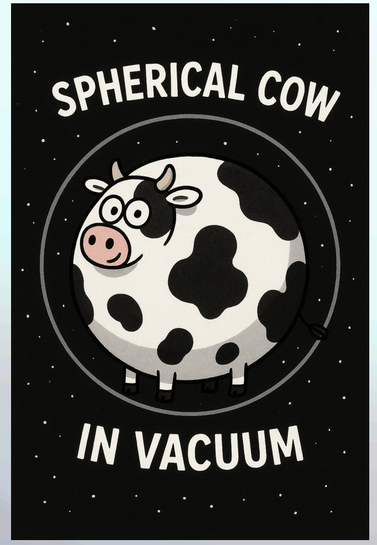
Prva eksperimentalna demonstracija nelokalne magije🪄🎩

*ili

Ljubavna priča između teorije i eksperimenta

(Pragma (πρᾶγμα): dugotrajna i postojana ljubav koja se razvija dugo vremena)



Teorija

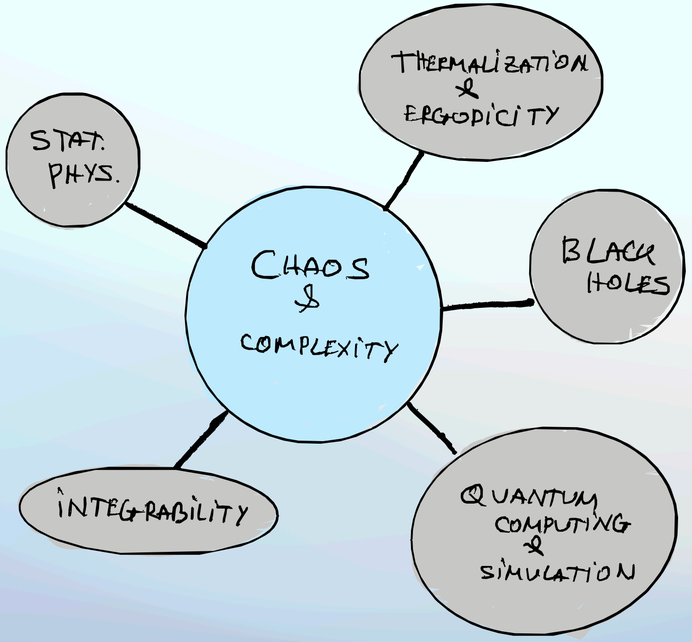
Eksperiment

Jovan Odavić 22/12/2025 - Beograd

arXiv: 2511.15576

Nešto ukratko o meni

- Statistička fizika i fizika kondenzonog stanja
- Teorija haosa i nelinearna dinamika
- Kvantna informatika
- ...ili fizičar višečestičnih korelisanih sistema

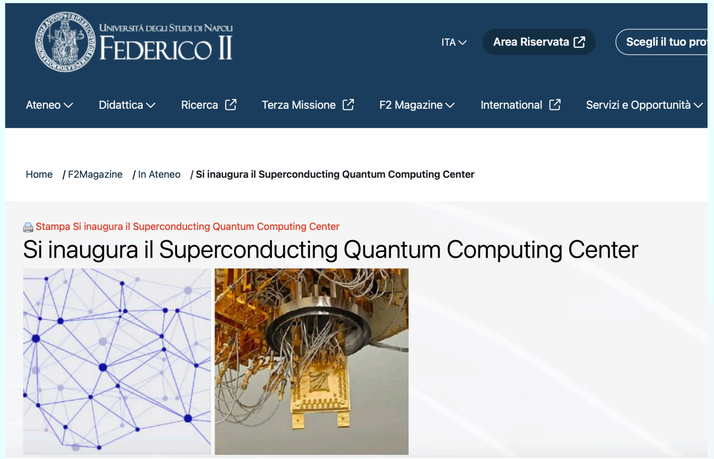


iz Novog Sada...

Vezuv 🌋

...u Napulj

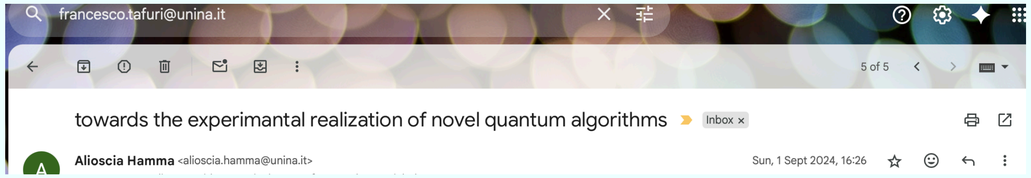
Kvantni računar u Napulju



- Prvi javni kvantni računar u Italiji
- Imali smo privilegiju da radimo prve eksperiment + benchmarking
- Razvijaju se na univerzitetima i u velikim kompanijama (Google, Microsoft, Amazon, IBM)

prof. Tafuri na inauguracije računara

Kolaboracija započeta pre više od godinu dana



Teorijaska grupa prof. Hamma

Eksperimentalna grupa prof. Tafuri

Ovogodišnja Nobelova nagrada

… za otkriće makroskopskom kvantno mehaničkog efekta tunelovanja i kvantizaciju u električnim kolima

Nobel Prize in Physics 2025

Ill. Niklas Elmehed © Nobel Prize Outreach

John Clarke

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

Michel H. Devoret

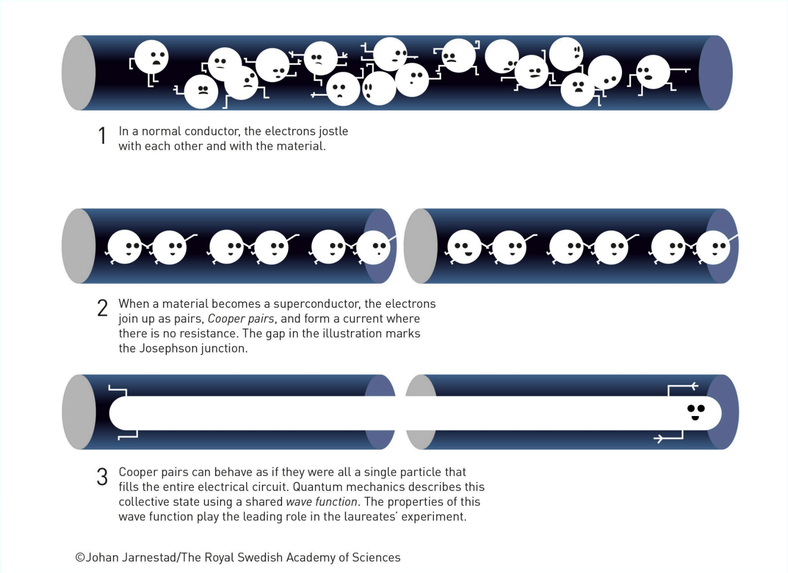
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John M. Martinis

