HOW DO WE GET TO A QUANTUM ADVANTAGE?

Blaise Vignon
CPO

ALICE & BOB

2 years old

27M€ raised

50 people

MINES ParisTech

ENS
ÉCOLE NORMALE SUPÉRIEURE

inria

QUANTUM CIRCUITS ARE MUCH SLOWER THAN CLASSICAL CIRCUITS

Gate time in some quantum media

Qubit type or technology	Superconducting[2]	Trapped ion	Photonic	Silicon-based
Gate operation time	~10–50 ns	~3-50 μs	~1 ns	~1–10 ns

Gate time in classical electronics

Production Year	Technology Node (nm)	Delay (ps)
1999	180	77.2
2001	130	34.7
2004	90	26.5
2007	65	19.8
2008	45	10.9
2010	32	9.8
2012	20	9.66
2013	16[a]	6.12
2013	14[a]	4.02
2015	10	3.24
2017	7	2.47

[a] The 2013 ITRS report labels a single "16/14"

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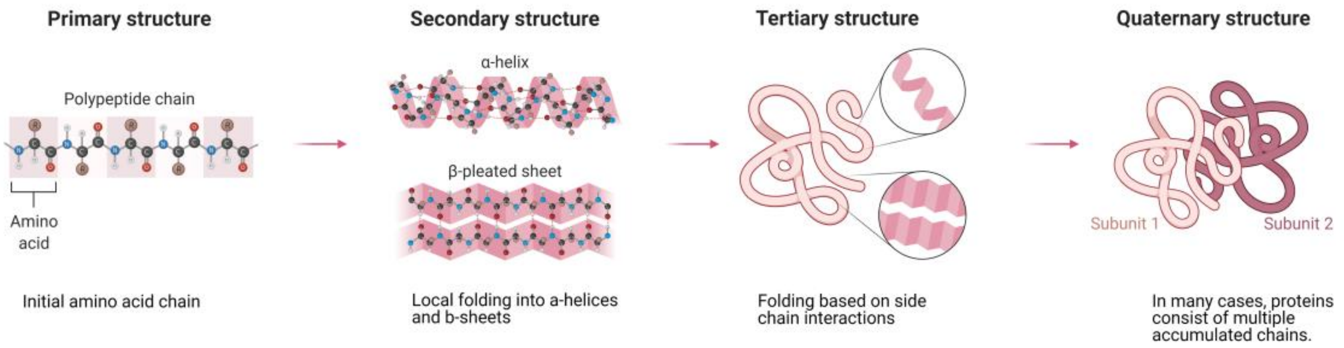
THIS IMPACTS WHICH PROBLEMS CAN BE USEFULLY SOLVED ON A QUANTUM COMPUTER

Quantum MonteCarlo, for example, promises a polynomial speedup, eaten away by gate speed differences

	n_{steps}	t_{step}	Total time	Logical qubits
Classical [65]	4×10^9	2.3×10^{-4}s	10.6 days	-
Quantum (parallel)	8.9×10^4	16.4 mins	2.8 years	$\sim 4 \times 10^4$
Quantum (serial)	8.9×10^4	25.2 hours	256 years	$\sim 10^4$



Antibody loop modelling on a quantum computer
Quantum Monte Carlo
Roche and Tencent

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ONLY A FEW ALGORITHMS EXHIBIT EXPONENTIAL SPEEDUP

Quantum Algorithm Zoo

Stephen Jordan

Microsoft Quantum

(A selection)

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> “If there exists a positive constant α such that the runtime C(n) of the best-known classical algorithm and the runtime Q(n) of the quantum algorithm satisfy $C = 2^{\Omega(Q^{\alpha})}$ then I call the speedup superpolynomial.”

SUPERPOLYNOMIAL SPEEDUP	POLYNOMIAL SPEEDUP
Quantum simulation	Exponential congruence
ODE and PDE	Subset sum
Shor	Grover (search)
Discrete-log	Constraint Satisfaction

Engineering

Crypto

Discrete optimization

Chemistry

EXPONENTIAL SPEEDUP ALGORITHM REQUIRE DEEP CIRCUITS

Deep circuits require low error rates, likely on the order of 10^{-12}

Running **Shor** on N bit key means: $n=O(N)$ $d=O(N^3)$

Actually $O(N^2 \log(N) \log(\log(N)))$ but let's keep things simple.

