Intermodulation products

Bosonic quantum error correction

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25. Oct 2023.
IEEE Quantum computing workshop, Milpitas, CA USA

CHALMERS
UNIVERSITY OF TECHNOLOGY

Overview

- Error correction
- Quantum error correction
- Bosonic quantum error correction

Error correction example

physical
state

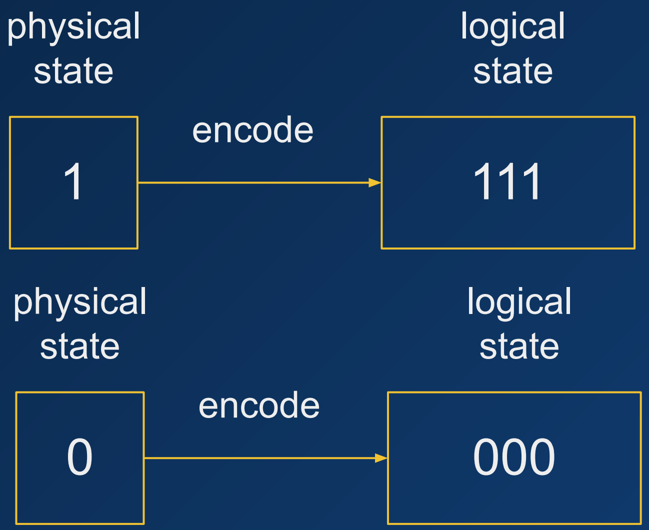
1

physical
state

0

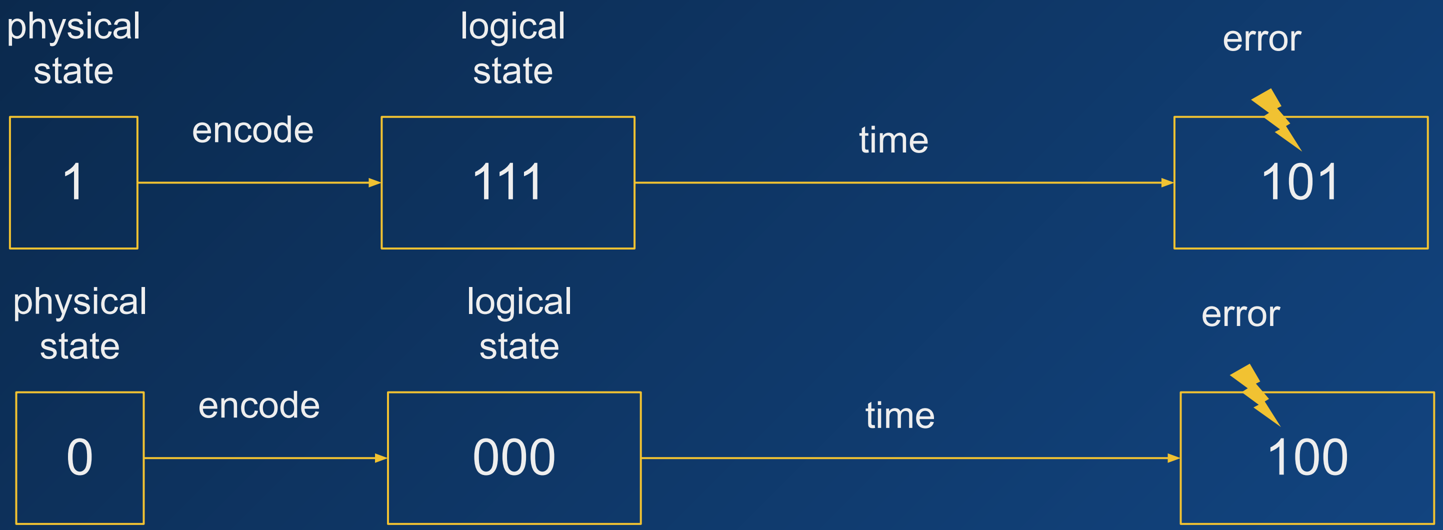
- Two possible states of one classical bit

Error correction example



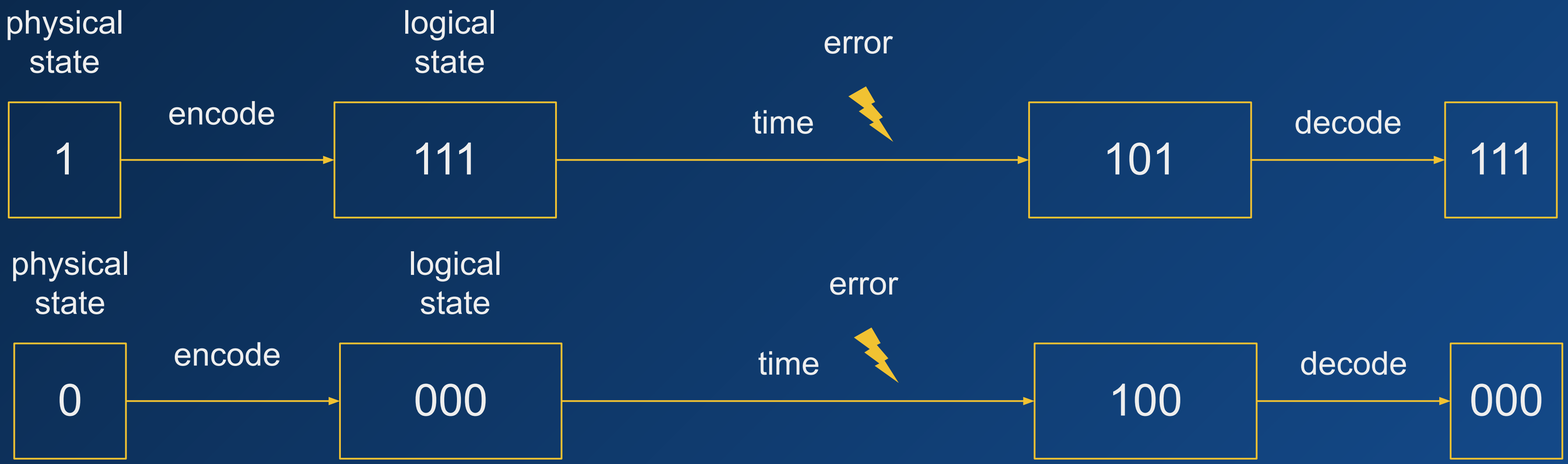
- Encode redundancy for example copy physical bit (repetition code)

