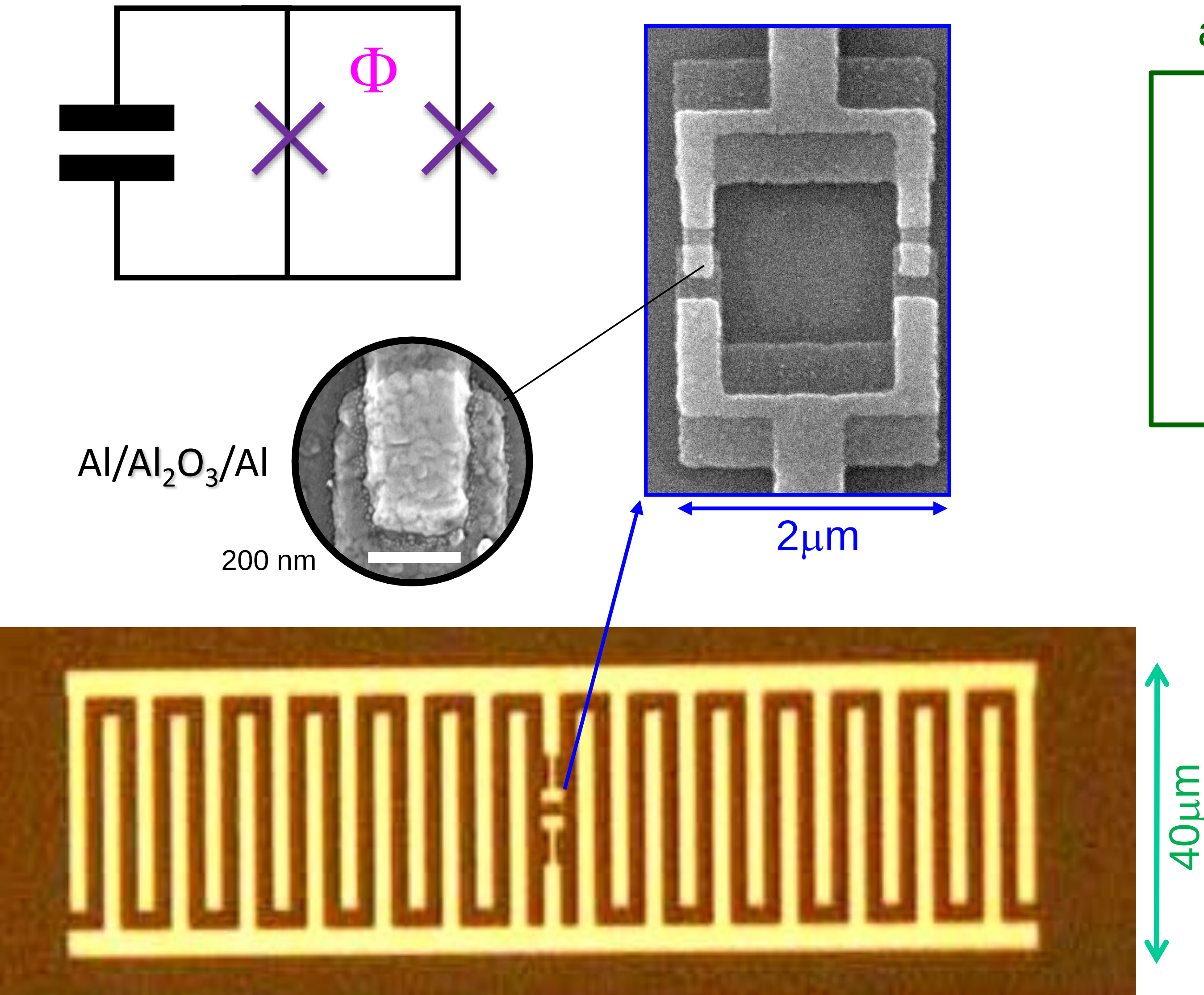




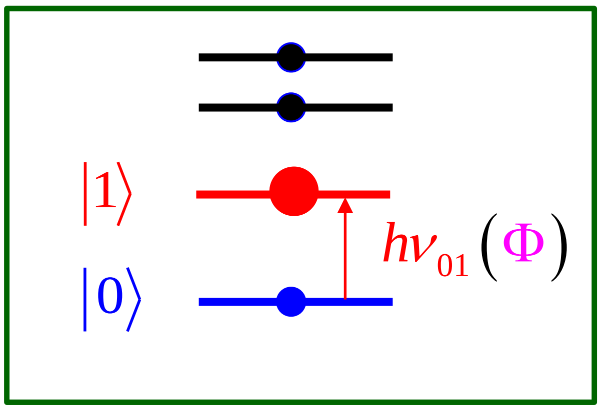
1) Making qubits with Josephson junctions
2) Circuit-QED architecture for qubit readout
3) Single-qubit gates with microwave and dc pulses
4) Example of the iSWAP two-qubit gate
5) Example of a simple algorithm: Grover with two qubits