Hence the **error budget** to run Shor is $O(N^4)$

RSA2048 → 10^{-12}

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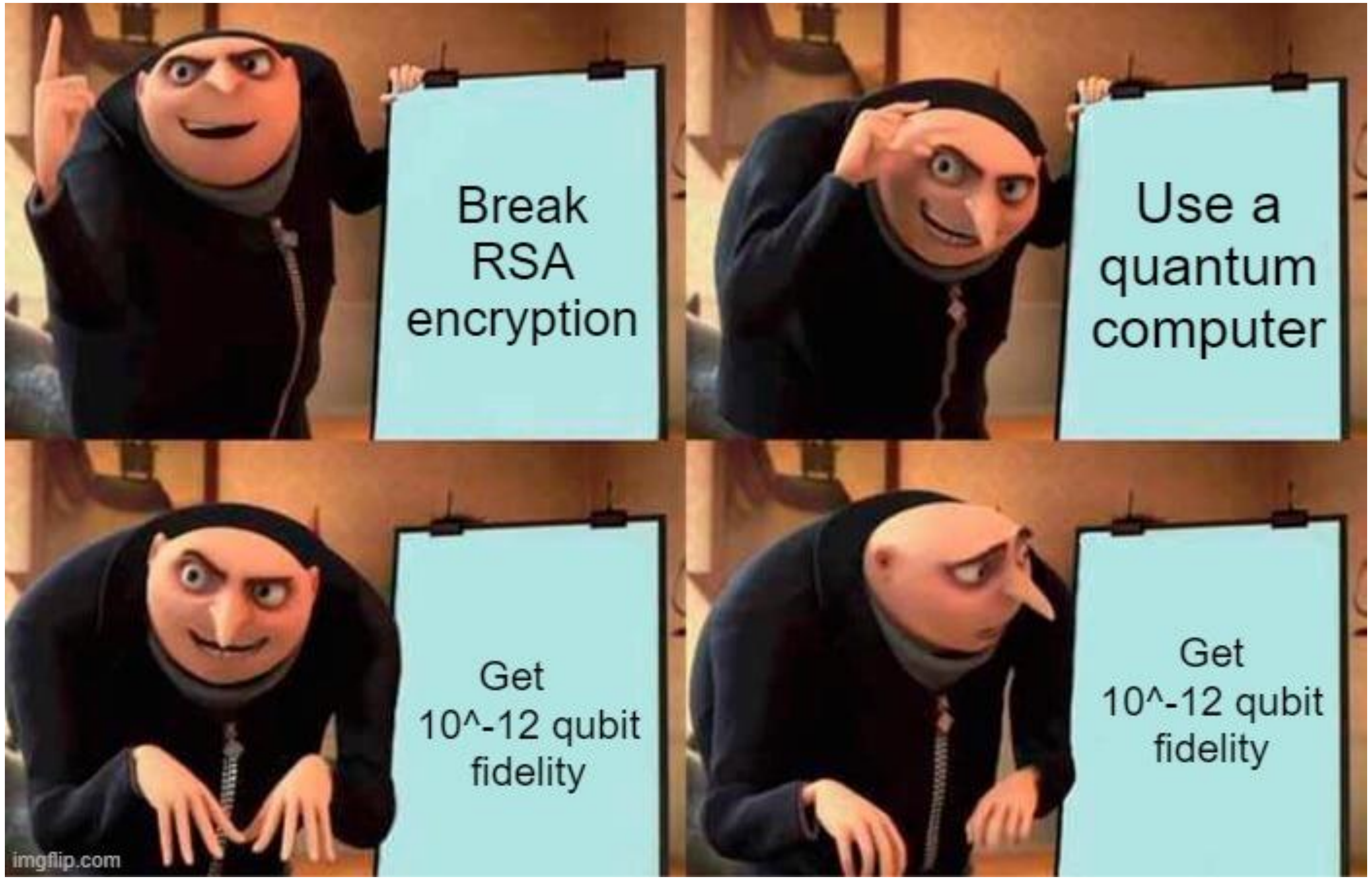
IN PRACTICE, QUANTUM ADVANTAGE LIKELY REQUIRES EXPONENTIAL SPEEDUP



