Qudits vs Qubits: Faster and More Reliable Quantum Gates?

A Comparative Study of Gate Efficiency and Noise Resilience

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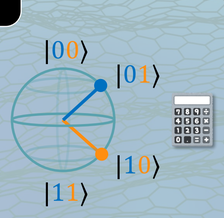
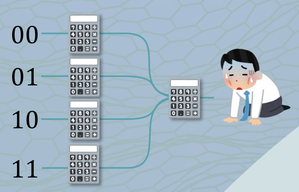
Background



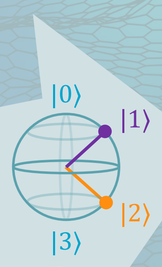


N classical bits

- Only one of the 2^N states at once

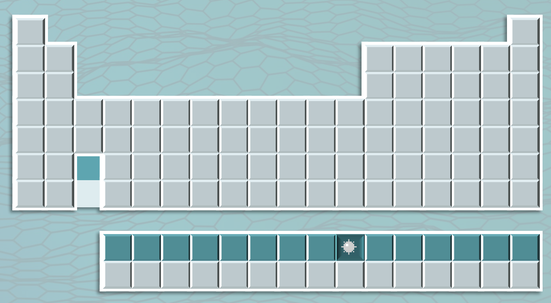
N qubits

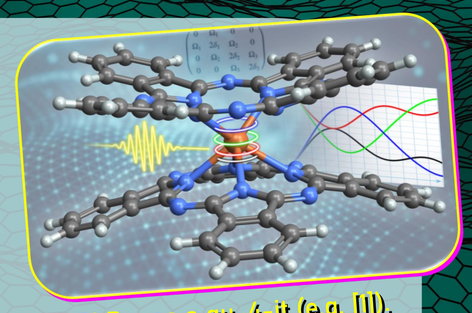
- Work with all 2^N states at once



N qudits

- Work with all d^N states at once





TbPc$_2$ as a qu-4-it (e.g. [1]).

- Lanthanide-organic complexes ⇒ Quantum Information Processing.[2]
- Ln^{3+} in Ln-based complexes ⇒ interesting optical and magnetic properties. [3]
- Nuclear (high spin + deformed) + electronic properties ($4f$-valence electrons) ⇒ individually addressable hyperfine levels = qu$d$its. [4-5]
- Qu$d$its = denser information <u>but</u> more decoherence channels vs. qubits. [6]

Open Quantum Systems : Lindblad Master Equation

$$\partial_t \rho = -i[H,\rho] + \gamma \sum_k L_k \rho(t) L_k^\dagger + \frac{1}{2}\{L_k^\dagger L_k, \rho(t)\}$$

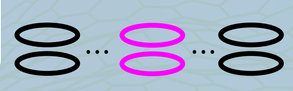
Average Gate Infidelity *

$$\bar{\mathcal{E}}_{d,N} = \gamma t \frac{d^{N-1}}{d^N+1} \sum_k \mathrm{Tr}(L_k^\dagger L_k)$$

"How much computational error does the noise cause?"