Error correction example



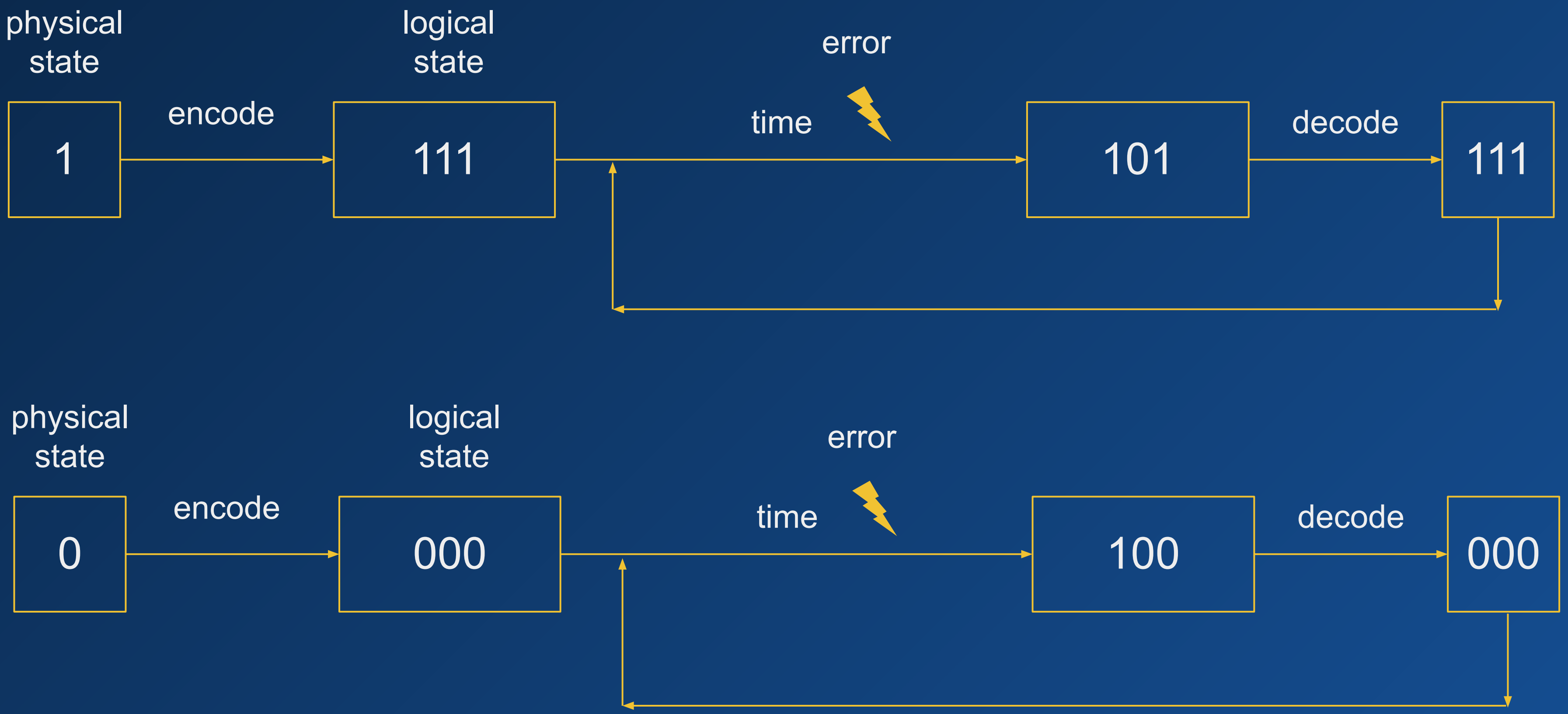
- Different types of errors, for example bit-flip errors
- Error rate is low (in modern computers about 10 000 years for a single bit to flip)

Error correction example



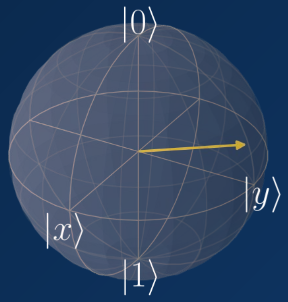
- Decoder detects if the error occurred and where it occurred
- Applies the correction
- Assumed perfect encode and decode circuits

Error correction example



Quantum error correction

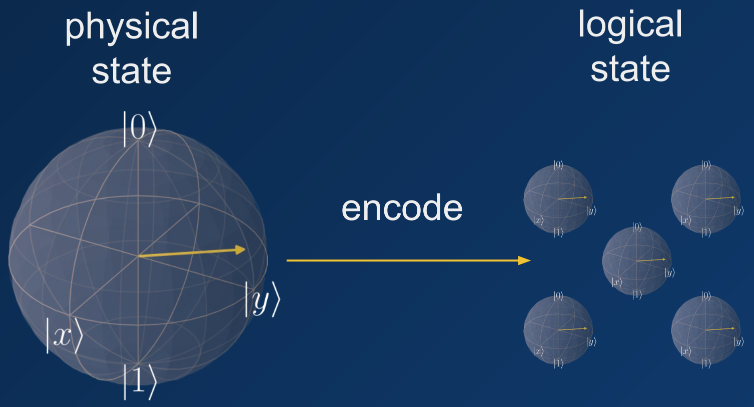
physical
state



$$|\psi\rangle = \cos{(\theta/2)}|0\rangle + \sin{(\theta/2)}e^{i\phi}|1\rangle$$

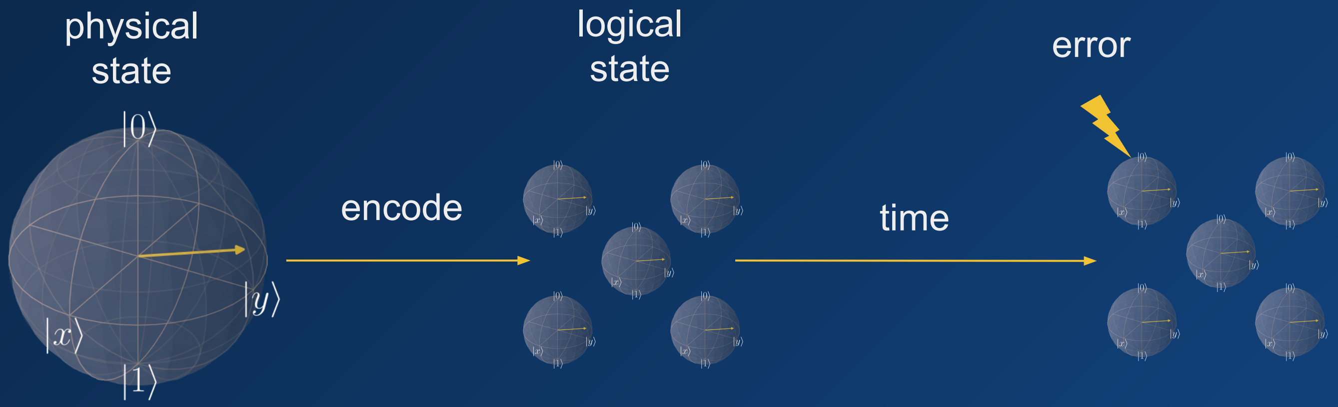
- State of a qubit can be any superposition of states 0 and 1.
- Superposition is defined with 2 real numbers
- Measurement projects the state into one of the basis states