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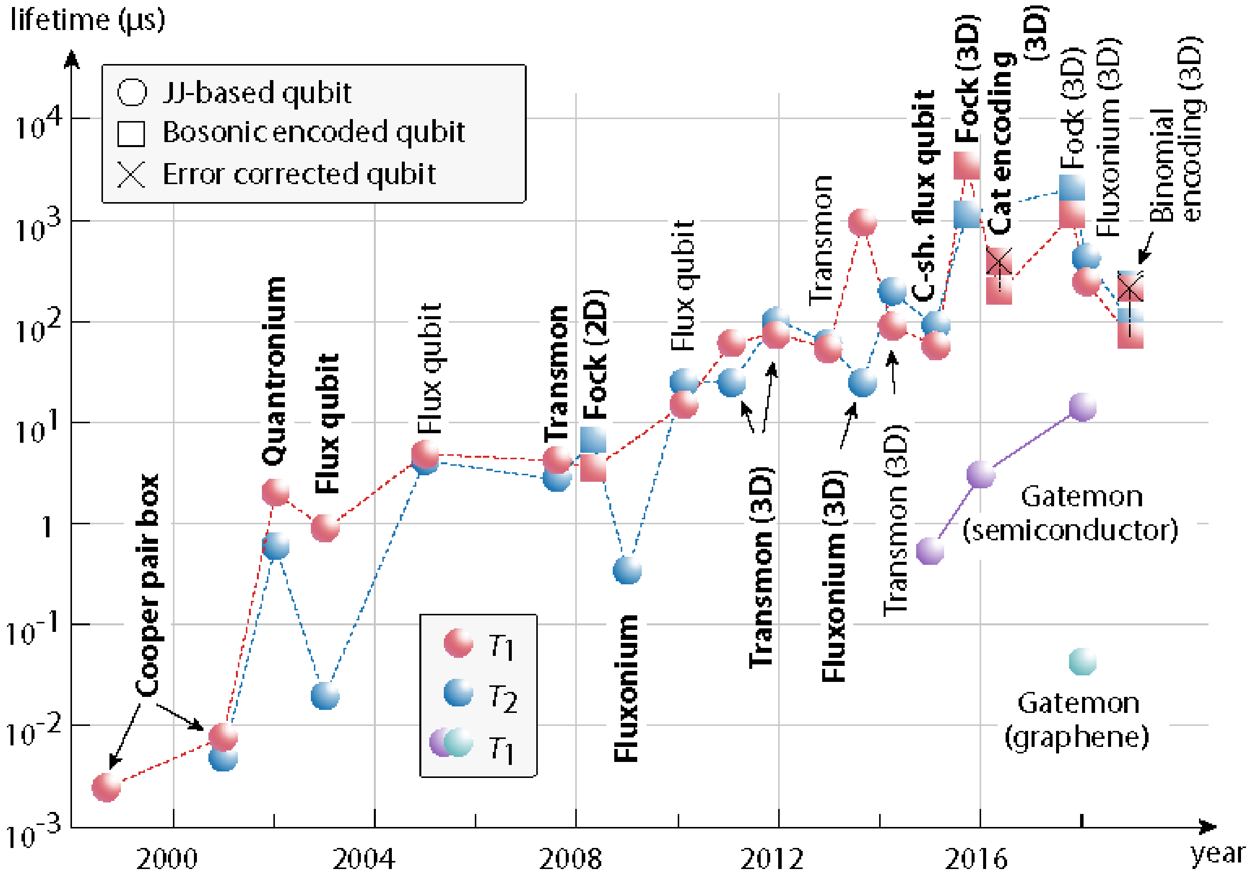
SUCH ERROR RATE CANNOT BE ACHIEVED BY PROGRESS ON MATERIAL SCIENCE ALONE

Superconducting materials progress seems to have plateaued



M. Kjaergaard, W.D. Oliver et al., Annual Review of Condensed Matter Physics, 2019.

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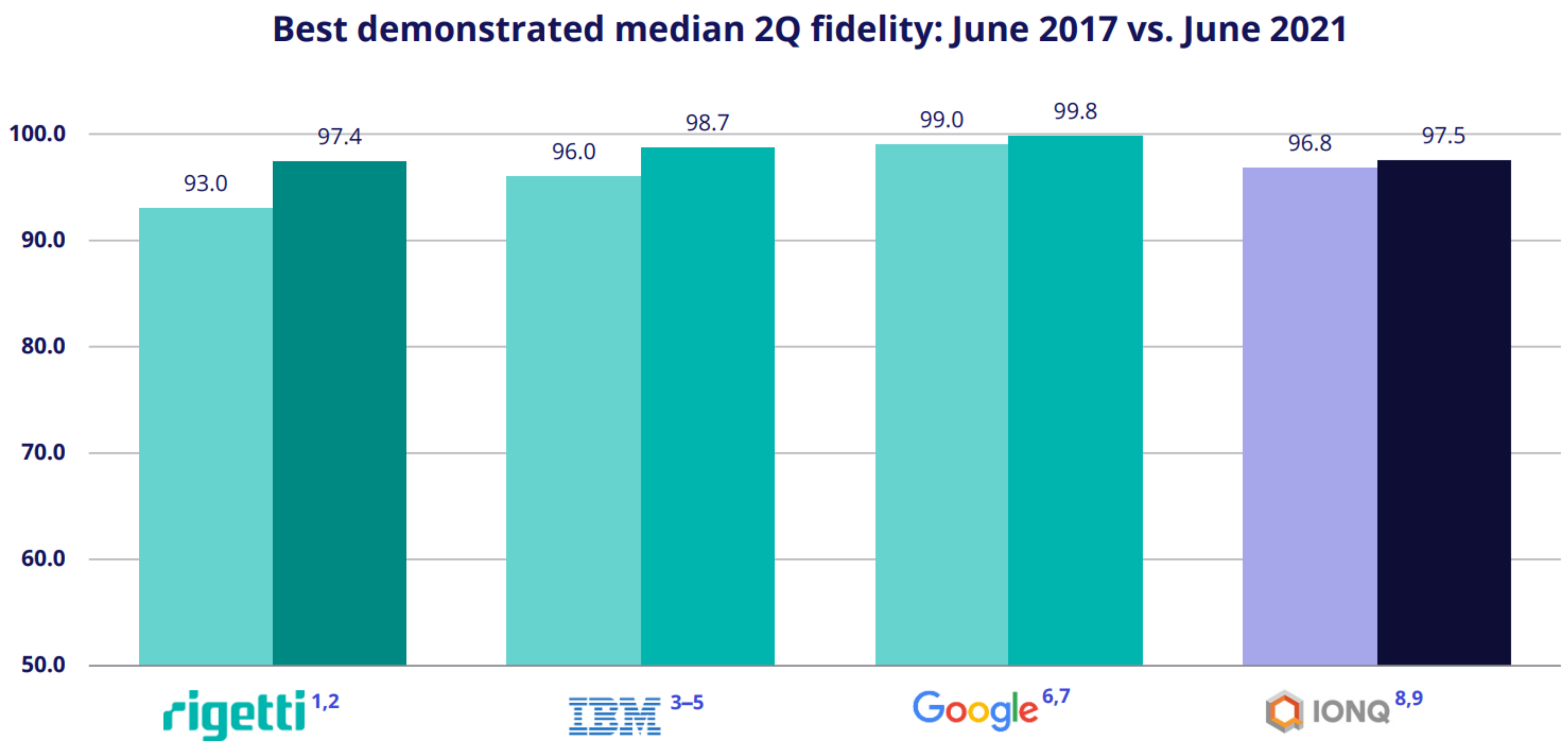
SUCH ERROR RATE CANNOT BE ACHIEVED BY PROGRESS ON MATERIAL SCIENCE ALONE