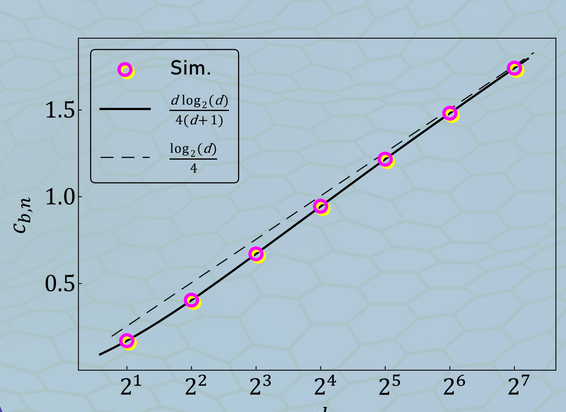
* First order in γt

Qubits

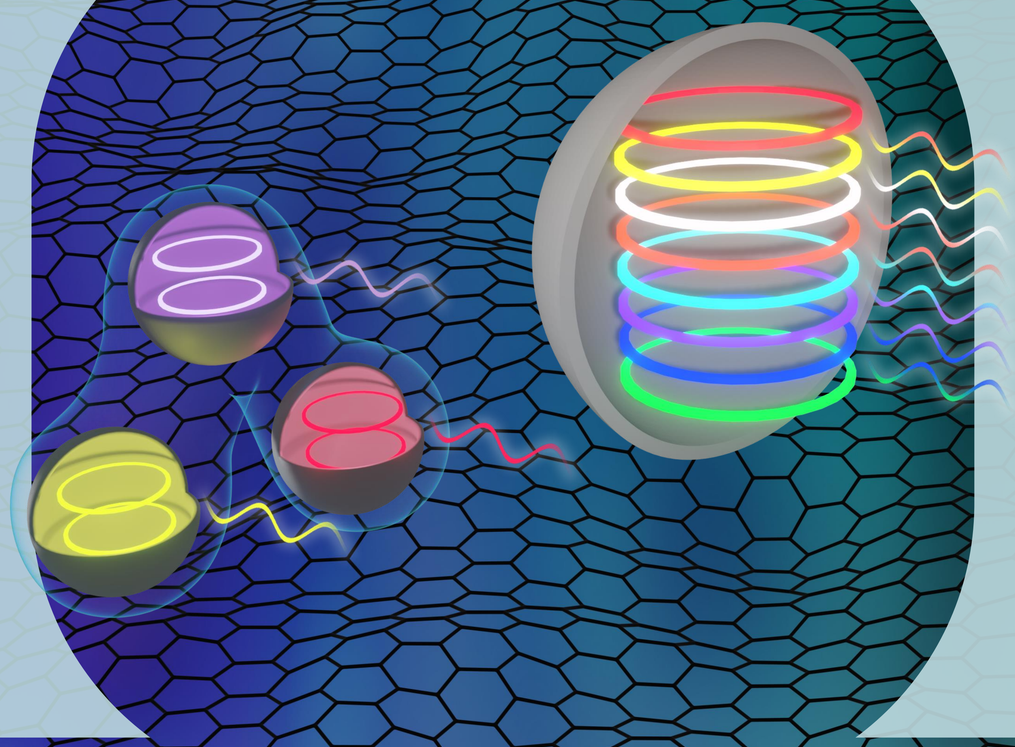


$$L_k = \underbrace{\mathrm{Id}^{(1)} \otimes \cdots}_{k-1} \; S_z^k \; \underbrace{\cdots \otimes \mathrm{Id}^{(n)}}_{n-k}$$

$$\bar{\mathcal{E}}_{b,n} = \gamma t c_{b,n}$$



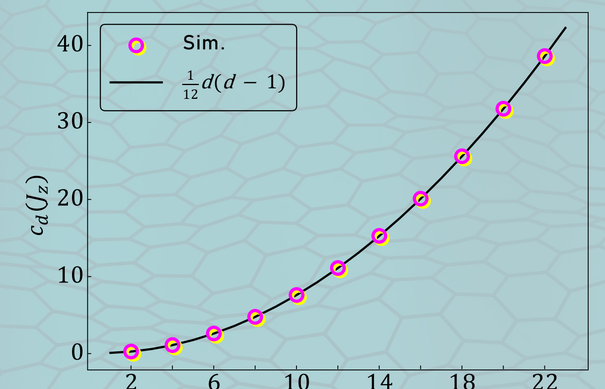
$$\Longrightarrow \mathcal{O}_\infty\left(\log_2(\gamma t d)\right)$$



Qudit

$$L = J_z = \mathrm{diag}\left(-\frac{d-1}{2}, \ldots, \frac{d-1}{2}\right)$$

$$\bar{\mathcal{E}}_d = \gamma t c_d$$



$$\mathcal{O}_\infty(\gamma t d^2) \Longleftarrow$$

State of the art

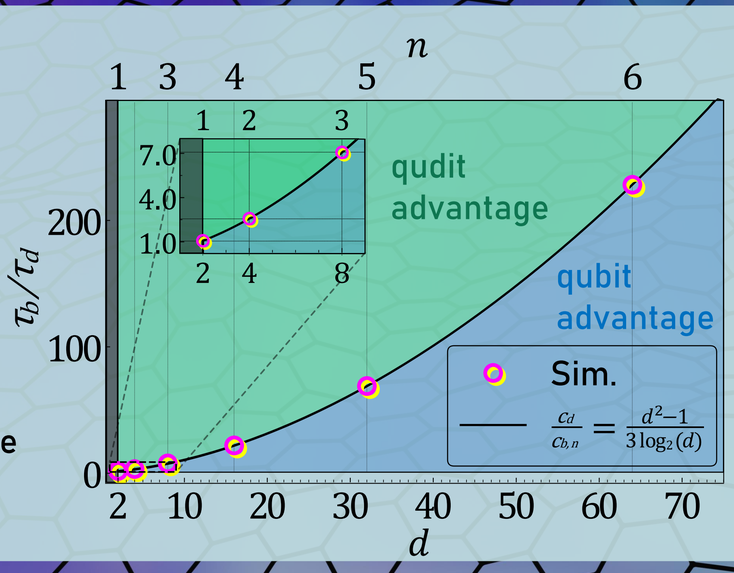
Figure of Merit

$$\tau = \gamma T_g$$

"How efficient is the gate relative to the decoherence time?"