Quantum error correction



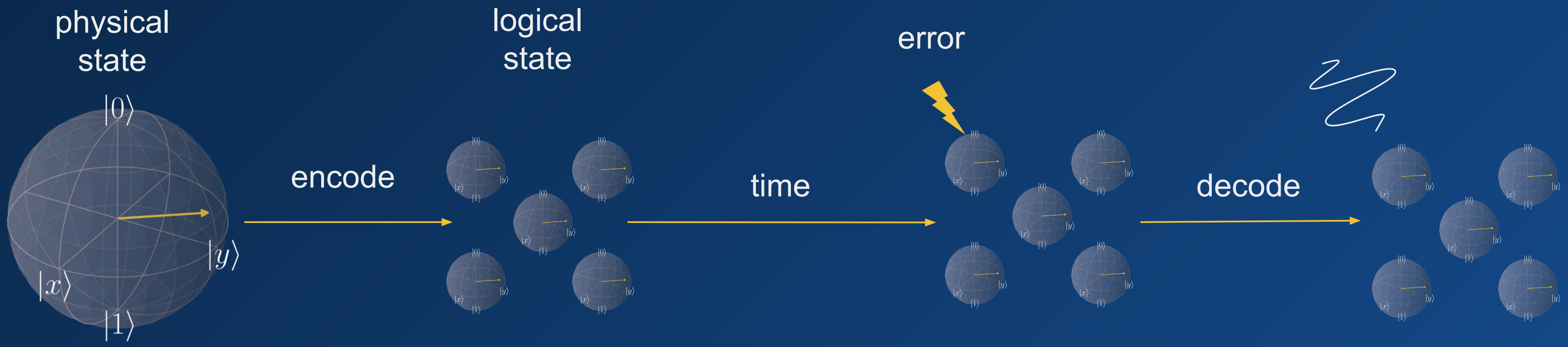
- No cloning theorem
- Two types of errors - bit-flip and phase-flip
- Surface code

Quantum error correction



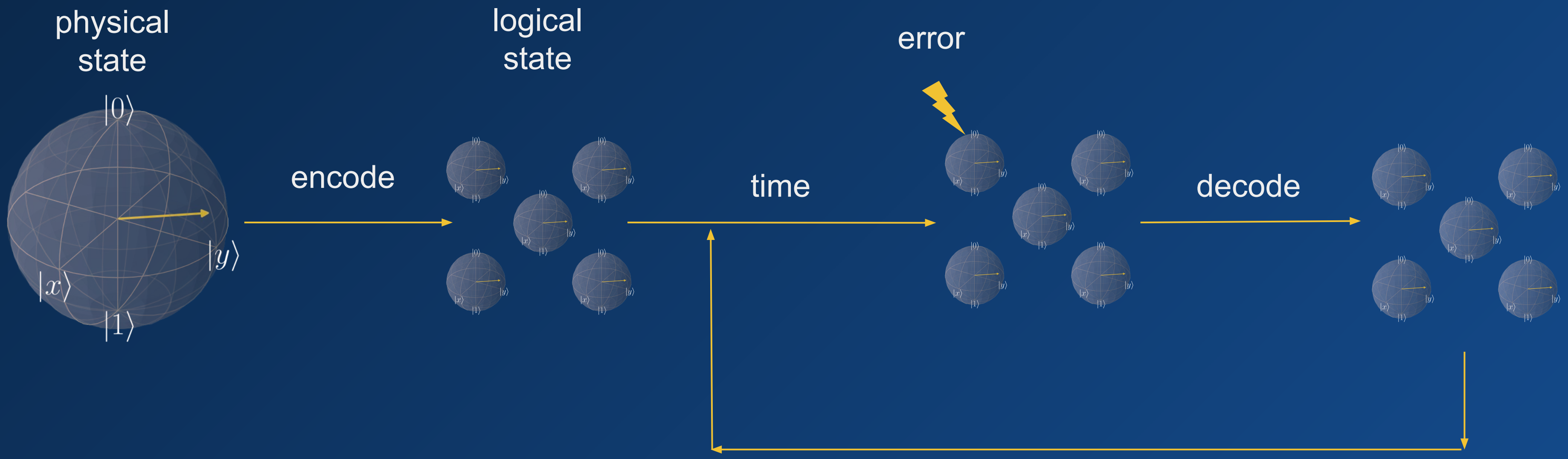
- Two types of errors - bit-flip and phase-flip

Quantum error correction



- Measure subset of qubits (ancilla qubits)
- Based on measurements decode where and which error(s) happened
- Measurements are imperfect

Quantum error correction



- Measure subset of qubits (ancilla qubits)
- Based on measurements decode where and which error(s) happened
- Measurements are imperfect

Fault tolerance

True fault tolerance requires good performance not only when physical bits fail, but also when the circuits we use for error correction are themselves imperfect and require additional (imperfect) circuitry to correct them.

Quantum speedup - Shor’s algorithm

- A lot of security today is based RSA cryptosystem. Security is based on the fact that factoring large numbers into their primes is hard. Hard here means that time needed to factor a number exponentially grows with the number size.
- Shor’s algorithm is one of few quantum algorithms that have a proven speedup and runs in polynomial time.

Resources needed to factor a 1024-bit number with Shor's algorithm.				
Technology	Neutral atoms	Superconducting	Ion traps	Best classical
Gate error	1×10^{-3}	1×10^{-5}	1×10^{-9}	
Avg. gate time	19 000 ns	25 ns	32 000 ns	
Execution time	2.62 years	10.81 hours	2.22 years	7431 years
No. qubits	5.29×10^{8}	4.57×10^{7}	1.44×10^{8}	
No. gates	1.02×10^{21}	2.55×10^{19}	5.10×10^{19}	
Dominant gate	CNOT	CNOT	CNOT	
Code distance	17	5	3	
Logical gate error	4.99×10^{-11}	2.95×10^{-11}	4.92×10^{-15}	
Logical gate time	1.29×10^{5} ns	2.10×10^{2} ns	5.96×10^{5} ns	
No. qubits per logical	3.73×10^{4}	3.23×10^{3}	1.16×10^{3}	
No. gates per logical	1.11×10^{5}	9.60×10^{3}	3.46×10^{3}	

M. Suchara, et. al, "QuRE: The Quantum Resource Estimator toolbox," *IEEE 31st International Conference on Computer Design (ICCD)*, 419-426 (2013).

Resources needed to factor a 1024-bit number with Shor’s algorithm

Technology	Superconducting needed	Superconducting today
Gate error	1×10^{-5}	6×10^{-3}
Avg. gate time	25 ns	30 ns
Execution time	10.81 hours	
No. qubits	4.57×10^{7}	4.7×10^{1}
No. gates	2.55×10^{19}	
Dominant gate	CNOT	CZ
Code distance	5	5
Logical gate error	2.95×10^{-11}	
Logical gate time	2.10×10^{2} ns	
No. qubits per logical	3.23×10^{3}	4.7×10^{1}
No. gates per logical	9.60×10^{3}	