Fidelity of 2-qubit gates has only improved by at most 5x in 4 years



Rigetti investor presentation
October 2021

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ERROR CORRECTION IS NECESSARY

"Fault tolerant" and "Universal" quantum computing are needed

Fault tolerance

We need to have strong enough error correction for our qubits error level

Universality

Ability to implement any quantum algorithm (without introducing uncorrectable errors)

QUANTUM ADVANTAGE

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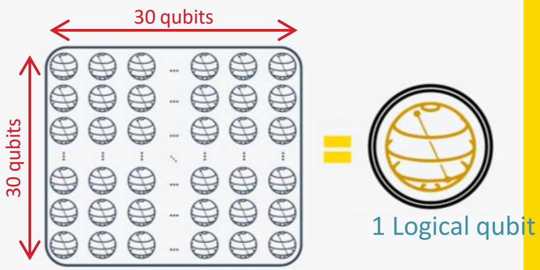
LSQ LITERALLY MEANS "A LOT OF QUBITS" : IS IT NECESSARY?

QUANTITATIVE APPROACH TO REDUCE ERRORS

30 physical qubits to correct each type of error



DEFINITION

Logical qubit

Qubit able to store quantum information with sufficiently low error probability

Universal qubit

Logical qubit able to perform any type of operation

Universal Quantum Computer would require 1,000,000+ physical qubits

1,000 Physical qubits → 30 x 30 → Bit-flips correction / Phase-flips correction → 1 Logical qubit

100,000 Physical qubits → 100 Logical qubits → 1 Universal qubit

1,000,000+ Physical qubits → 10+ Universal qubits → 1 Universal Quantum Computer

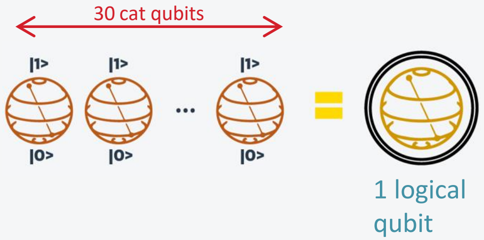
Players following this strategy

Google | IBM | rigetti | IONQ | intel | PsiQuantum

With 127 physical qubits

A&B´S QUALITATIVE APPROACH

Only 30 cat qubits needed to correct phase-flip errors



1,000x fewer physical qubits to build a Universal Quantum Computer

01.

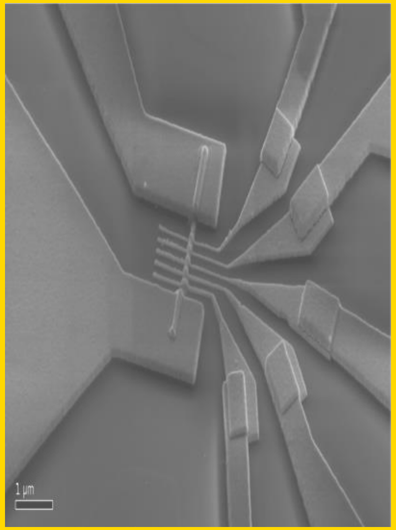
Cat Qubit:
Autonomous error-correction of bit flips by design

02.

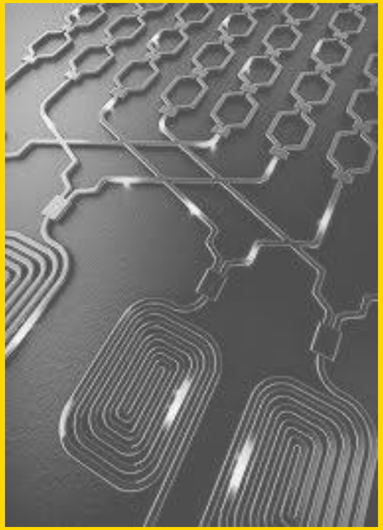
Shortcut to universality

	"QUANTITATIVE" APPROACH: STANDARD QUBITS		BY DESIGN APPROACH: CAT QUBITS
1 LOGICAL QUBIT	1,000 physical qubits	vs / 30	30 cat qubits
1 UNIVERSAL QUBIT	100,000 physical qubits	vs **/ 1,000**	90 cat qubits