1. Making qubits with superconducting circuits

Ex: transmon qubit = nonlinear superconducting LC oscillator at 5-10 GHz



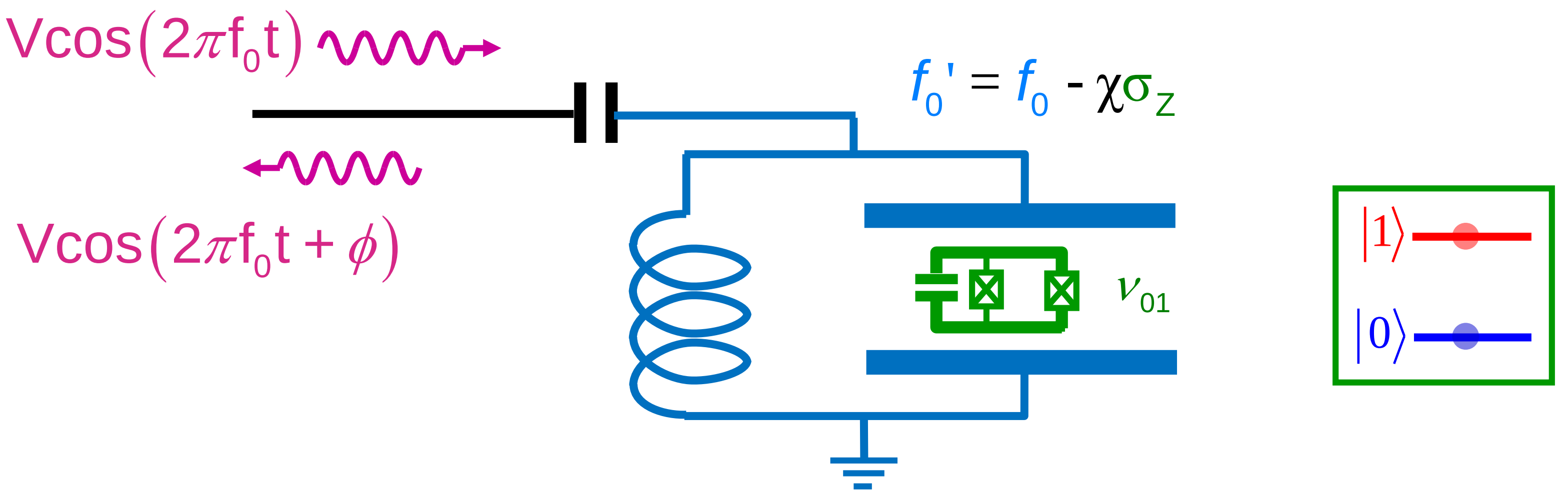
artificial two-level atom

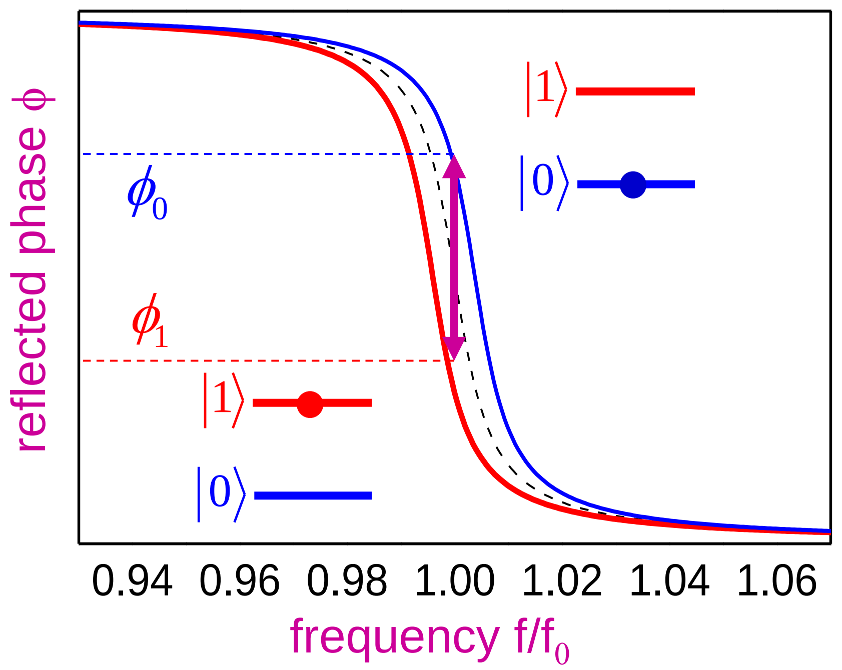


or effective spin 1/2

$$\hat{H} = -h\nu_{01}\hat{\sigma}_z / 2$$

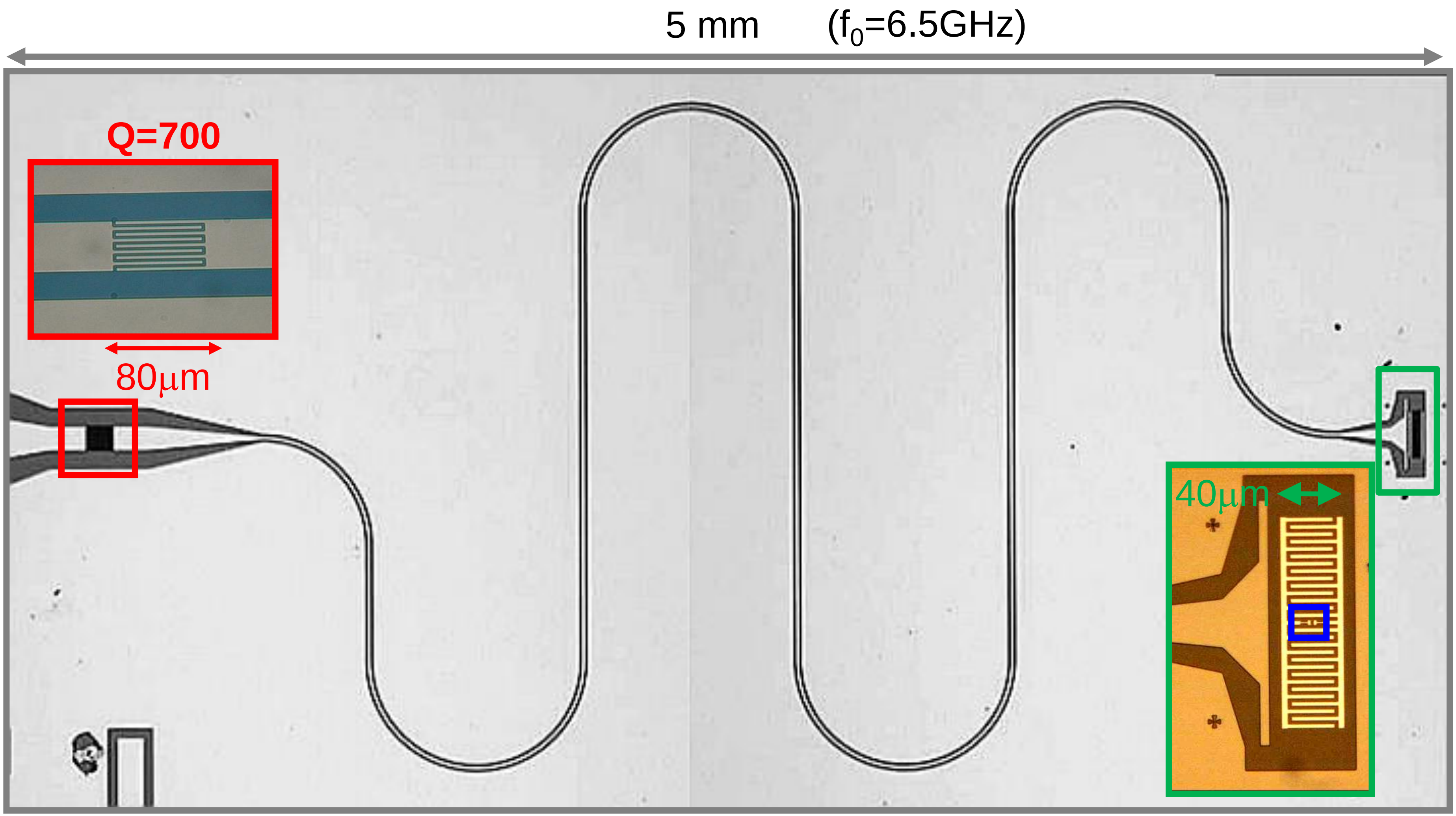
2. Circuit-QED architecture to readout a Josephson qubit