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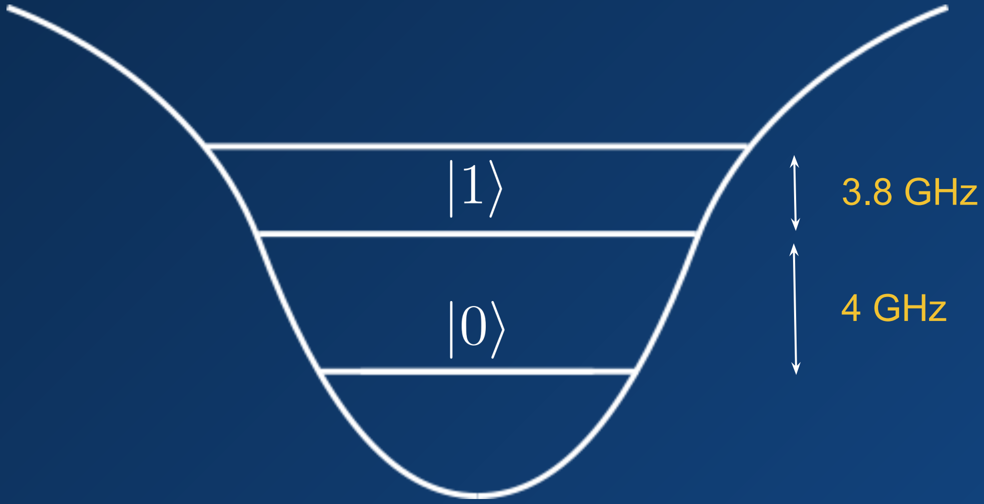
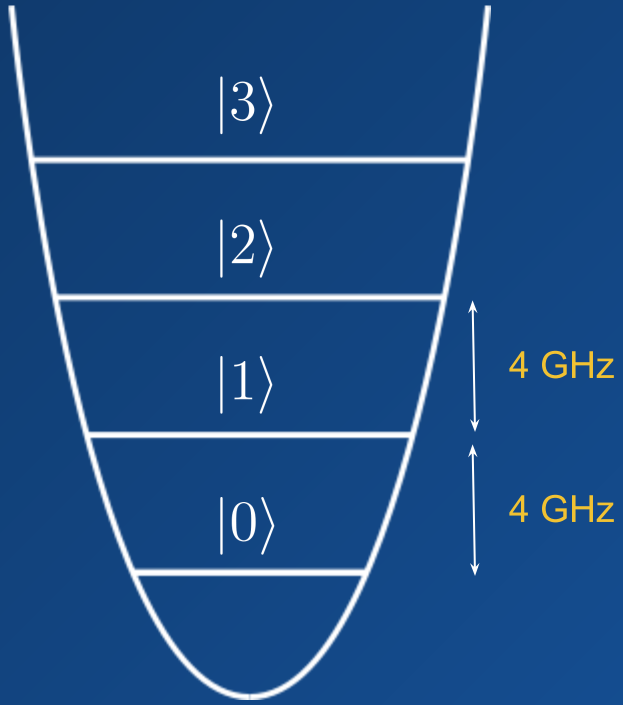
Google Quantum AI. Suppressing quantum errors by scaling a surface code logical qubit. *Nature* **614**, 676–681 (2023).