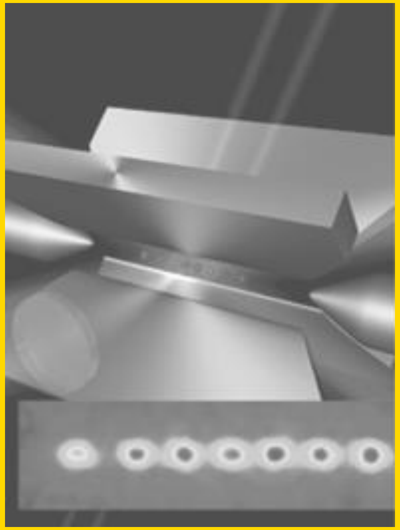
ALICE AND BOB IN THE ZOOLOGY OF QUBITS



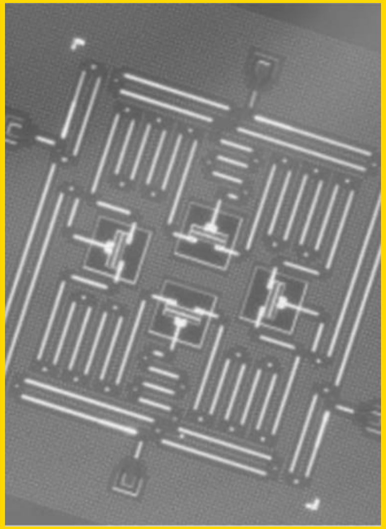
Spin qubits



Photons

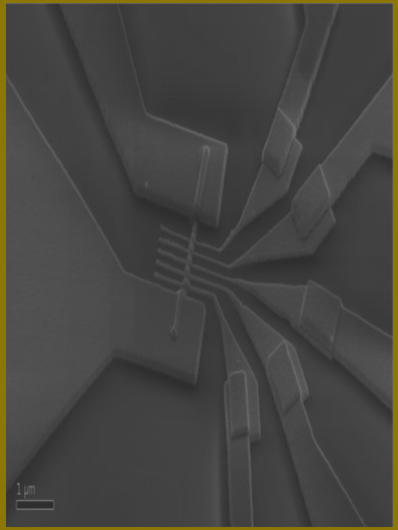


Ions / Atoms

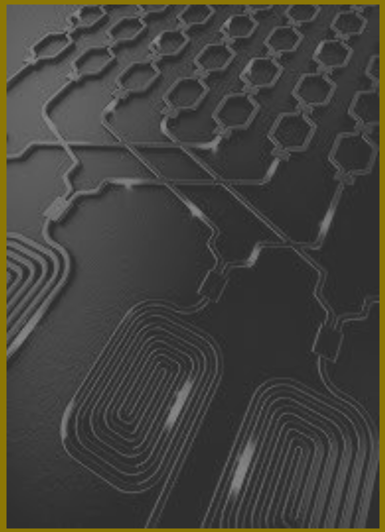


Superconducting circuits

ALICE AND BOB IN THE ZOOLOGY OF QUBITS



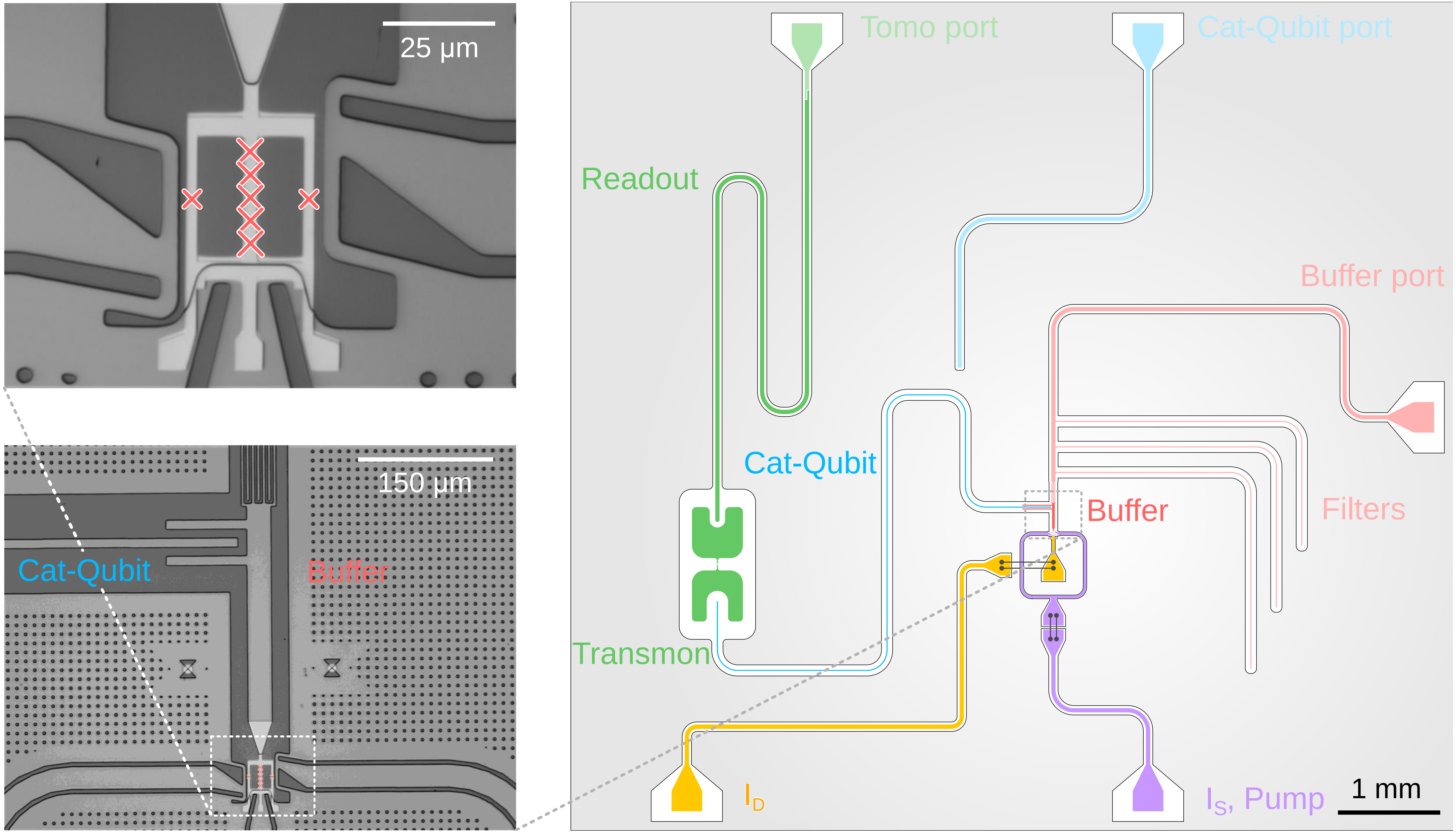
Spin qubits



Photons

Ions / Atoms

Superconducting circuits



25 μm
150 μm
Cat-Qubit
Buffer
Tomo port
Cat-Qubit port
Readout
Buffer port
Cat-Qubit
Buffer
Filters
Transmon
I_D
I_S, Pump
1 mm

A&B AT THE FOREFRONT OF THE QUANTUM RACE

Same league as Google

Amazon as following suit