Prize share: 1/3

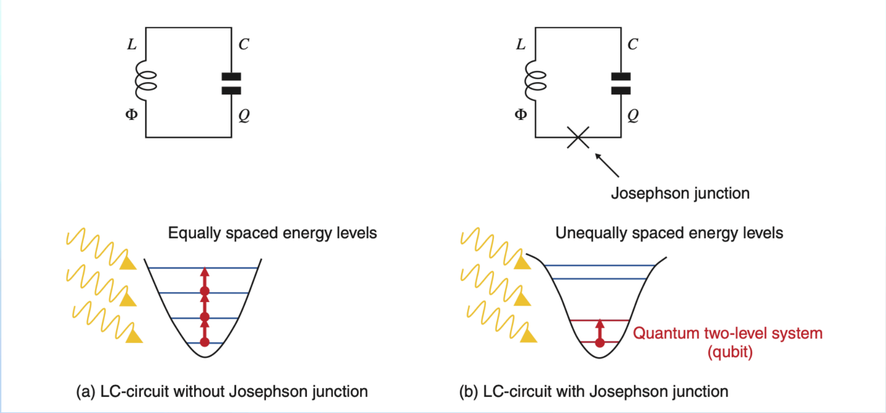
Ključni detalji superprovidnih qubit-a



Kvantni efekti -> Potrebna niska temperature!

Poznati luster (CHANDELIER)

Napuljska laboratorija



Normalni metal—> kontinuirani spektar kvazičestičnica

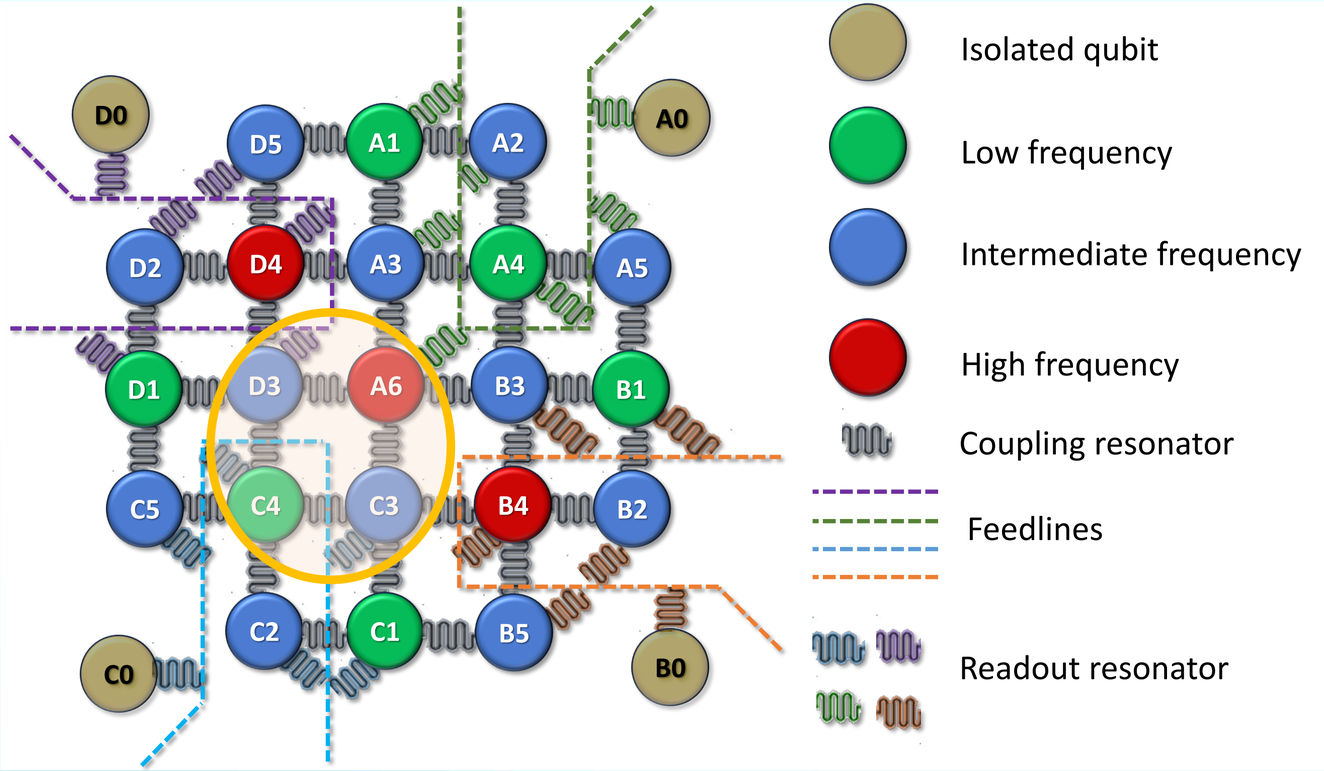
Superprovodnik—> otvori 'rupu' (gap) u spectra I mogućnost diskretnih nivoa

If one could use the quantum levels in this superconducting gap, these states would be expected to be similar to the electronic state of a free atom, i.e., it is characterized by the long-lived discrete energy spectrum.

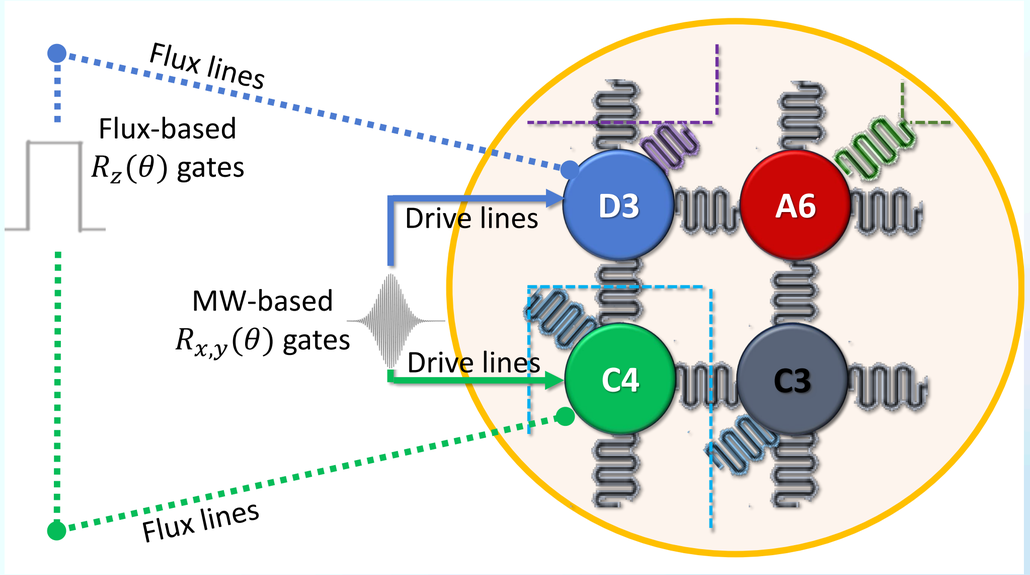
https://doi.org/10.53829/ntr200801sp6

Kvantni procesor - Noisy Intermediate Scale Quantum (NISQ) čip

John Preskill, Quantum **2**, 79 (2018)



Superprovodni kvantni procesor. Shema procesora.