γ : strenght of the noise

T_g : duration of a gate



How can a qudit catch-up with equivalent qubits ?

<u>Longer coherence</u> and <u>faster gates</u> (smaller τ) alone are not sufficient.

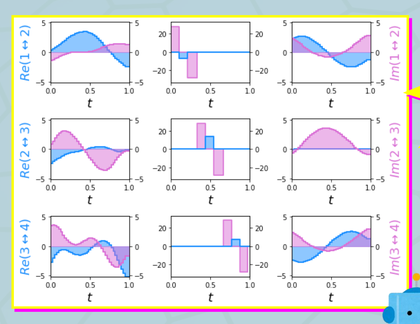
⇒ They need to be <u>MUCH</u> better.

Physical platforms with qudit advantages exist!

	d	n	T_2	T_g	$\sim \log_{10}(\tau)$	
	2	2	~ 10 µs	60 ns	−2	[7]
	2	2	~ 2 µs	51 ns	−2	[8]
	2	17	~ 30 µs	~ 100 ns	−3	[9]
	2	24	~ 100 ms	~ 200 µs	−3	[10]
	4	1	0.32 ms	~ 100 ns	−4	[11]
	3	2	~ 100 ms	~ 100 µs	−3	[12]
	4	2	∞	–	−∞	[13]
	52	1	–	~ 100 ns	–	[14]

What now?

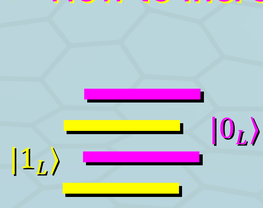
› How to engineer faster gates?

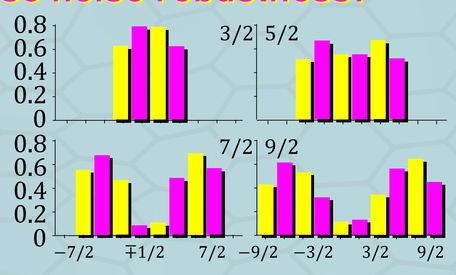


Quantum Optimal Control

Numerical methods to explore the space of possible pulses

› How to increase noise robustness?





Smart *"encodings"* to remove the first k^{th} orders of noise.[15]

⇒ 1 <u>physical</u> qudit = 1 <u>logical</u> qubit

› What happens for multiple qudits?

$$\tau_N = \gamma_N T_{g,N}$$

$$\gamma_N =^? N\gamma \qquad T_{g,N} =^? N T_g$$

[1] S. Thiele, F. Balestro, R. Ballou et al. *Science*, 2014, 344(6188), 1135
[2] A. Kinos, D. Hunger, R. Kolesov et al. *arXiv preprint*, 2021, arXiv:2103.15743
[3] K.S. Kumar, D. Serrano, A.M. Nonat et al. *Nature Communications*, 2021, 12, 2152
[4] H. Biard, E. Moreno-Pineda, M. Ruben et al. *Nature Communications*, 2021, 12, 4443
[5] C. Godfrin, A. Ferhat, R. Ballou et al. *Physical. Review Letters*, 2017, 119, 187702
[6] M. Otten, K. Kapoor, et al. *Physical Review A*, 2021, 104, 012605
[7] M. Kjaergaard, M. E. Schwartz, A. Greene et al. *arXiv preprint*, 2020, arXiv:2001.08838
[8] I. S. Madjarov, J. P. Covey, A. L. Shaw et al. *Nature Physics*, 2020, 16, 857
[9] S. Krinner, N. Lacroix, A. Remm et al. *Nature*, 2022, 605, 669
[10] I. Pogorelov, T. Feldker, C. D. Marciniak et al. *PRX Quantum*, 2021, 2, 020343
[11] E. Moreno-Pineda, C. Godfrin, F. Balestro et al. Chemical Society Reviews, 2018, 47, 501
[12] M. Ringbauer, M. Meth, L. Postler et al. *Nature Physics*, 2022, 18, 1053
[13] Y. Chi, J. Huang, Z. Zhang et al. *Nature Communications*, 2022, 13, 1166
[14] A. Larrouy, S. Patsch, R. Richaud et al. *Physical Review X*, 2020, 10, 021058
[15] Petiziol, F., Chiesa, A., Wimberger, S. et al. *npj Quantum Inf*, 2021, 7, 133

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