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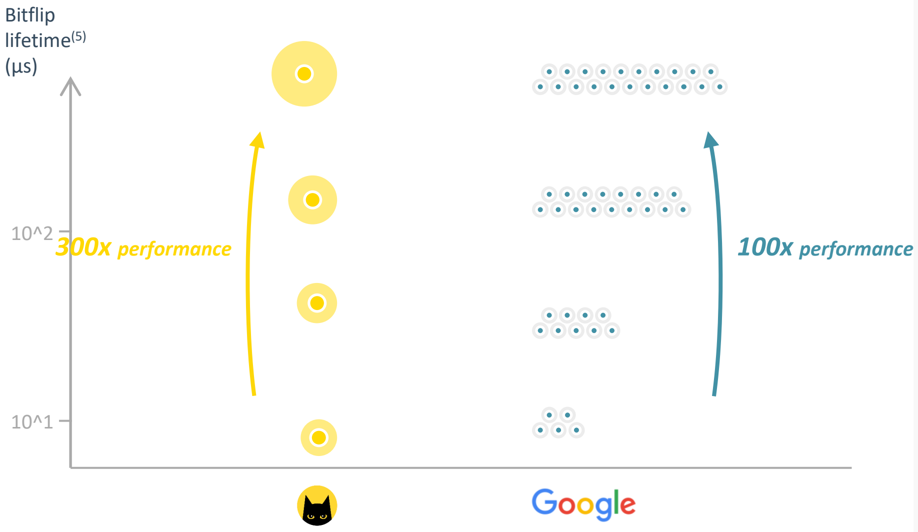
01. vs Google

1 ≈ **21**

A&B cat qubit | *Performance based* | Google physical qubits(4)

1 single cat qubit *(with different error correcting parameters)*

From 5 to 21 physical qubits



02. vs amazon

Amazon **chose the cat qubit technology for its quantum strategy**, validating A&B's approach:

100% of scientific papers quoted(1)

151x quotes(2)

› Amazon **lags a few years behind**

› Amazon **depends on A&B's "ATS"(3)**

(1) Quoted in Amazon's announcing blog post, (considering technical papers and not contextualization)