2. Circuit-QED architecture to readout a Josephson qubit

Typical implementation (Quantronics) with λ/2 coplanar waveguide resonator



(optical+e-beam lithography)

Δ =1GHz => $\left|\phi_{|1\rangle} - \phi_{|0\rangle}\right| \approx 10°$

2. Circuit-QED architecture to readout a Josephson qubit

A key figure of merit is the single-shot readout error rates (or readout fidelity)

|0> ➡ $P(0) = 1-\varepsilon_0$

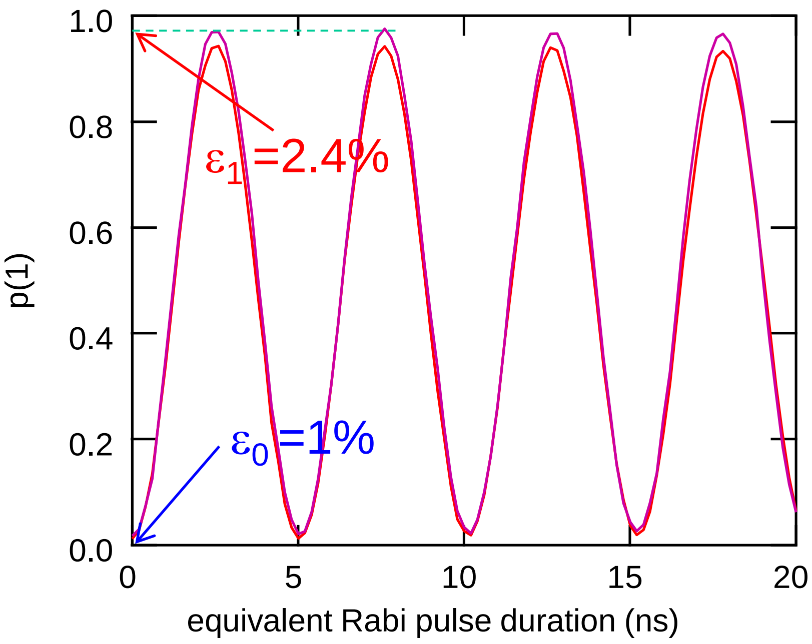
|1> ➡ $P(1) = 1-\varepsilon_1$

$\text{Fidelity} = 1 - \varepsilon_0 - \varepsilon_1$

Fidelity limited by

- qubit relaxation during measurement time
- noise of first amplifier

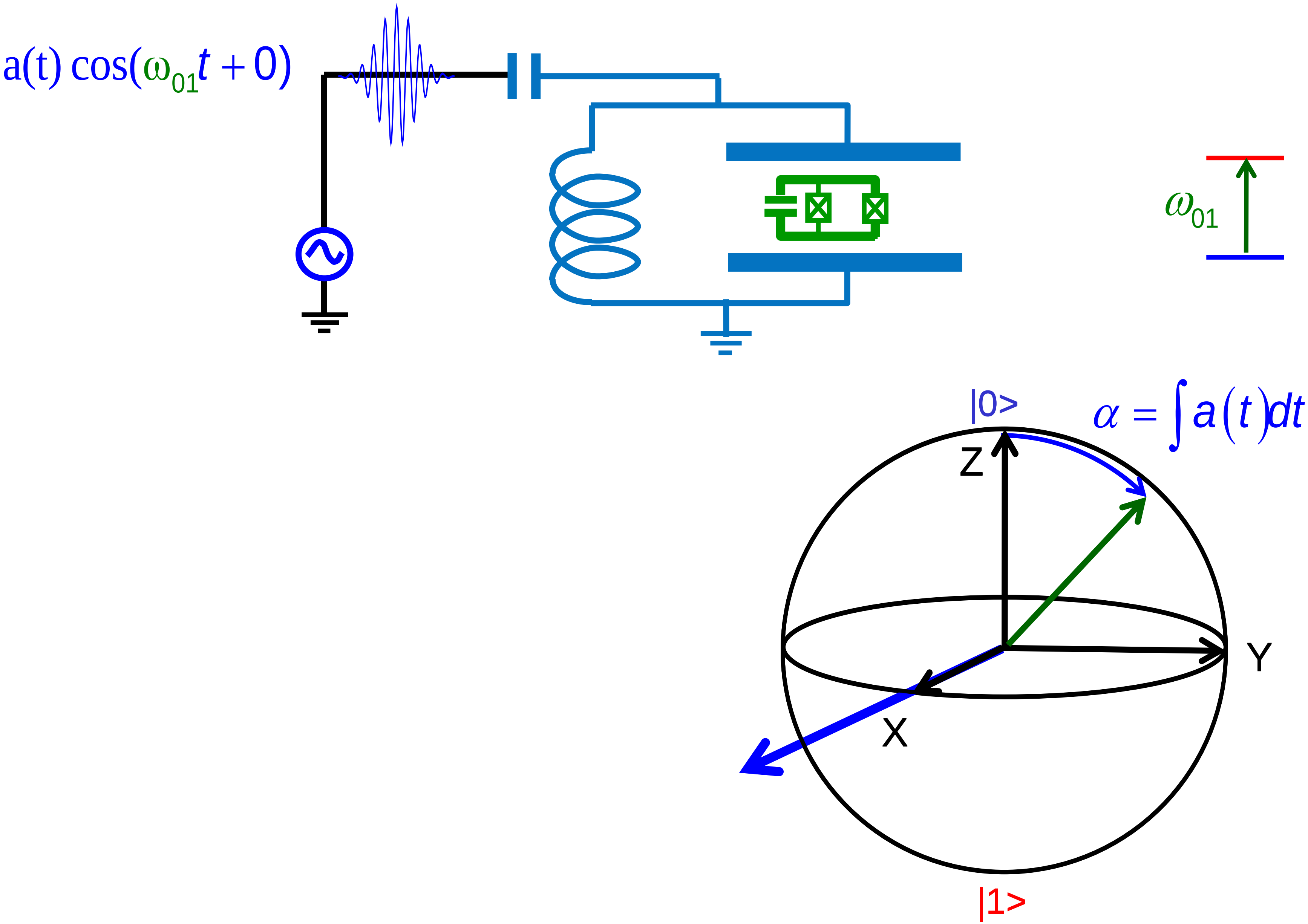
Quantronics 2014 (Josephson bifurcation amplifier)