Qubits vs. resonators

Qubit - “two level” system



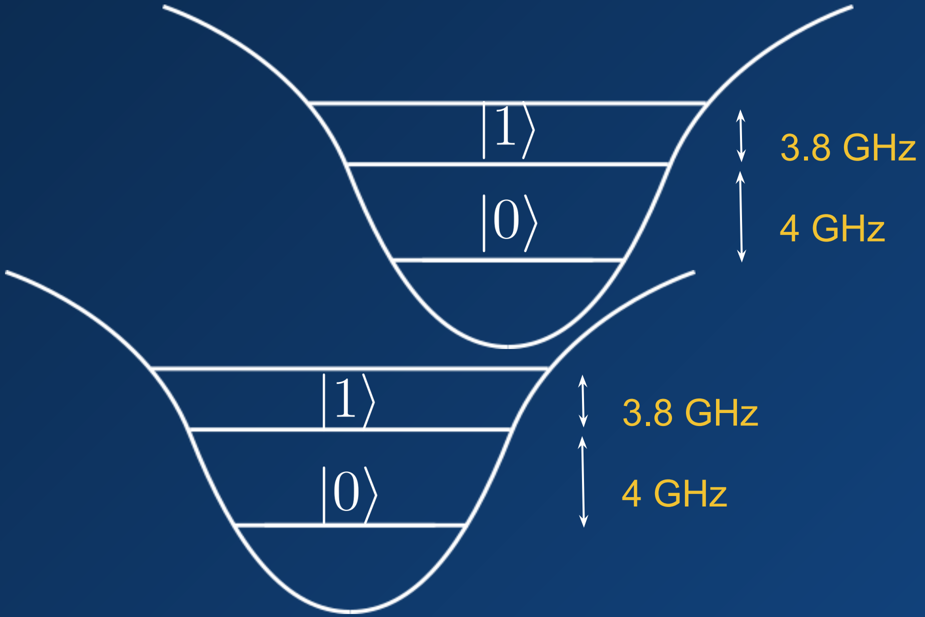
Resonator - multi-level system



Encoding logical qubit

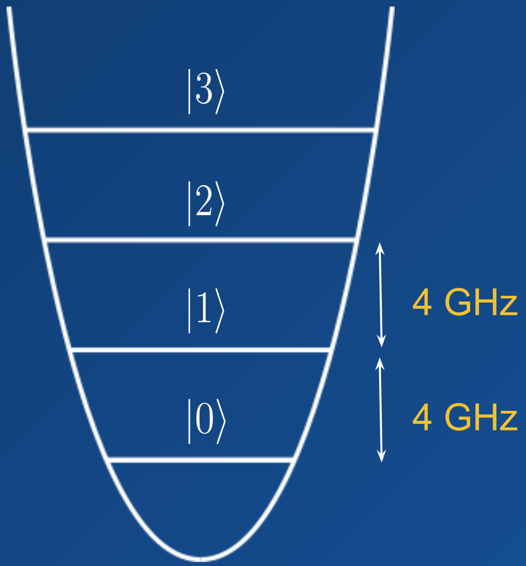
2 qubits - 1 logical qubit

$$a_0|00\rangle + a_1|01\rangle + a_2|10\rangle + a_3|11\rangle$$



Resonator - multi-level system

$$a_0|0\rangle + a_1|1\rangle + a_2|2\rangle + a_3|3\rangle$$

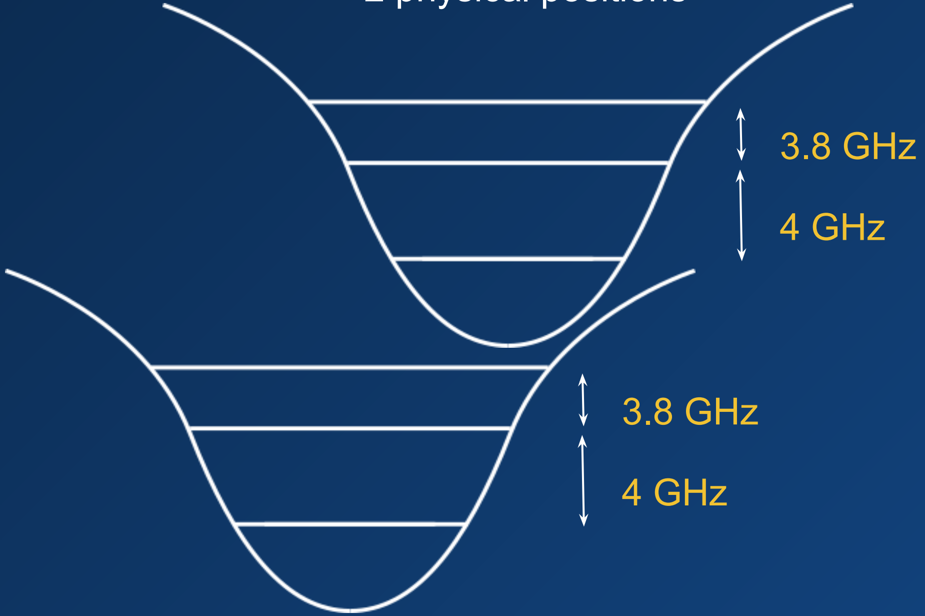


Encoding logical qubit

2 qubits - 1 logical qubit

$$a_0|00\rangle + a_1|01\rangle + a_2|10\rangle + a_3|11\rangle$$

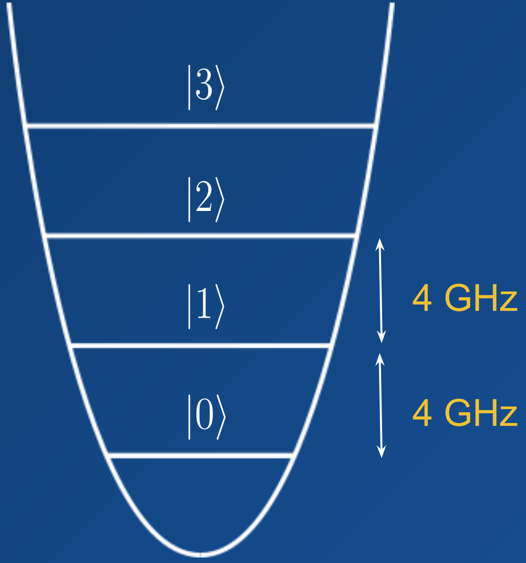
2x2=4 possible errors in
2 physical positions



Resonator - multi-level system

$$a_0|0\rangle + a_1|1\rangle + a_2|2\rangle + a_3|3\rangle$$

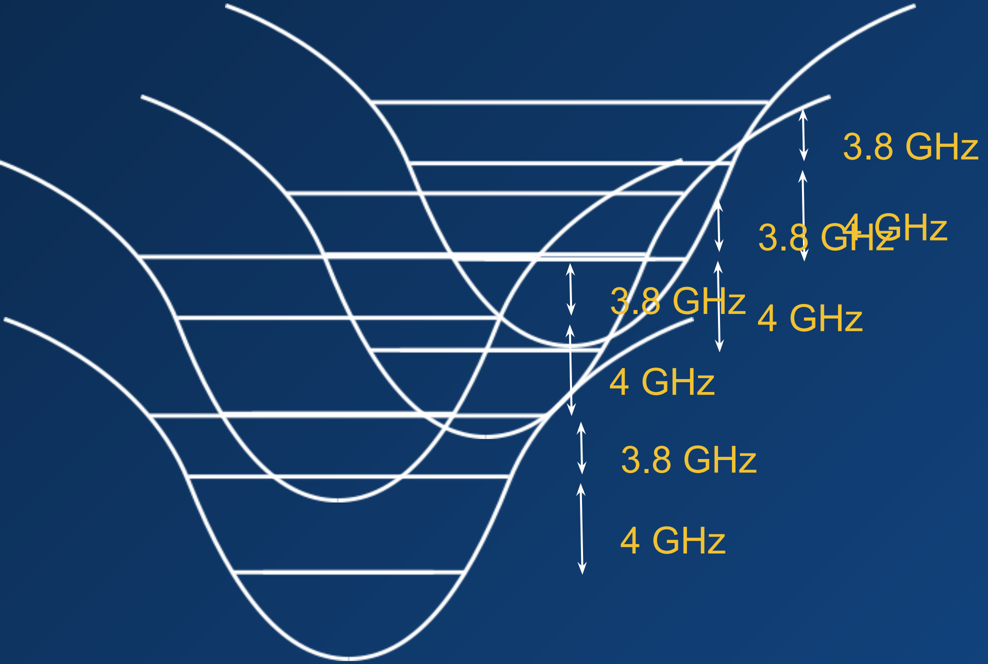
1 dominant error in
1 physical positions