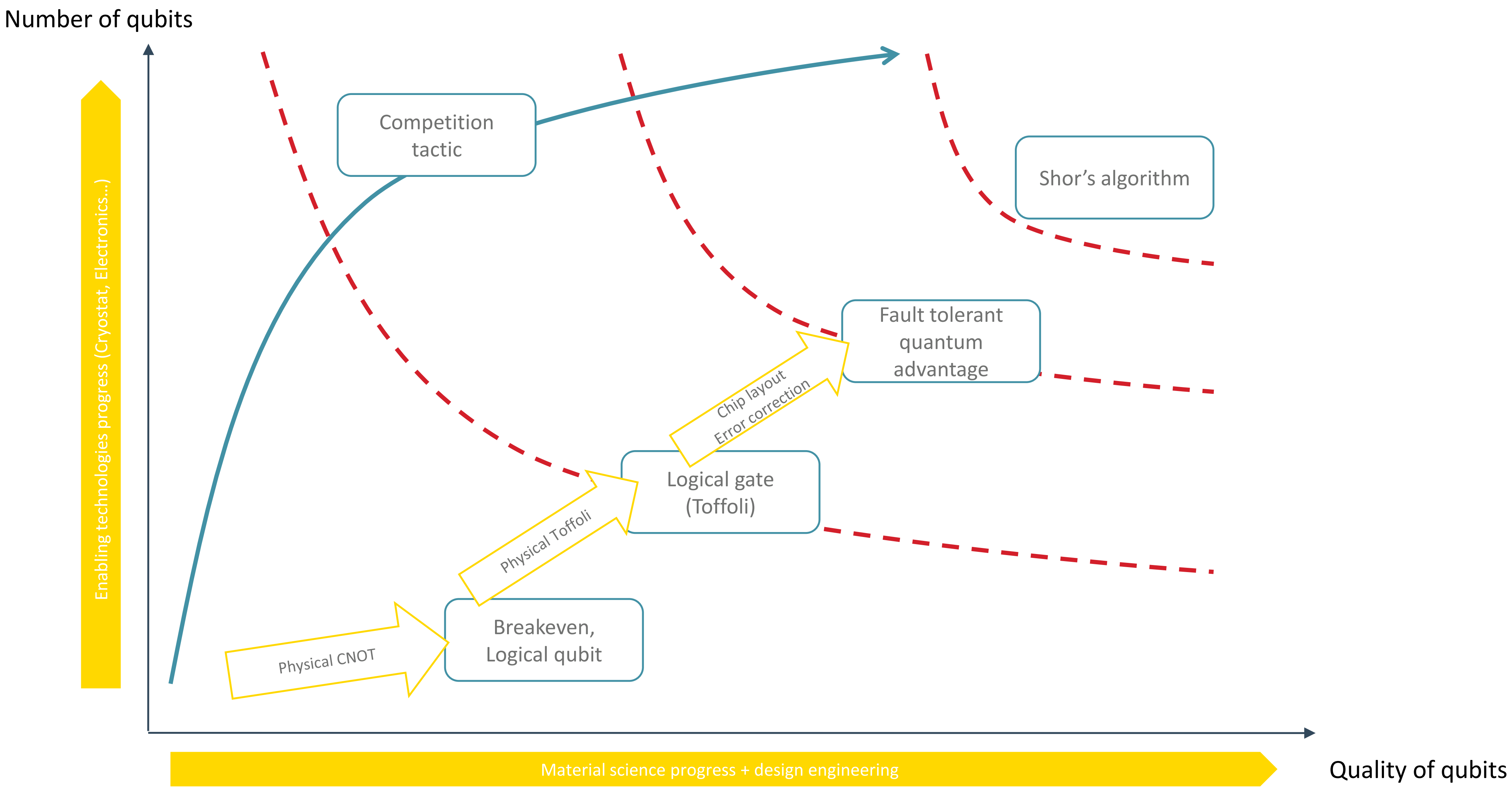
(2) Quoted in Amazon's long form

(3) Asymmetrically Threaded SQUIDs

(4) ArXiv

(5) Source: Management (Appendix 7.7)

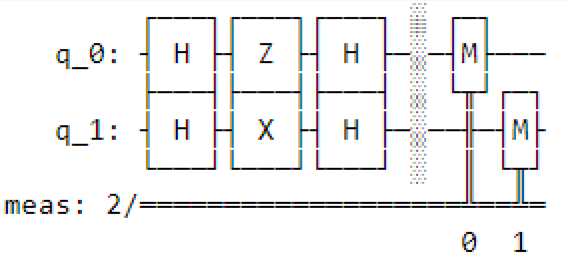
OUR PROJECTED TRAJECTORY DRAWS A SHORTCUT