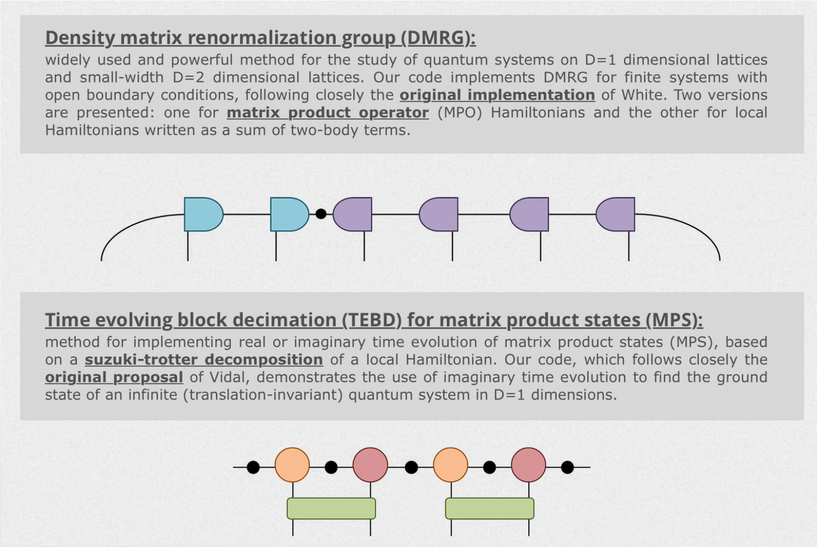
Qubit par (D3-C4) na koji smo bili fokusirani

40+ qubit procesor uskoro dostupan, ali takođe rade na novom tipu qubit-a —> za više detalje pitati eksperimentalce

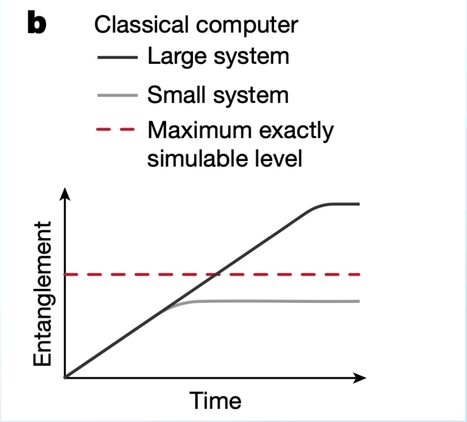
Interagujući mnogočestični kvantnih sistemi

- Simulacije veoma izazovane klasično —> Mali broj konstituenata ili aproksimacije za termodinamički relevantne i velike sisteme

- Uvid iz polja kondezovane materije: efikasne simulacije koristići tenzorke metode —> Matrix Product States and Density Matrix Renormalization Group: David Pérez-García , Norbert Schuch, and Frank Verstraete, Rev. Mod. Phys. **93**, 045003 (2021)



tensors.net



Shaw, A.L., Chen, Z., Choi, J. *et al.* Benchmarking highly entangled states on a 60-atom analogue quantum simulator. *Nature* **628**, 71–77 (2024). https://doi.org/10.1038/s41586-024-07173-x

Zapravo, kvantni računari bi trebalo da pomognu baš pri efikasnoj simulaciji kvantih sistema!

Kvantno-informatički uvid

- Specifična tip <u>kvantih kola</u>

- Isključivo kvantna kola sa **Clifford** elementima gde su završna stanja veoma **kvantno spregnuta (zapreletenost ili 'entanglement')** stabilizujuća kola

Hadamard $$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Fazni element $$S = \begin{bmatrix} 1 & 0 \\ 0 & e^{-i\pi/2} \end{bmatrix}$$

kontrolisano+NOT $$\mathrm{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

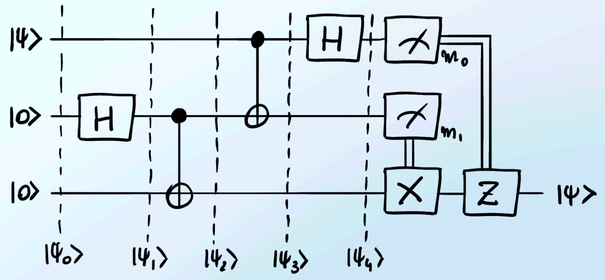
- Ne svako kvantno kolo može da se predstavi Clifford elementima!

Diskretna kvantna mehanika

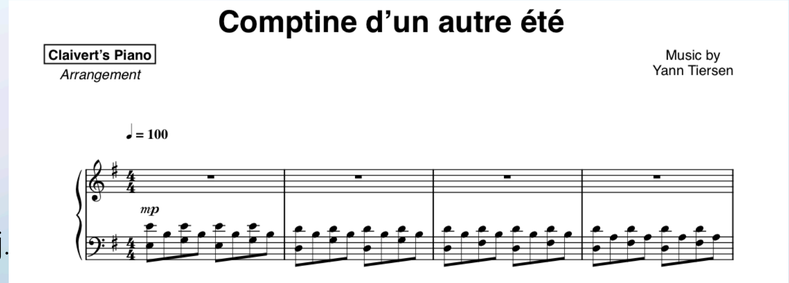
Svaka validna formulacije/representacija kvantne mehanike sačinjena je od 3 osnovna elementa

1. Priprema stanja
2. Unitarna evolucije —> Kvante kapije (quantum gates)
3. Merenje

Protokol za kvantnu teleportaciju kvatnog stanja



Muzičke note/ sa leva na desno. Početak, note I kraj.



*aproksimacija kontinuirane dinamike —->Troterizacija

Opovrgavanje Guglove tvrdnje o kvantnoj nadmoć iz 2019

Jedan od pristupa je koristio blago perturbisana Clifford kola

Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buell, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, ... John M. Martinis Show authors

Nature **574**, 505–510 (2019) | Cite this article

Dobitnik Nobelove nagrade

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HOME > SCIENCE ADVANCES > VOL. 10, NO. 3 > FAST AND CONVERGED CLASSICAL SIMULATIONS OF EVIDENCE FOR THE UTILITY OF QUANTUM COMPUTING...