Today :

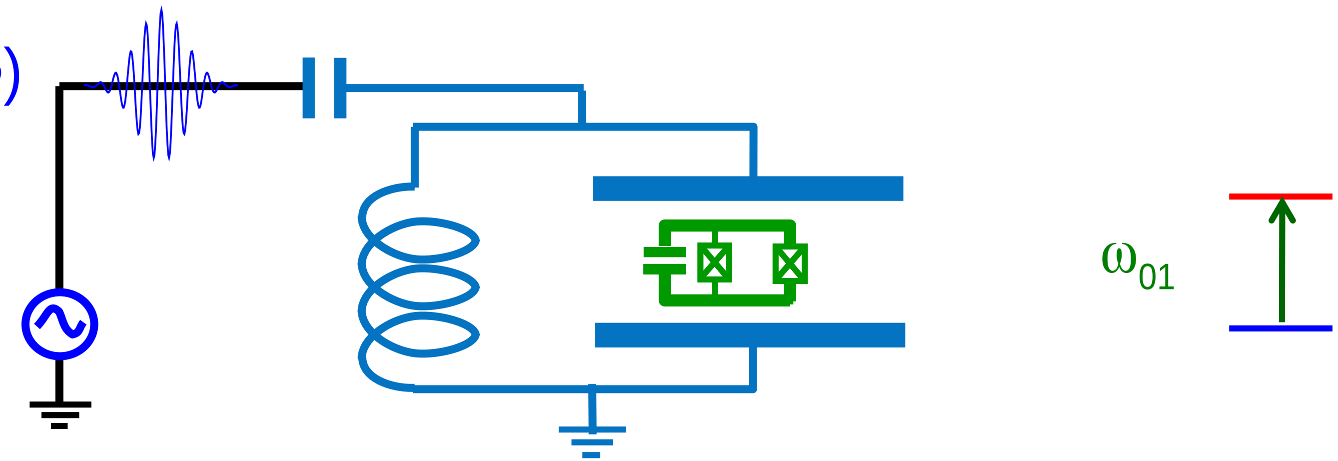
ε_0 , ε_1 < 0.2% in 500 ns with quantum limited parametric amplifiers

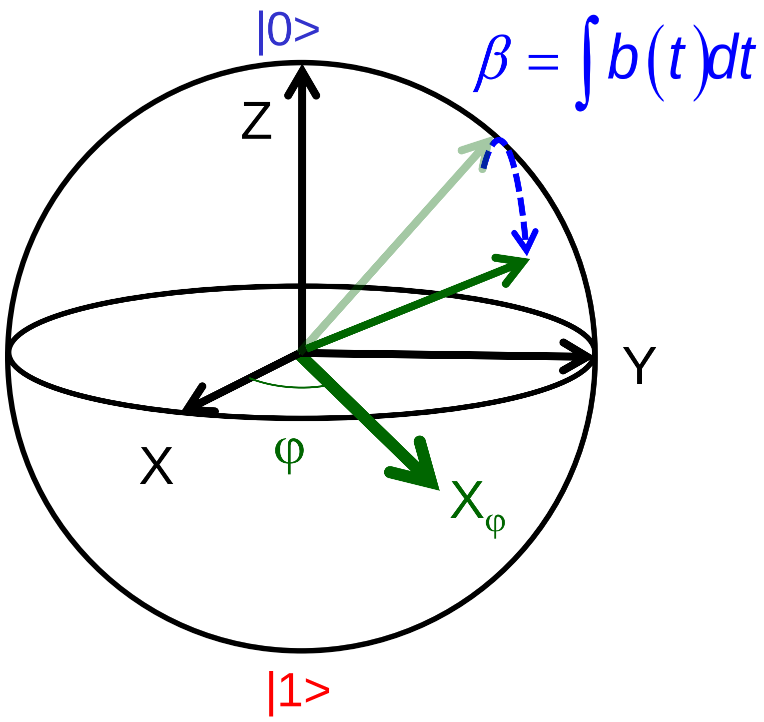
3. Single qubit gates: rotation around X



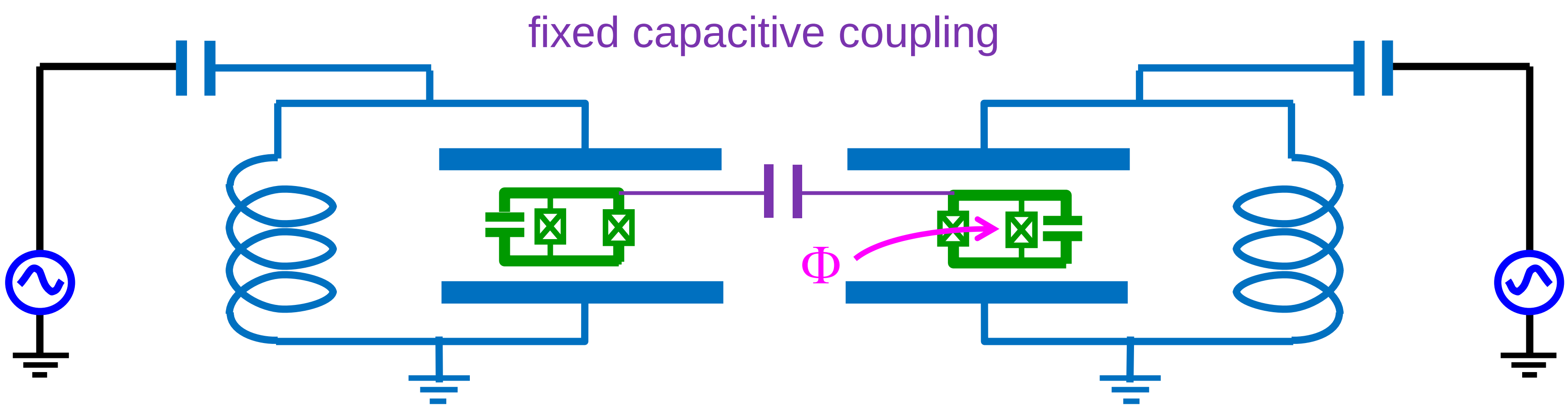
3. Single qubit gates: rotation around X_φ in equator