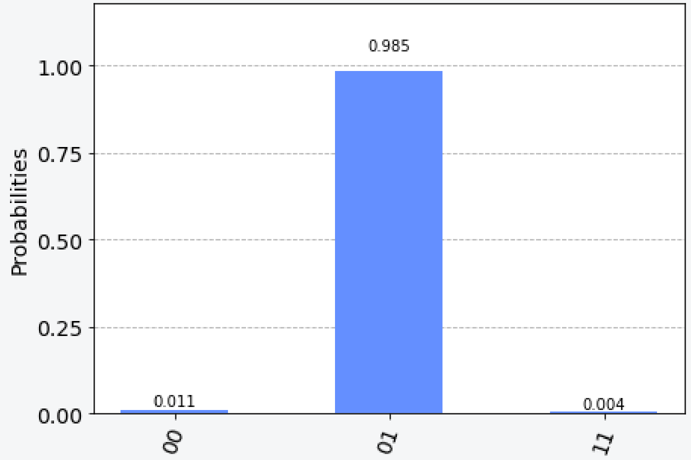



TIME FOR YOU TO GET READY

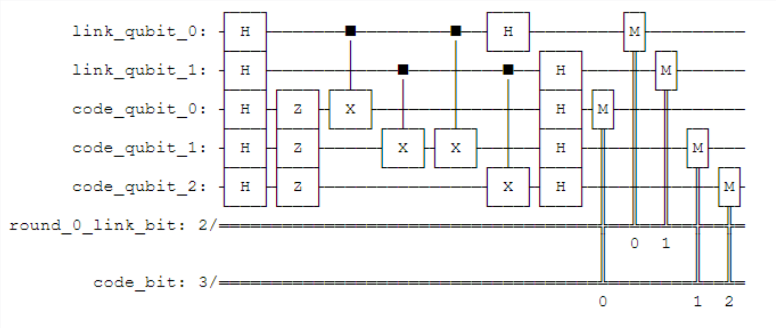
YOU CAN TEST OUR HARDWARE THANKS TO A NOISE MODEL RUNNING ON AER SIMULATOR

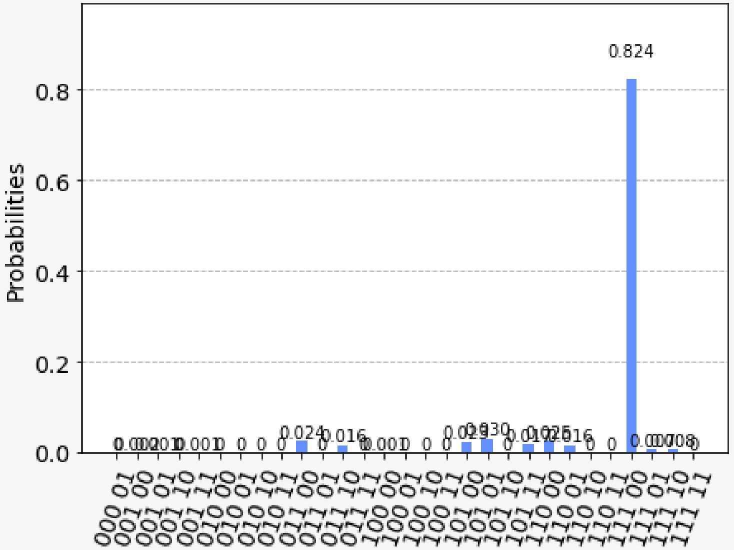
Try and test our noise model on simple circuits:





Implement repletion code and measure logical errors:





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THE PHYSICAL NOISE MODEL IS BACKED BY OUR PREVIOUS PUBLICATIONS

Error Rates and Resource Overheads of Repetition Cat Qubits

Jérémie Guillaud* and Mazyar Mirrahimi
QUANTIC team, Inria Paris, 2 rue Simone Iff, 75012 Paris, France.
(Dated: April 1, 2021)

We estimate and analyze the error rates and the resource overheads of the repetition cat qubit approach to universal and fault-tolerant quantum computation. The cat qubits stabilized by two-photon dissipation exhibit an extremely biased noise where the bit-flip error rate is exponentially suppressed with the mean number of photons. In a recent work, we suggested that the remaining phase-flip error channel could be suppressed using a 1D repetition code. Indeed, using only bias-preserving gates on the cat qubits, it is possible to build a universal set of fault-tolerant logical gates at the level of the repetition cat qubit. In this paper, we perform Monte-Carlo simulations of all the circuits implementing the protected logical gates, using a circuit-level error model. Furthermore, we analyze two different approaches to implement a fault-tolerant Toffoli gate on repetition cat qubits. These numerical simulations indicate that very low logical error rates could be achieved with a reasonable resource overhead, and with parameters that are within the reach of near-term circuit QED experiments.

Repetition Cat Qubits for Fault-Tolerant Quantum Computation

Jérémie Guillaud[1,*] and Mazyar Mirrahimi[1]
[1]*QUANTIC Team, Inria Paris, 2 rue Simone Iff, 75012 Paris, France*
(Dated: December 18, 2019)

We present a 1D repetition code based on the so-called cat qubits as a viable approach toward hardware-efficient universal and fault-tolerant quantum computation. The cat qubits that are stabilized by a two-photon driven-dissipative process, exhibit a tunable noise bias where the effective bit-flip errors are exponentially suppressed with the average number of photons. We propose a realization of a set of gates on the cat qubits that preserve such a noise bias. Combining these base qubit operations, we build, at the level of the repetition cat qubit, a universal set of fully protected logical gates. This set includes single-qubit preparations and measurements, NOT, controlled-NOT, and controlled-controlled-NOT (Toffoli) gates. Remarkably, this construction avoids the costly magic state preparation, distillation, and injection. Finally, all required operations on the cat qubits could be performed with slight modifications of existing experimental setups.

Contact me:
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GET READY FOR QUANTUM ADVANTAGE

A&B is delivering a lean roadmap towards fault tolerant quantum computing.

We could unlock your wildest quantum dreams with quantum error correction.

Are you ready to explore use cases ?