RESEARCH ARTICLE | PHYSICS

Fast and converged classical simulations of evidence for the utility of quantum computing before fault tolerance

TOMISLAV BEGUŠIĆ, JOHNNIE GRAY, AND GARNET KIN-LIC CHAN Authors Info & Affiliations

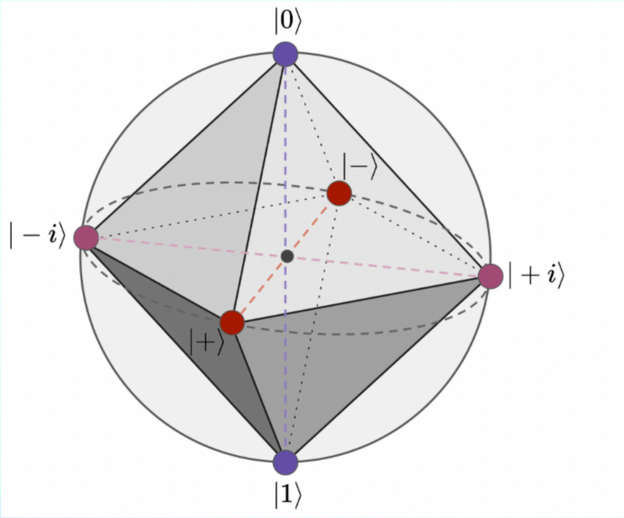
SCIENCE ADVANCES • 17 Jan 2024 • Vol 10, Issue 3 • DOI: 10.1126/sciadv.adk4321

N.B. Preskočiću celokupno polje **'kvatne korekcije grešaka' (quantum error correction)** gde Clifford operacije igraju veoma bitnu ulogu —> sledeća Nobelova nagrada!

Stabilizator stanja

na primeru jednog qubit-a

ograničen Hilbertov prosper —> 6 čistih kvantnih stanja

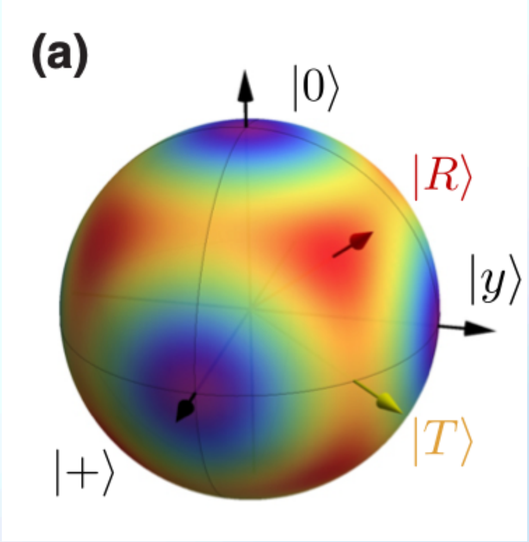


Octahedron na Blohovoj sferi—-> Koristesći samo 1-qubit kvantne kapije (https://pennylane.ai/qml/demos/tutorial_clifford_circuit_simulations).

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$S = \begin{bmatrix} 1 & 0 \\ 0 & e^{-i\pi/2} \end{bmatrix}$$

Ne-Clifford kvantne kapije omogućavaju eksploraciju celokupnog Hilbertovog prostora



PRX QUANTUM **4,** 010301 (2023)

Sve van ovine 6 stanja **—>ne-stabilizatornost ili "magija"**

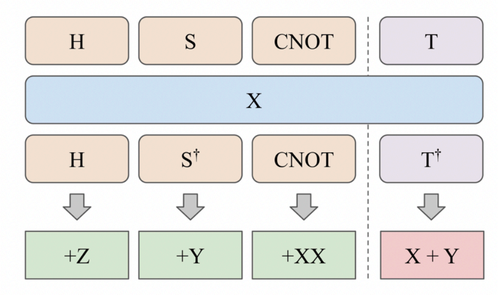
Paradigma Clifford+T kvantnih kola

- Clifford metod za simulaciju kvantnih kola ne funkcioniše ukoliko se dodaju **T elementi** (1-qubit)

$$T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$

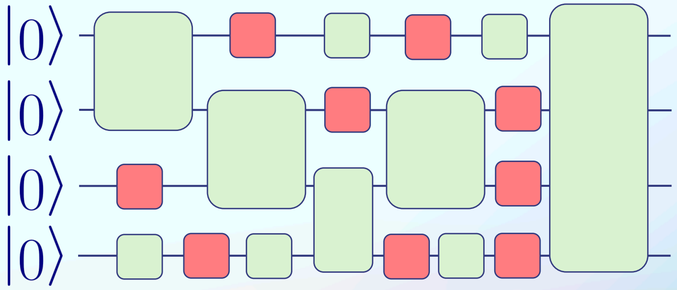
- Eksponencijalno teža simulacija ukoliko je magija pristuna —> Aaronson, S. and Gottesman, D. 'Improved Simulation of Stabilizer Circuits', Physical Review A, **70**(5) (2004)

Dinamika operatora

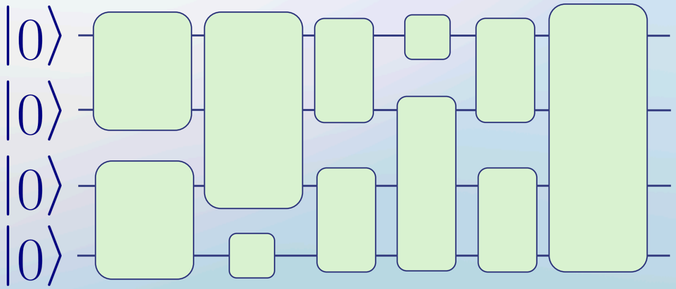


(https://pennylane.ai/qml/demos/tutorial_clifford_circuit_simulations).