$b(t)\cos(\omega_{01}t+\varphi)$





5. Simple example of the iSWAP$^{1/2}$ two-qubit gate

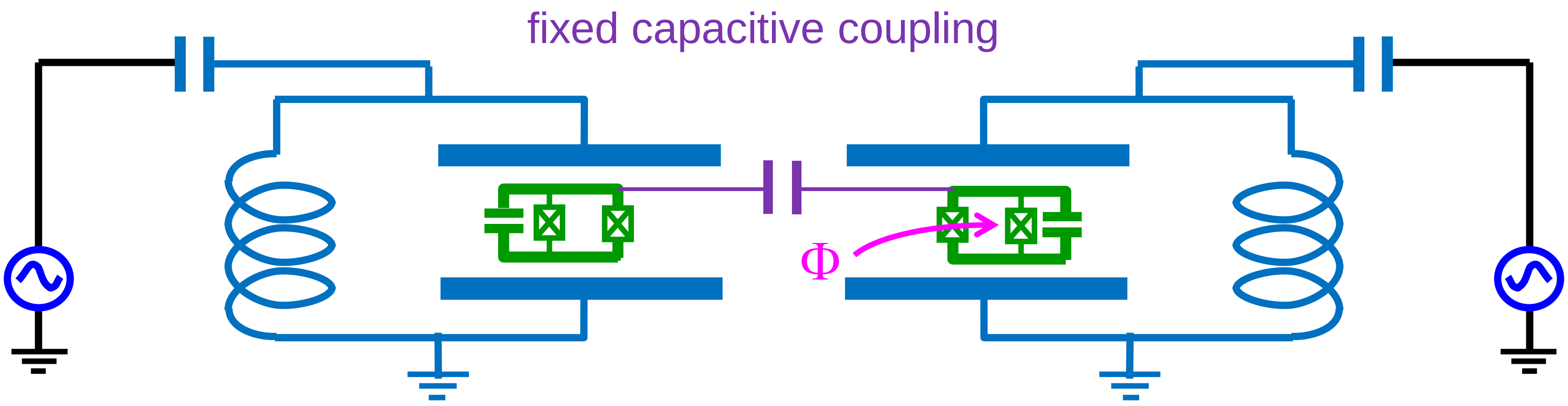


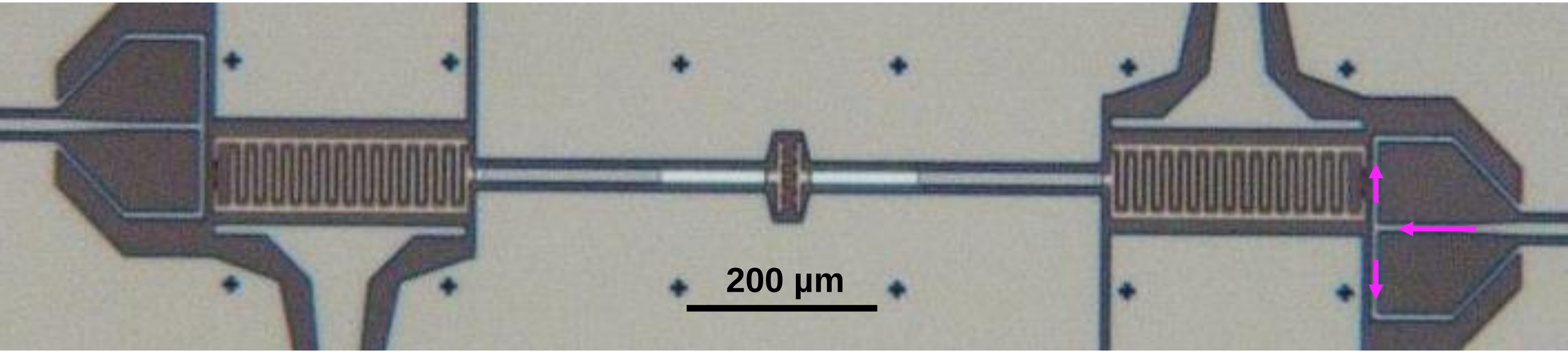
$$H/h = -\frac{\nu_{01}^{A}}{2}\sigma_z^A - \frac{\nu_{01}^{B}}{2}\sigma_z^B + g\left(\sigma_+^A\sigma_-^B + \sigma_-^A\sigma_+^B\right)$$

qubits coupled only on resonance $\nu_{01}^{I} = \nu_{01}^{II}$ $\quad U_{\text{int}}\left(\frac{\pi}{2g}\right) = \sqrt{i\text{SWAP}}$