Encoding logical qubit

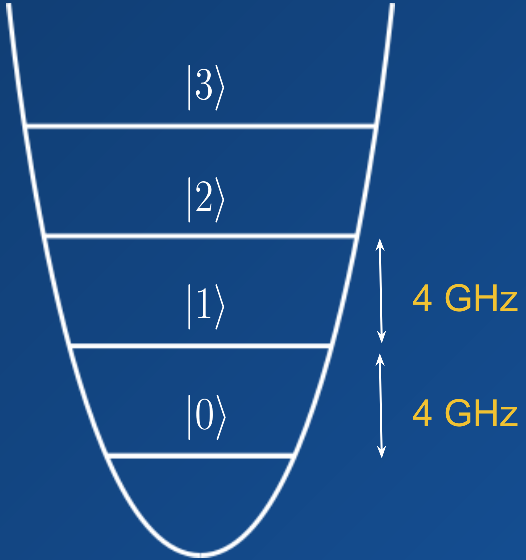
n qubits - 1 logical qubit

nx2=2n possible errors in
n physical positions



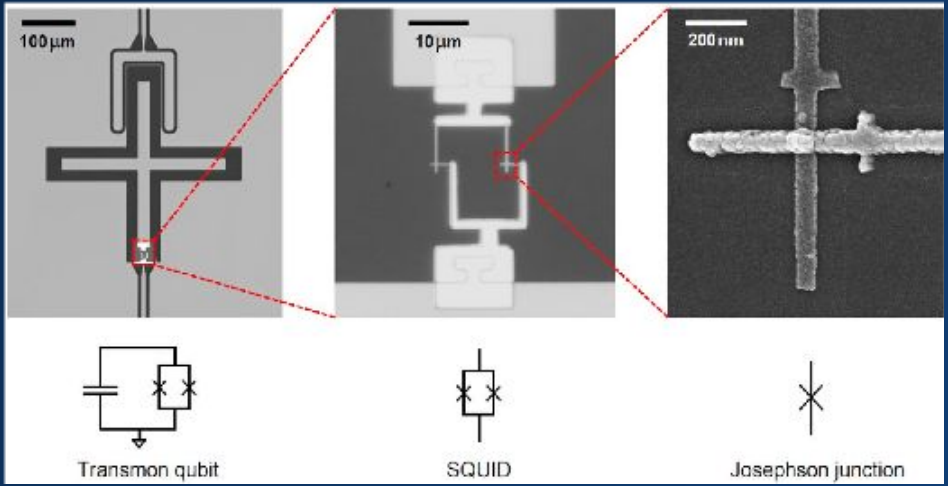
Resonator - multi-level system

1 dominant error in
1 physical positions



Qubits vs. resonators

Qubit - “two level” system



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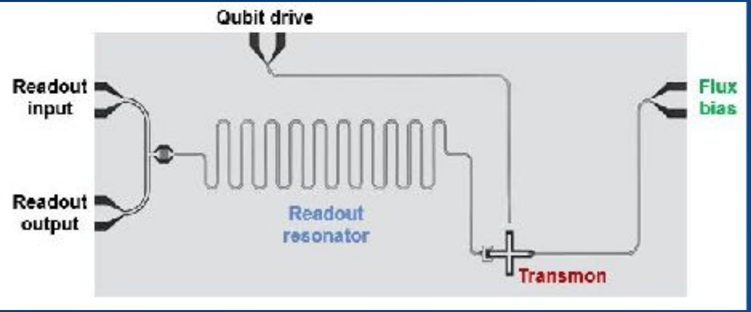
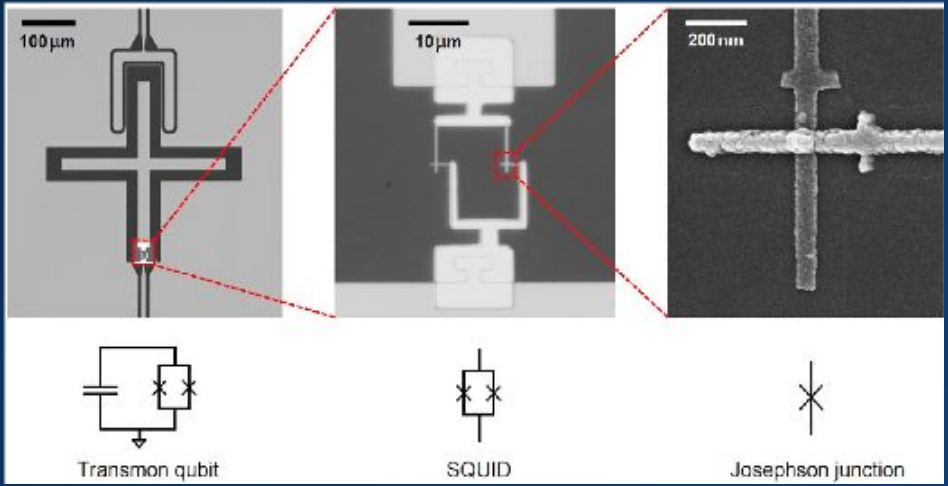


Figures borrowed from Thomas E. Roth arxiv:2106.11352

Qubits vs. resonators

Qubit - “two level” system



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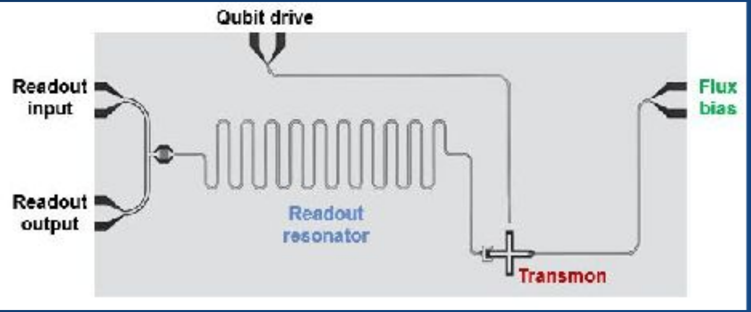

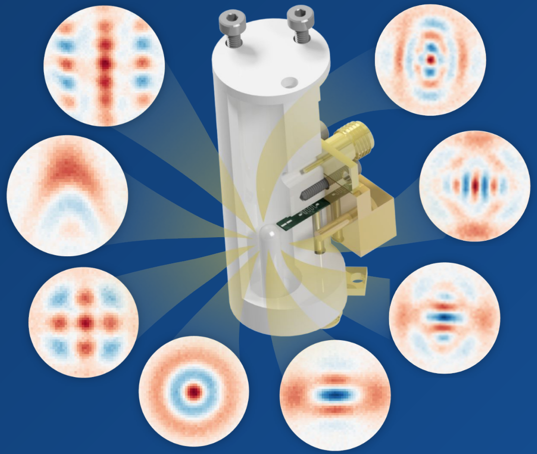

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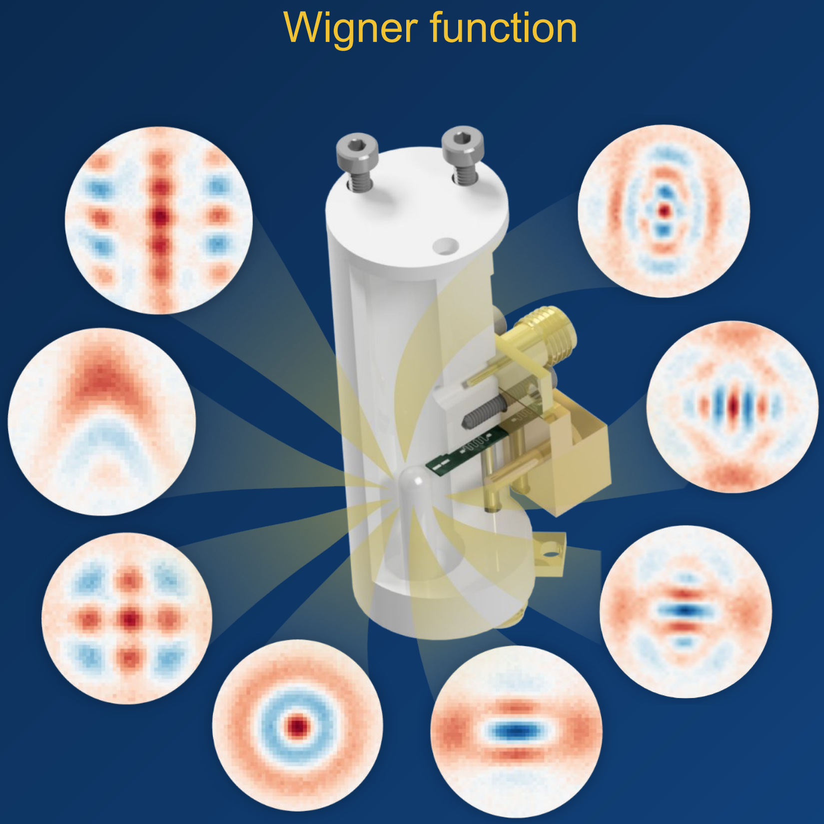
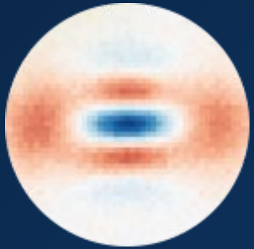
Bosonic states

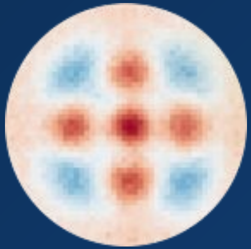


- quasiprobability distribution in iq plane
- Fingerprint for bosonic states
- negative (blue) regions indicate that the states are non-gaussian resource states

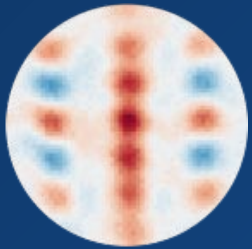
Bosonic encodings - encode binary qubit in multidimensional resonator



Cat code
Can protect against photon loss
Can be used to make noise-biased qubits

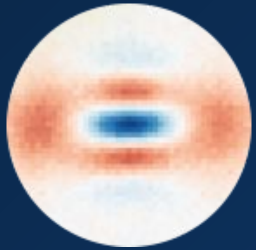


Binomial code
Can protect against photon loss



GKP code
Can protect against small displacements

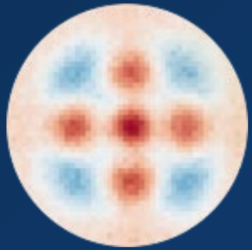
Bosonic encodings - encode binary qubit in multidimensional resonator