cena simulacije kvantnih kola

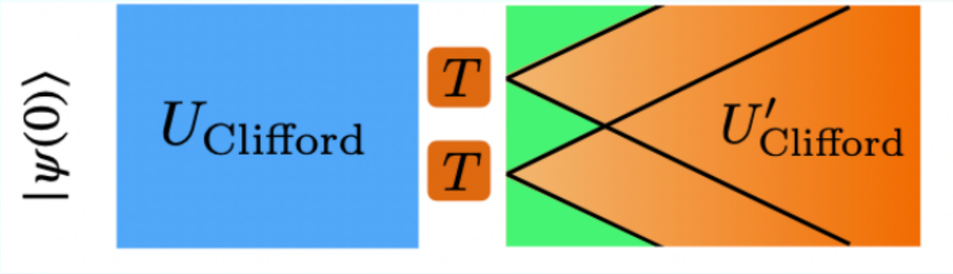


$\exp(n)$ **Magija**

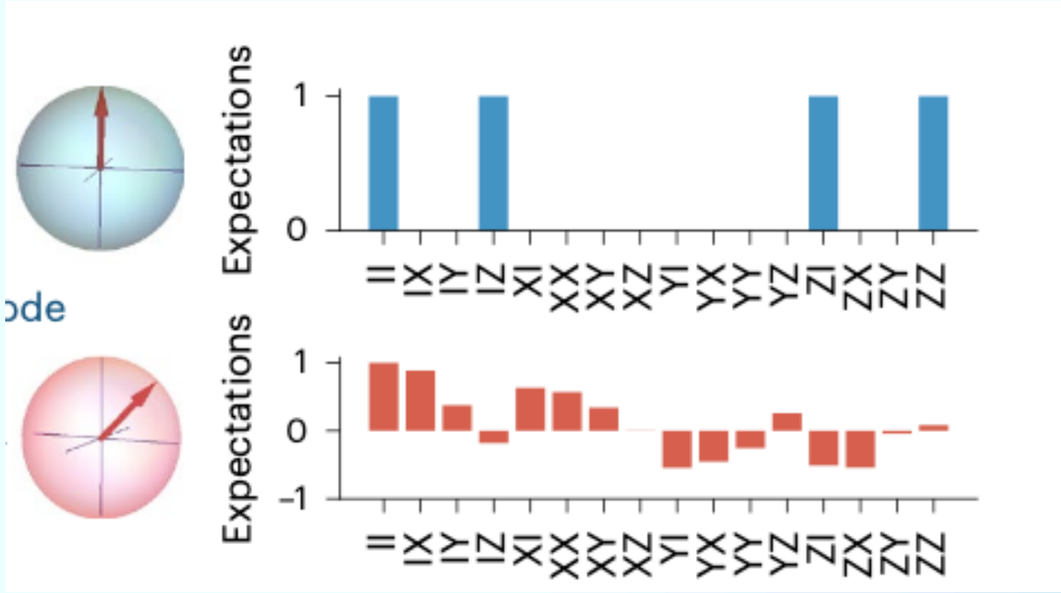


$\mathrm{poly}(n)$ **bez magije**

Efekti T elemenata



SciPost Phys. 9, 087 (2020)



Niroula, P., White, C.D., Wang, Q. *et al.* Phase transition in magic with random quantum circuits. *Nat. Phys.* 20, 1786–1792 (2024)

Entropija stabilizacije kao observable kola kvantifikuje ‘udaljenost’ od stabilizatora (nula za ta stanja)

L. Leone, S.F.E. Oliviero, A. Hamma PRL **128**, 050402(2022)

$$M_\alpha(\psi) = \frac{1}{1-\alpha}\log_2 \mathcal{P}_\alpha(\psi), \qquad \mathcal{P}_\alpha(\psi) = \frac{1}{d}\sum_{P\in\mathcal{P}_N} |\mathrm{Tr}(P\psi)|^{2\alpha}, \qquad \psi = |\psi\rangle\langle\psi| \qquad d = 2^N$$

Entropija stabilizacije u eksperimentu

.... uzorkovanje (sampling) - Nasumična Merenja (Randomized Measurements)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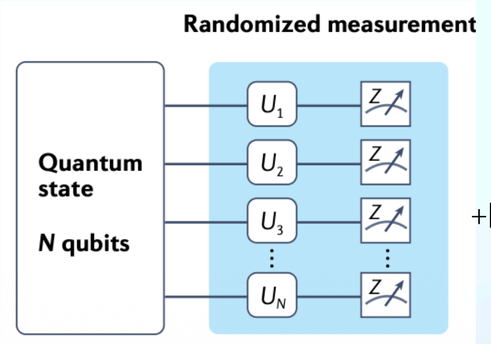
HOME > SCIENCE > VOL. 364, NO. 6437 > PROBING RÉNYI ENTANGLEMENT ENTROPY VIA RANDOMIZED MEASUREMENTS

REPORT

Probing Rényi entanglement entropy via randomized measurements

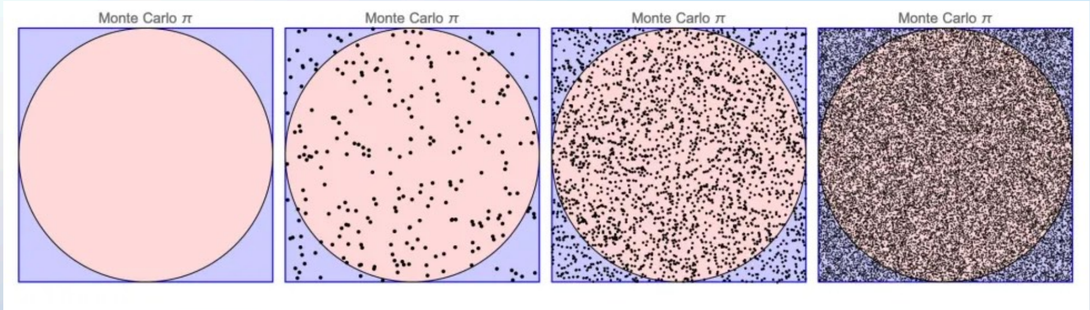
TIFF BRYDGES, ANDREAS ELBEN, PETAR JURCEVIC, BENOÎT VERMERSCH, CHRISTINE MAIER, BEN P. LANYON, PETER ZOLLER, RAINER BLATT, AND CHRISTIAN F. ROOS Authors Info & Affiliations

SCIENCE • 19 Apr 2019 • Vol 364, Issue 6437 • pp. 260-263 • DOI: 10.1126/science.aau4963