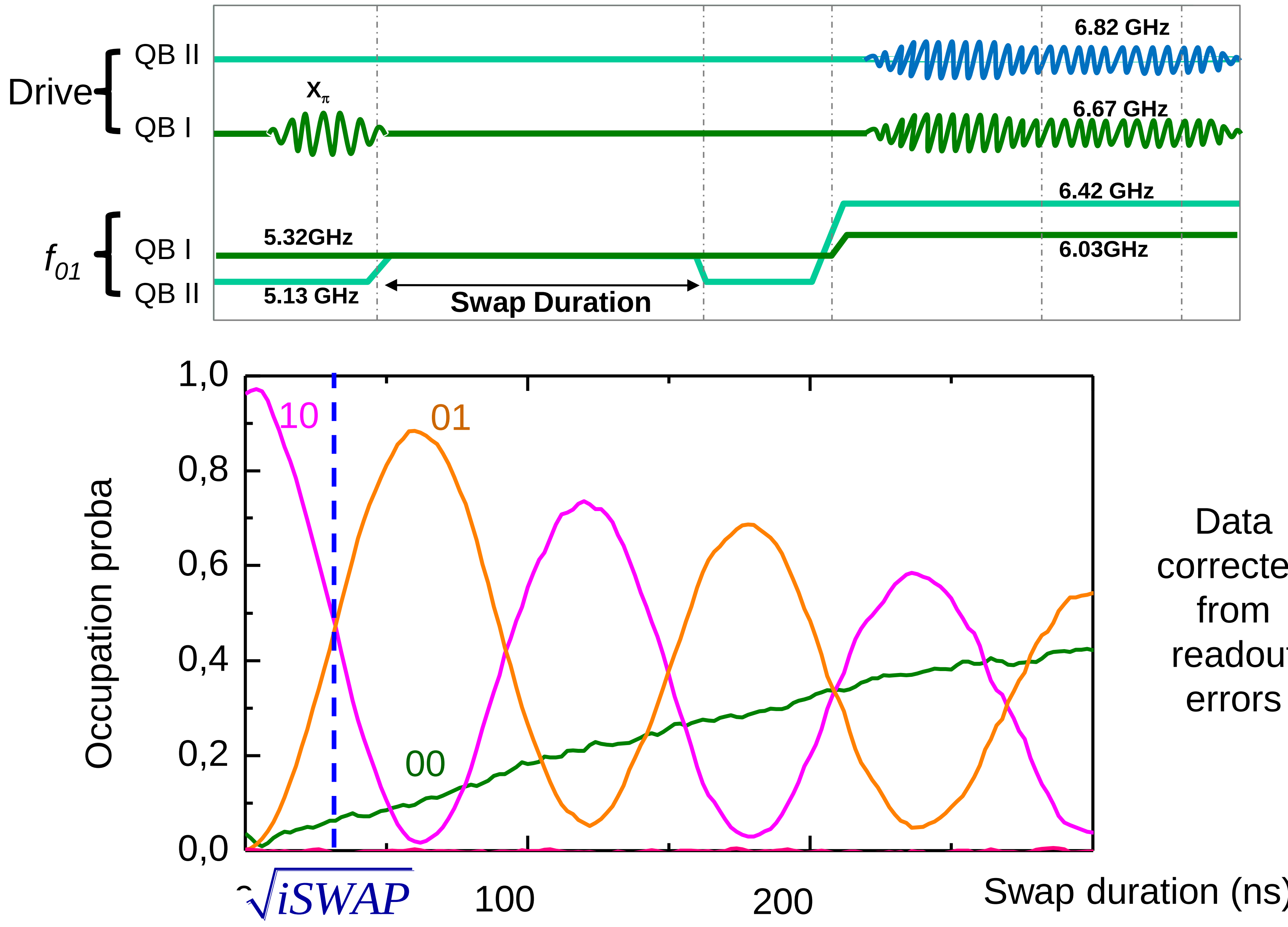
Fastest entangling gate $\quad |01\rangle \Rightarrow \frac{|01\rangle + i|10\rangle}{\sqrt{2}}$