Cat code

Can protect against photon loss

Can be used to make noise-biased qubits



Binomial code

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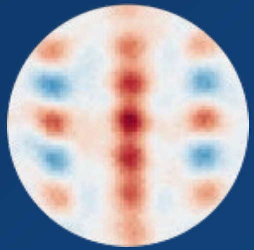

GKP code

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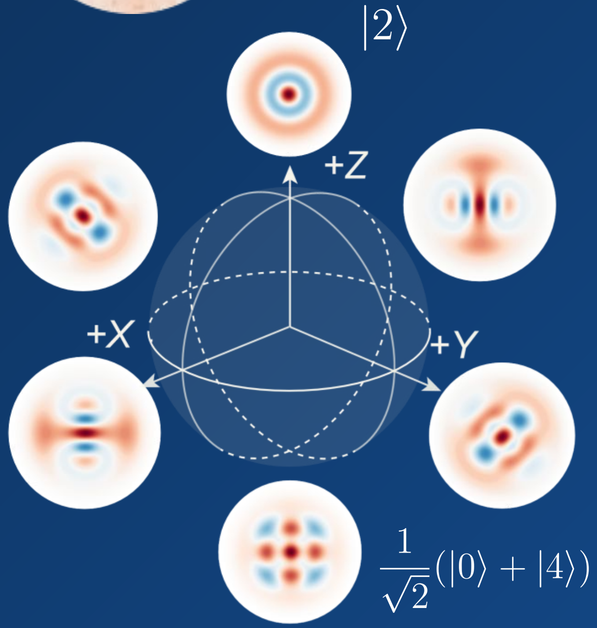
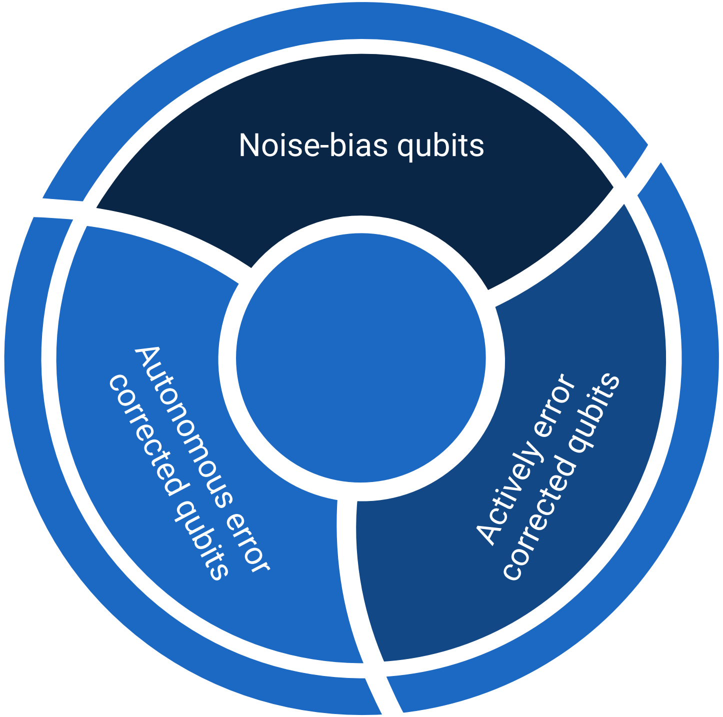


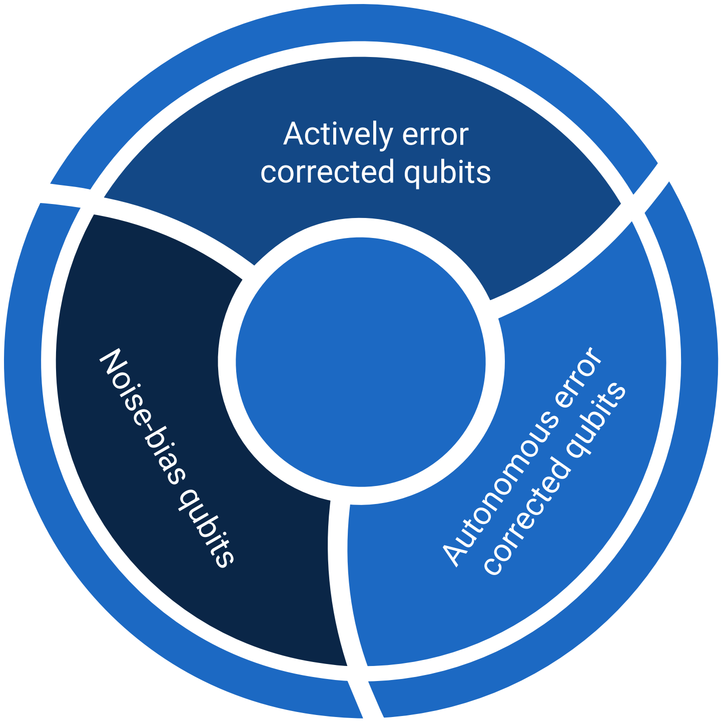
Bosonic encodings



Dissipative-cat	Kerr-cat
C. Berdou et al. “One Hundred Second Bit-Flip Time in a Two-Photon Dissipative Oscillator”, PRX Quantum 4, 020350 (2023) R. Lescann et al. “Exponential suppression of bit-flips in a qubit encoded in an oscillator”, Nat. Phys. 16(5), 509 (2020)	A. Grimm et al. “Stabilization and operation of a kerr-cat qubit”, Nat. 584(7820), 205 (2020) S. Puri et al. “Engineering the quantum states of light in a kerr-nonlinear resonator by two-photon driving”, npj Quantum Inf. 3(1), 18 (2017)

- 60x less qubits to form a logical qubit
- 1D chain instead of 2D grid

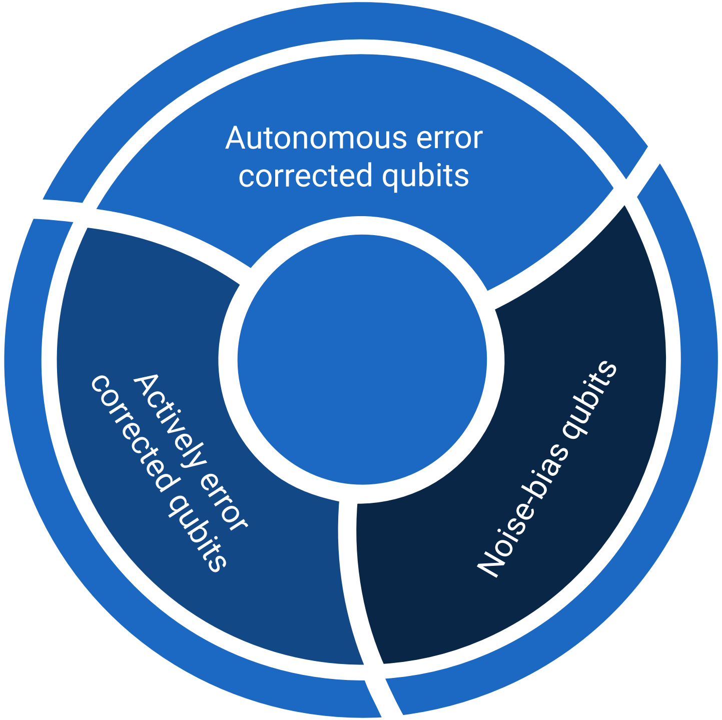
Bosonic encodings



Cat code N. Ofek et al. “Extending the lifetime of a quantum bit with error correction in superconducting circuits”, Nat. 536 (2016) **Binomial code** Z. Ni et al. “Beating the break-even point with a discrete-variable-encoded logical qubit”, Nat. 616.5660 (2023)	**GKP-code** V. Sivak et al. “Real-time quantum error correction beyond break-even”, Nat. 616.5055 (2023) P. Campagne-Ibarcq et al. “Quantum error correction of a qubit encoded in grid states of an oscillator”, Nat. 584.7821 (2020)