+klasična obrada podataka

slično Monte Karlo metodama u statističkoj fizici



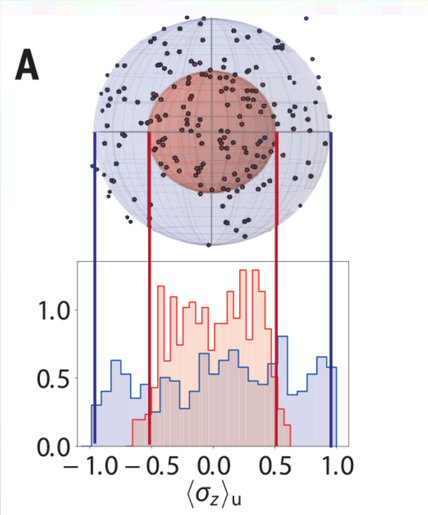
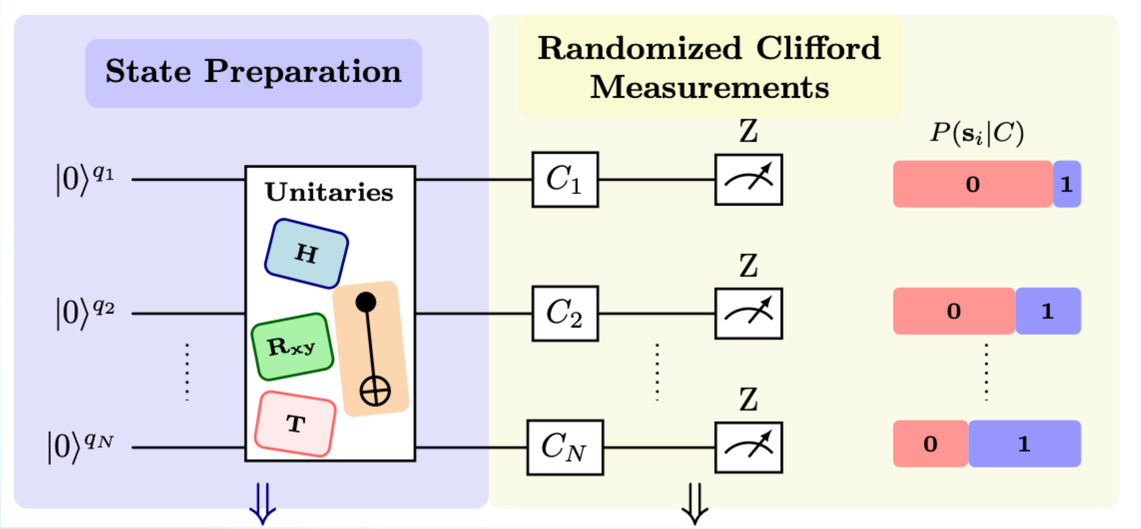


Fig. 1. Measuring second-order Rényi entropies through randomized measurements. (**A**) Single-qubit Bloch sphere. The purity is directly related to the width of the distribution of measurement outcomes after applying random rotations u_i. Initial pure state (blue) and mixed state (red) cases are shown. See text. (**B**) Generalization to multiple qubits: Measuring N_A-qubit

Nasumična Clifford Merenja - Randomized Clifford Measurement (RCM)

Oliviero, S.F.E. et al. 'Measuring magic on a quantum processor', npj Quantum Information, 8(1) (2022)

$$M_2(|\psi\rangle) = -\log_2 \mathcal{W} + \log_2 \mathcal{P} - \log_2 d,$$



RCM protocol—> uzorkovanje stanja sa identičnom količinom magije

24 Clifford 1-qubit operatora

A/P	I	X	Y	Z
I	I	X	Y	Z
H	H	XH	YH	ZH
HS	HS	XHS	YHS	ZHS
S	S	XS	YS	ZS
SH	SH	XSH	YSH	ZSH
HSH	HSH	$XHSH$	$YHSH$	$ZHSH$

Table I: Single-qubit Clifford gates (modulo global phase $U(1)$) used in Eqs. (2) and (3), where the columns are Pauli operators $P = \{I, X, Y, Z\}$ and rows are coset representatives $A = \{I, H, HS, S, SH, HSH\}$. H is the Hadamard gate, and S is the $\pi/2$ phase gate.

$$\mathcal{P} = d \sum_{\vec{\mathbf{s}}} (-2)^{-\|\vec{\mathbf{s}}\|_2} \, \mathbb{E}_C\big[P(\mathbf{s}_1|C)P(\mathbf{s}_2|C)\big], \quad \mathcal{W} = -\sum_{\vec{\mathbf{s}}} (-2)^{-\|\vec{\mathbf{s}}\|_4} \, \mathbb{E}_C\big[P(\mathbf{s}_1|C)P(\mathbf{s}_2|C)P(\mathbf{s}_3|C)P(\mathbf{s}_4|C)\big].$$

arXiv: 2511.15576

Šta je nelokalna magija

- Nelokalna magic wastage kad se magija proširi u stanju koje je kvantnom spregnuto (entangled): arXiv:2403.07056
- Protokol: pripremiti stanja sa nelokalnom magijom i zatim pokušati izbrisati lokalni deo

$$M_2^{\mathrm{NL}}(|\psi\rangle) = \min_{U_A, U_B} M_2(U_A \otimes U_B |\psi\rangle)$$

Vizuelizacija kvantne spletenosti I nelokalne magije u slučaju dva qubit-a ili kvantna spina-1/2.

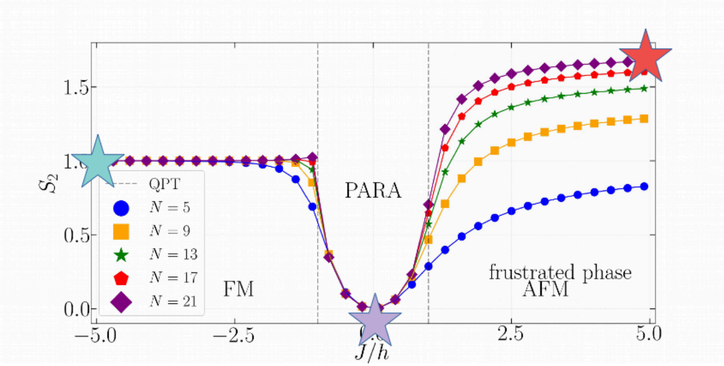
arXiv: 2511.15576

Primer kvantnom spinskog models koji isključivo sadrži nelokalnu magiju

1d transverse field Ising model (TFIM)

$$H = J\sum_{i=1}^{L}\sigma_i^x\sigma_{i+1}^x - \lambda\sum_{i=1}^{L}\sigma_i^z.$$

Antiferomagnetni režim sa periodički graničnim uslovima vodi do frustracije sistema



Limits

- FM Greenberger–Horne–Zeilinger state

$$|GHZ\rangle = \frac{1}{\sqrt{2N}}\left(|+\rangle^{\otimes N} + |-\rangle^{\otimes N}\right)$$

- PARA

$$|\psi\rangle = |+ \text{ or } -\rangle^{\otimes N}$$

- frustrated AFM W-state

$$|W\rangle = \frac{1}{\sqrt{N}}\left(|100...0\rangle + |010...0\rangle + ... + |000...1\rangle\right)$$

SciPost Physics

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Complexity of frustration: A new source of non-local non-stabilizerness

Jovan Odavić, Tobias Haug, Gianpaolo Torre, Alioscia Hamma, Fabio Franchini, Salvatore Marco Giampaolo

SciPost Phys. 15, 131 (2023) · published 3 October 2023

doi: 10.21468/SciPostPhys.15.4.131 pdf BiBTeX RIS Submissions/Reports Check for updates