5. Simple example of the iSWAP$^{1/2}$ two-qubit gate



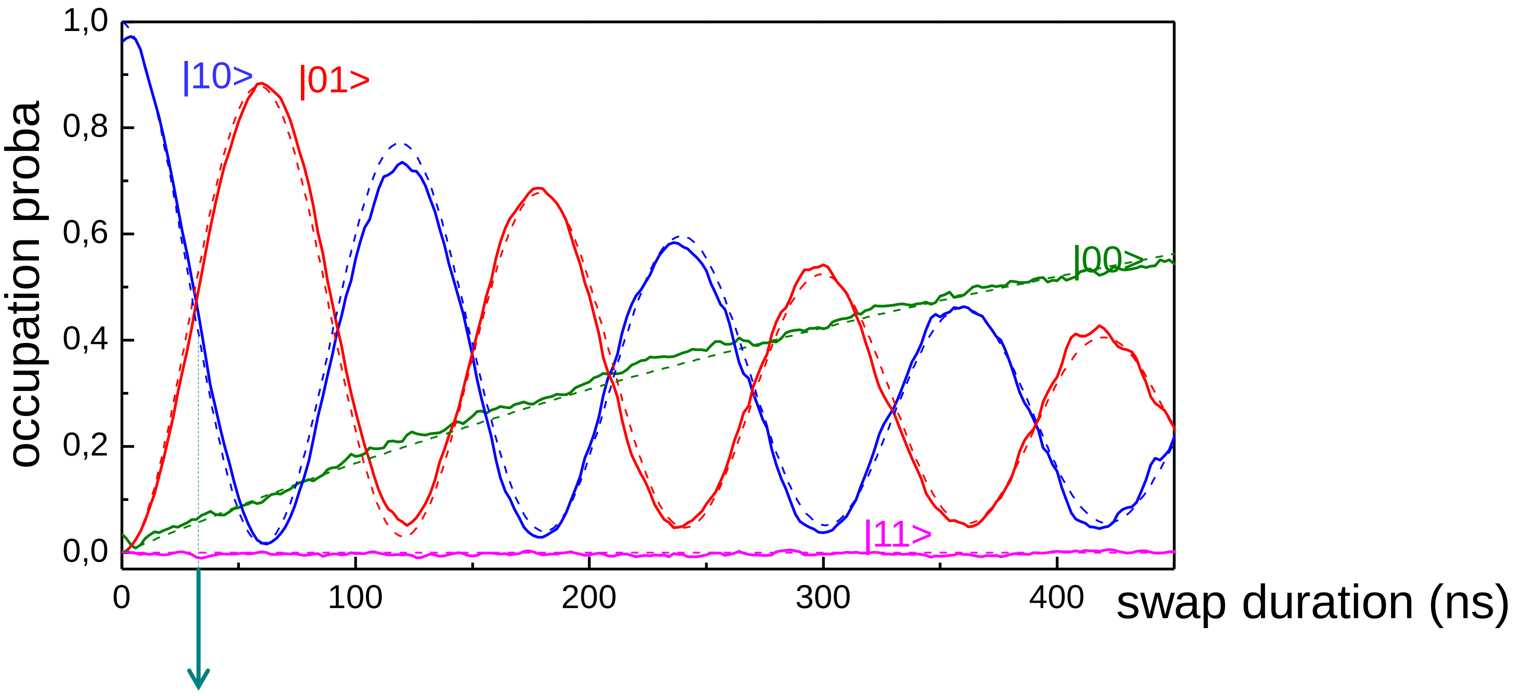


4. Simple example of the iSWAP$^{1/2}$ two-qubit gate



Data corrected from readout errors

4. Characterizing the iSWAP$^{1/2}$ two-qubit gate



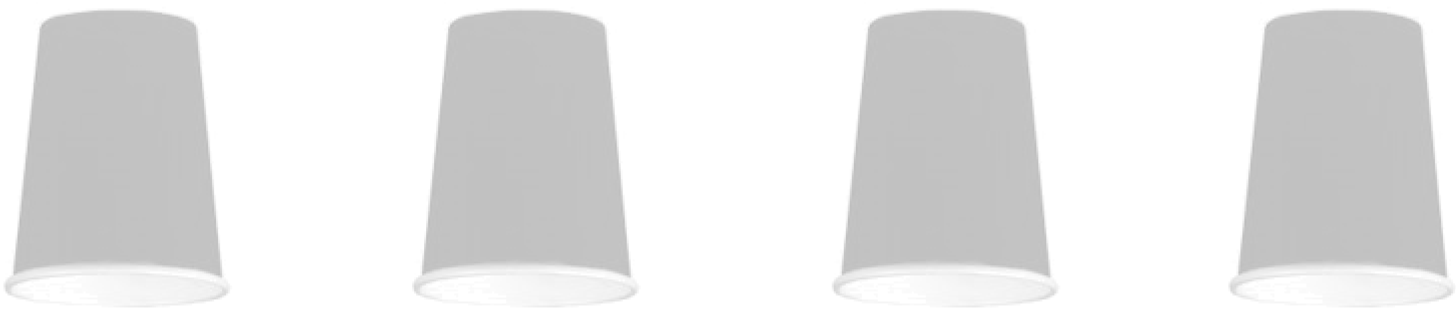
gate tomography F=92%

Todays gate fidelity F>98%

5. The grover search algorithm: a benchmark for quantum speedup

$x, y \in \{00, 01, 10, 11\}$

$$f_y(x) = \begin{cases} 1, & x = y \\ 0, & x \neq y \end{cases}$$



$f_{01}(00)=0$ $f_{01}(01)=1$ $f_{01}(10)=0$ $f_{01}(11)=0$

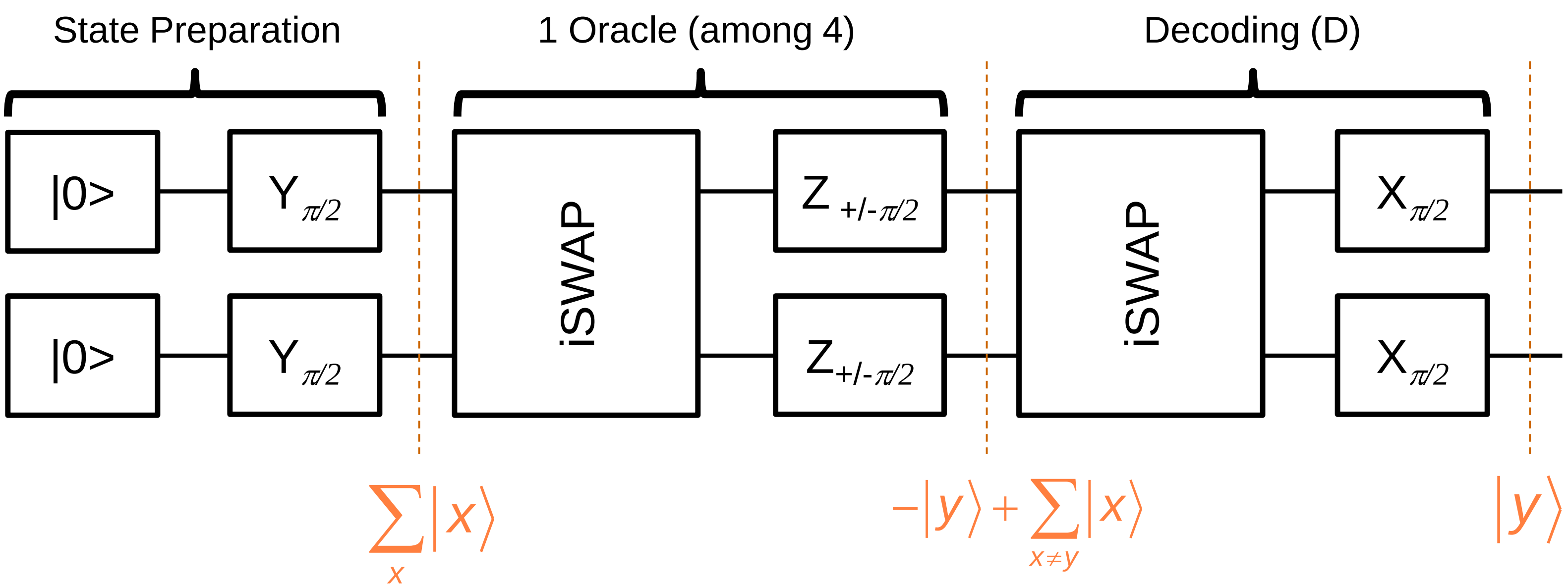
CLASSICALLY

Random trial: probability of success 1/4

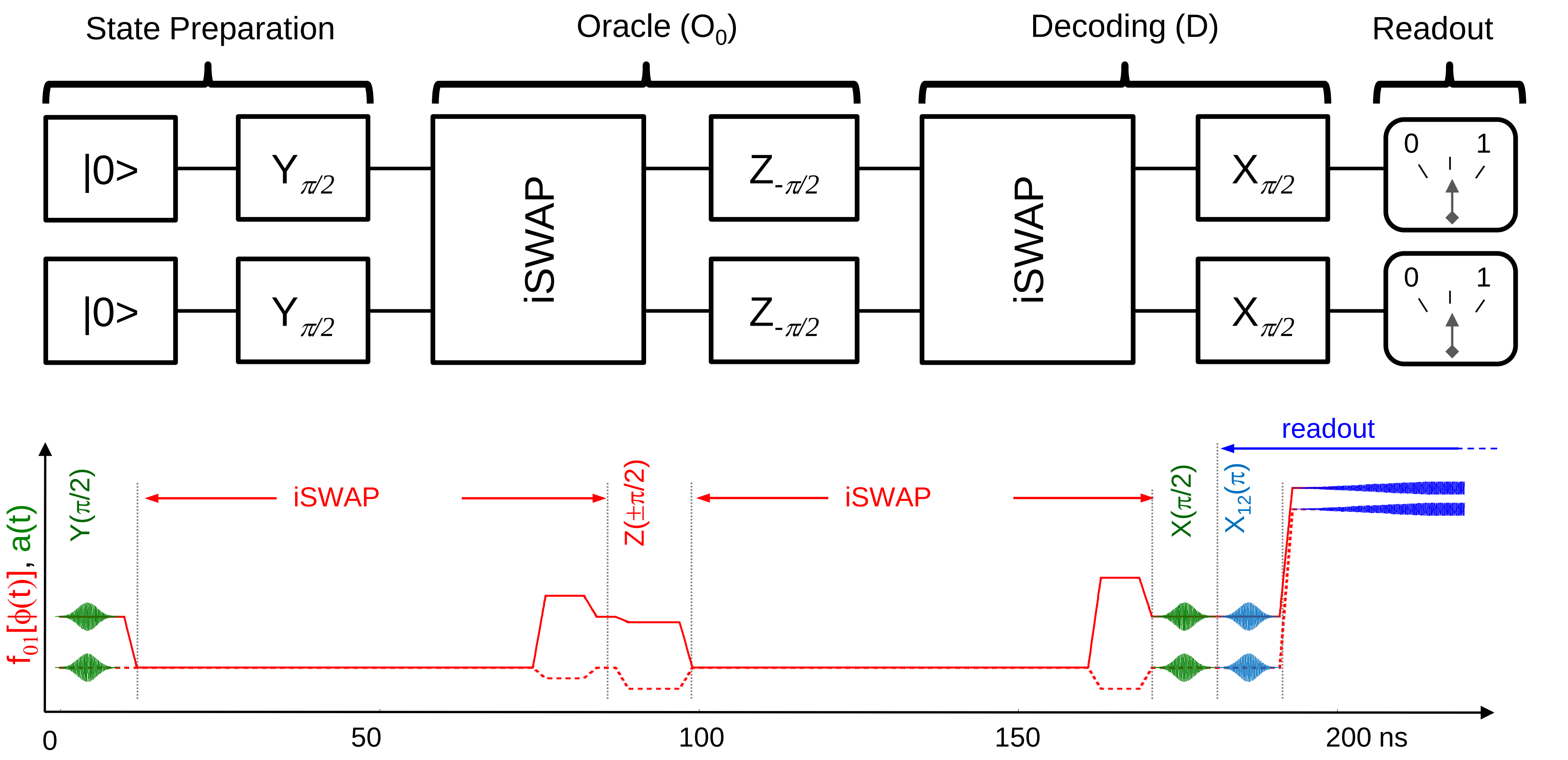
QUANTUM-MECHANICALLY

Grover's search algorithm : probability can reach 1 !

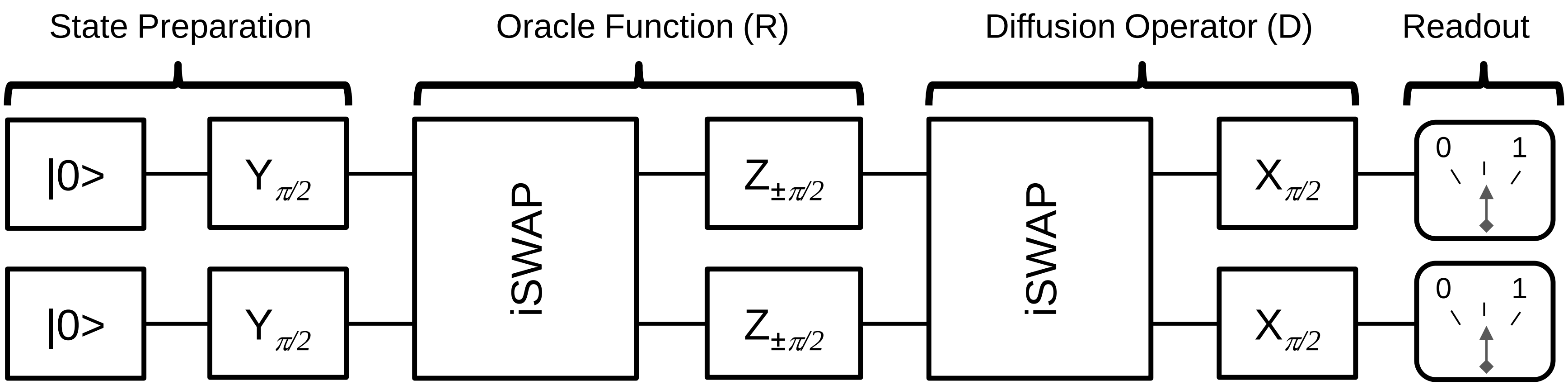
6. The grover search algorithm: encoding

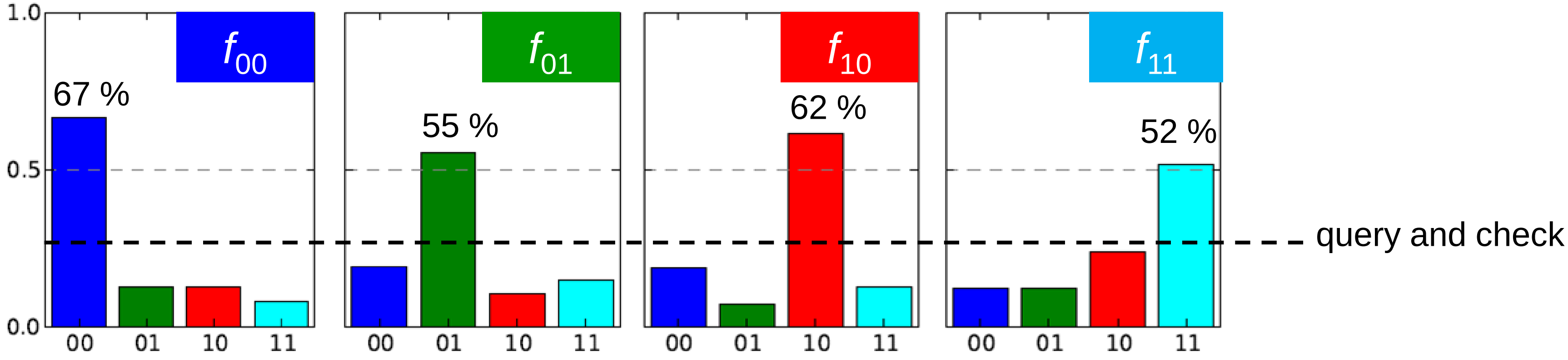


5. The grover search algorithm: pulse implementation



5. The grover search algorithm: success probability





F_i **> 25 %** for all oracles → **Quantum speedup achieved!**

Dewes et. al., PRB Rapid Comm **85** (2012)

What we have seen:

- Superposition and entanglement is the fuel
- Big problem: Decoherence => good qubits + error correction => overhead
- Competition between hardware platforms (atoms, photons, spins, circuits)
- Example: superconducting circuits (~ 100 two qubit gates coherent times)

Recent demonstration

- Error correction demonstrated with very limited improvement
- Operational 17 qubit toy processors – 2000 qubit AQC annealers
- « Calculation » of very simple diatomic molecules

Current research trends (not exhaustive)

- Surface code: an architecture robust against decoherence at the price of a huge overhead
- Stabilization of quantum states by dissipation engineering
- Hybrid architectures combining circuits for fast gates and spins for long memory

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