- The first (Ofek) experiment to demonstrate break-even
- The only experiment so far to show beyond break-even (2x better encoded qubit compared to physical)

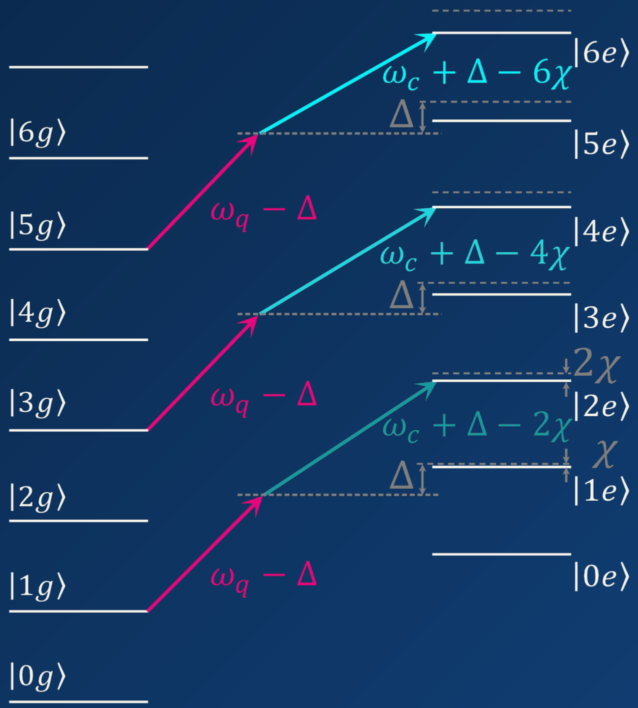
Bosonic encodings



Cat-code	GKP-code
J. M. Gertler et al. “Protecting a bosonic qubit with autonomous quantum error correction”, Nat. 590 (2021)	D. Lachance-Quirion et al. “Autonomous quantum error correction of Gottesman-Kitaev-Preskill states”, arXiv:2310.11400 (2023)

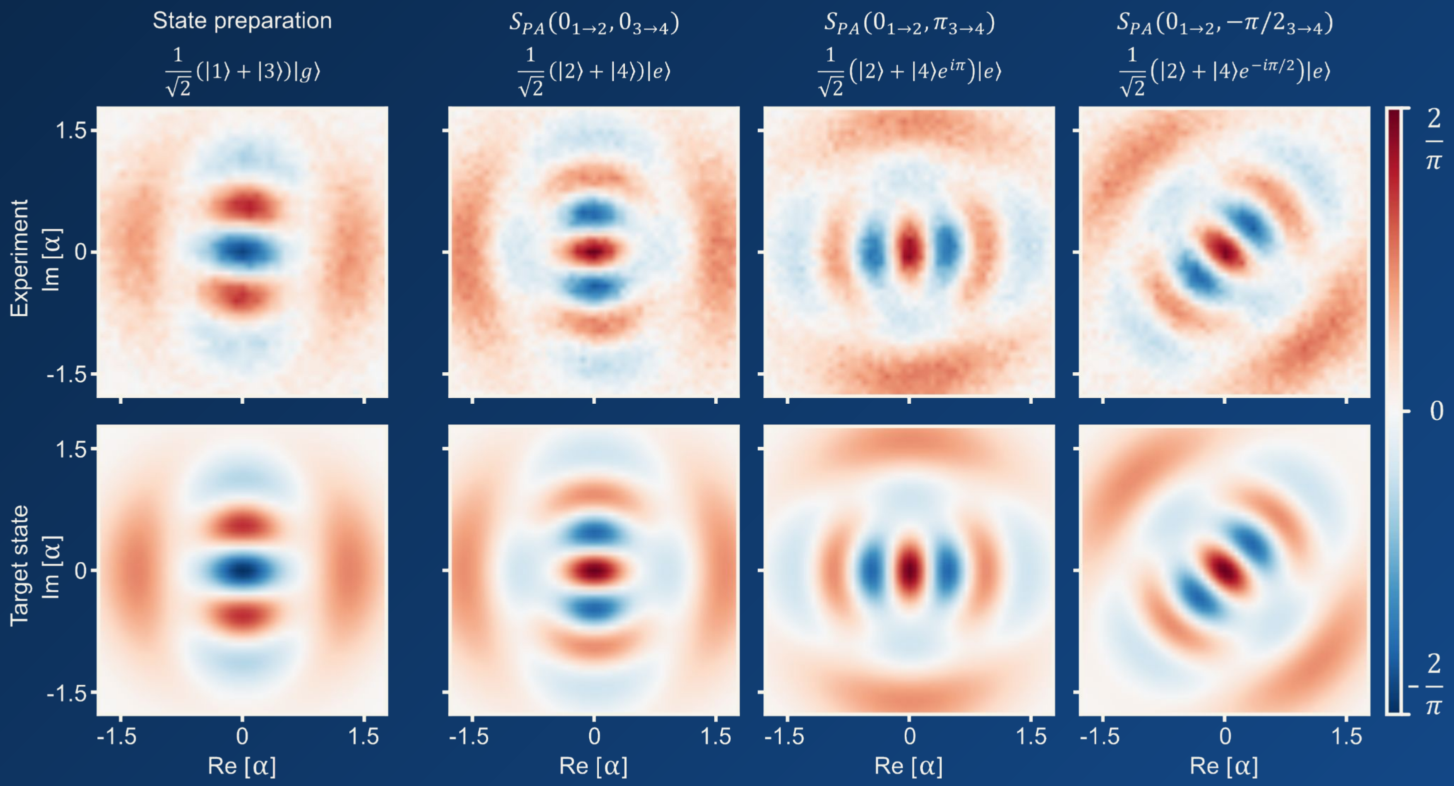
- Attractive because there is feedback necessary

Step towards autonomous error correction - selective photon addition



M. Kudra et. al Experimental realization of deterministic and selective photon addition in a bosonic mode assisted by an ancillary qubit arxiv:2212.12079 (2022).

Step towards autonomus error correction - selective photon addition



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Microwave control electronics

Intermodulation products

- Low latency
- High density outputs/inputs
- Synchronization of many channels/units
- No analog mixers! Direct digital synthesis makes everything simpler
- Cost effective, same technology used for 5G

Conclusion

- It is remarkable that quantum error correction is possible even in theory.
- The experimental demonstrations to date are at the very edge of demonstrating break-even and slightly beyond
- There is some way to go until useful quantum computers

Steven M. Girvin, Introduction to Quantum Error Correction and Fault Tolerance, arXiv:2111.08894