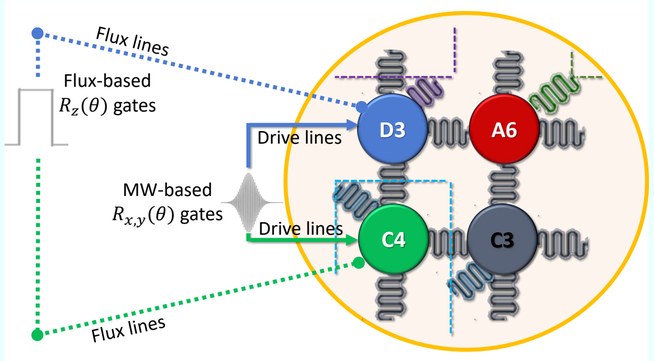
Nelokalna magija još nije eksperimentalno detektovana

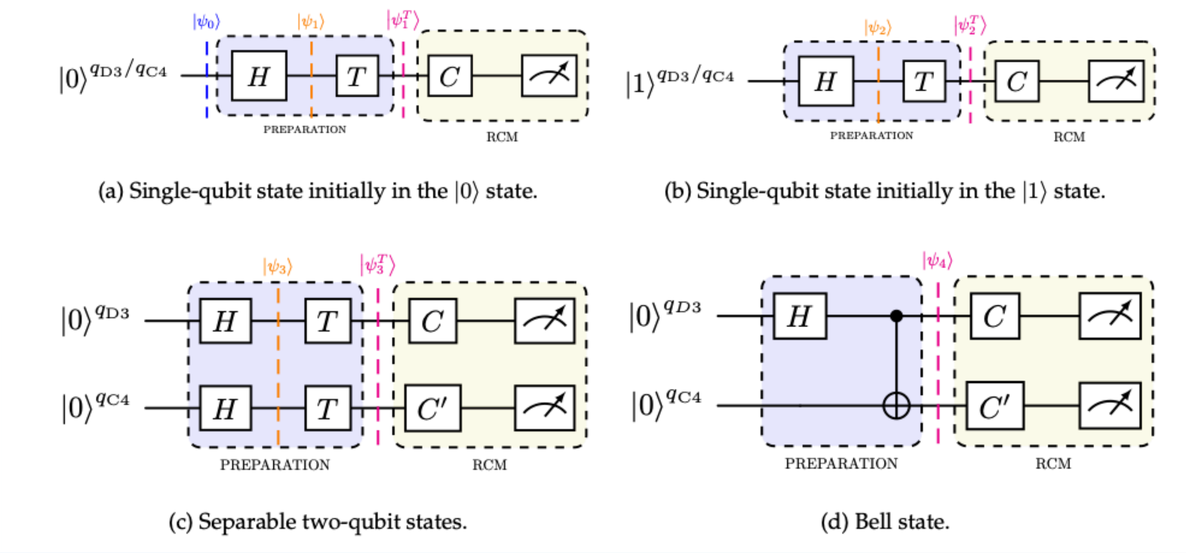
Stoga smo je po prvi put izmerili na kvantom procesoru!

	Class 1	Class 2	Class 3
Notation	Local Magic(LM)	Local+Non-Local Magic(M)	Non-Local Magic(NLM)
Local	✓	✓	✗
Non-Local	✗	✓	✓
Local Erasure	Complete	Partial	Null

arXiv: 2511.15576

Benchmark and identifikacija izvora šuma (noise)





(a) Single-qubit state initially in the $|0\rangle$ state.

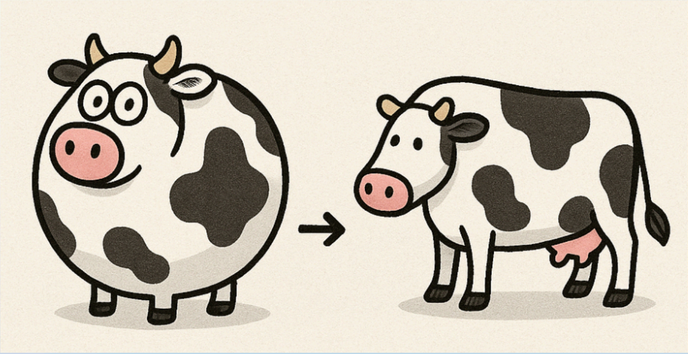
(b) Single-qubit state initially in the $|1\rangle$ state.

(c) Separable two-qubit states.

(d) Bell state.

	$F_{RO}(\%)$	$F_{RB}(\%)$	$T_2^{\text{Echo}}(\mu s)$	$T_2^*(\mu s)$	$T_1(\mu s)$	$M_2^{\text{exp}}(\Psi^{M_2^{\text{th}}=0})$	$M_2^{\text{exp}}(\Psi^{M_2^{\text{th}}\neq 0})$
(a)							
D3	94 ± 1	99.75 ± 0.01	31.1 ± 0.7	25 ± 6	23.3 ± 0.1	$\|\Psi_0\rangle$ 0.1 ± 0.1	
						$\|\Psi_1\rangle$ 0.1 ± 0.1	$\|\Psi_1^T\rangle$ 0.5 ± 0.1
	96 ± 1	99.910 ± 0.002	39.9 ± 0.7	33 ± 6	30.0 ± 0.1	$\|\Psi_1\rangle$ 0.1 ± 0.1	$\|\Psi_1^T\rangle$ 0.4 ± 0.1
						$\|\Psi_2\rangle$ 0.1 ± 0.1	$\|\Psi_2^T\rangle$ 0.4 ± 0.1
C4	95 ± 1	99.925 ± 0.003	38.8 ± 1.1	24 ± 2	36.2 ± 0.1	$\|\Psi_1\rangle$ 0.1 ± 0.1	$\|\Psi_1^T\rangle$ 0.4 ± 0.1
						$\|\Psi_2\rangle$ 0.1 ± 0.1	$\|\Psi_2^T\rangle$ 0.4 ± 0.1
(b)	$F_{RO}(\%)$	$F_{RB}(\%)$	$F_{RB}^{CZ}(\%)$	$Cross^{MW}(\%)$	$Cross^{ZZ}(kHz)$		
D3	83 ± 1	99.746 ± 0.014	99 ± 2	~ 0.12	~ 99	$\|\Psi_3\rangle$ 0.1 ± 0.1	$\|\Psi_3^T\rangle$ 0.8 ± 0.1
C4	91 ± 1	99.905 ± 0.003		~ 1.57	~ 100	$\|\Psi_3\rangle$ 0.1 ± 0.1	$\|\Psi_3^T\rangle$ 0.8 ± 0.1
(c)							
D3	92 ± 1					$\|\Psi_4\rangle$ 0.2 ± 0.1	
C4							

Table 1: Experimental magic measured for the quantum states in Fig. 3. Systematic investigation of the experimental magic for single- and two-qubit quantum states, involving qubits D3 and C4, as a function of: the readout fidelity F_{RO}, the average single-qubit gates fidelity measured by Randomized Benchmarking, F_{RB}, both in the isolated case (a) and simultaneously (b), statistical relaxation, Ramsey and Echo coherence times (T_1, T_2^* and T_2^{Echo}, respectively). For the two-qubit circuits, we have also reported an estimation of the drive and ZZ crosstalk on the investigated pair [55–58]. A discussion on the error estimation is reported in App. B.



arXiv: 2511.15576

Naš posao kao teoretičara

1.2 Strategies to counter errors

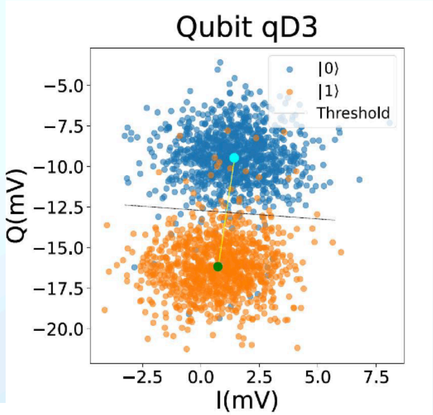
1. **Do nothing and hope for the best.** We can only run short circuits befor
our computation is overwhelmed by the noise. This regime is called the *Nois*
Intermediate-Scale Quantum (NISQ) regime [16].

Error Mitigation and Error Correction Lecture Notes - Philippe Faist

...je bio da razumemo I razložimo izvore grešaka koje naš procesor ima na osnovu preliminarnih i benchmark eksperimenata

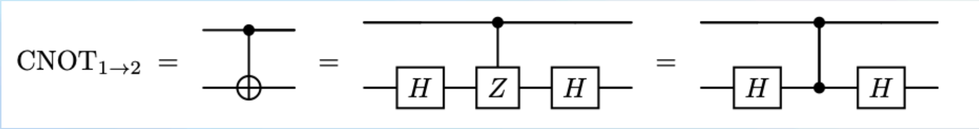
Nasumični bit-flip

$$0 \to 1 \quad \text{or} \quad 1 \to 0.$$



1. Greške pri samom merenju

2. CNOT kvantni elementi (depolarizujući šum)



$$\mathcal{E}(\rho) = \frac{pI}{2} + (1-p)\rho. \tag{8.100}$$

The effect of the depolarizing channel on the Bloch sphere is illustrated in Figure 8.11.

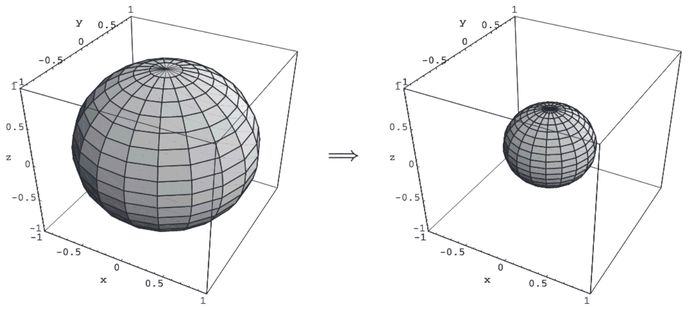
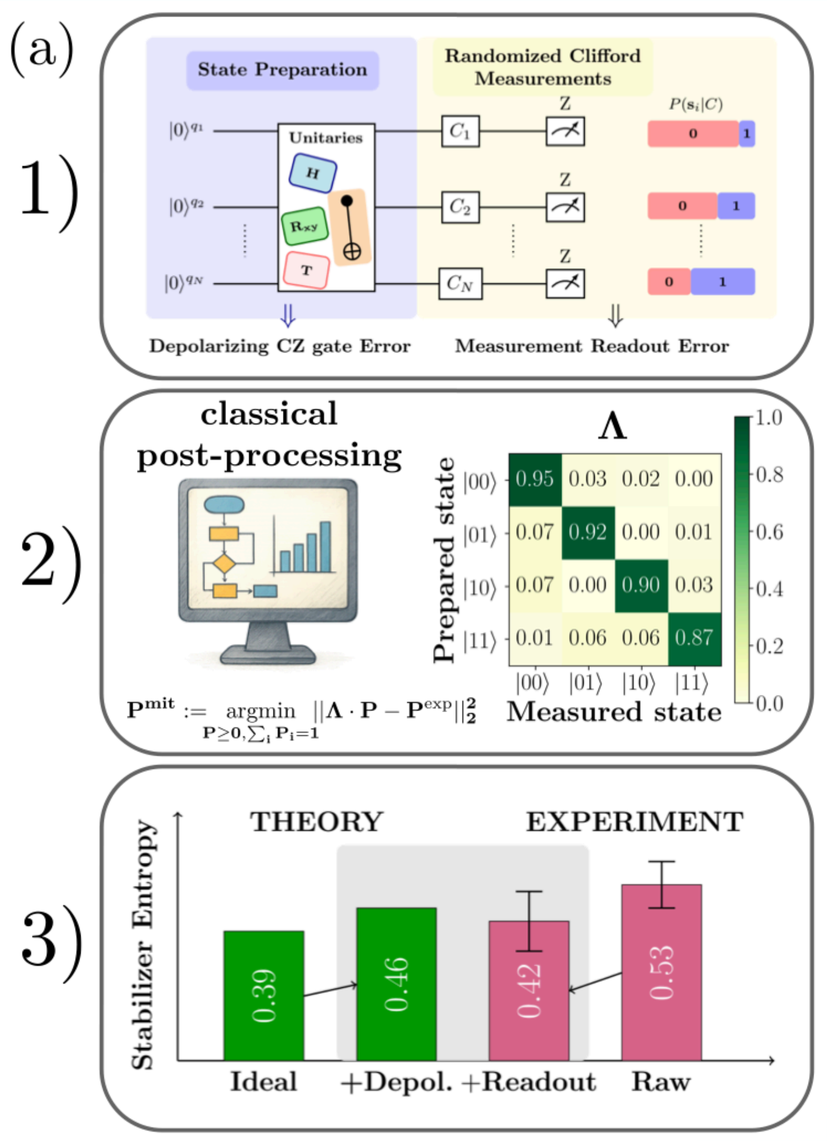


Figure 8.11. The effect of the depolarizing channel on the Bloch sphere, for $p = 0.5$. Note how the entire sphere contracts uniformly as a function of p.

arXiv: 2511.15576

Workflow

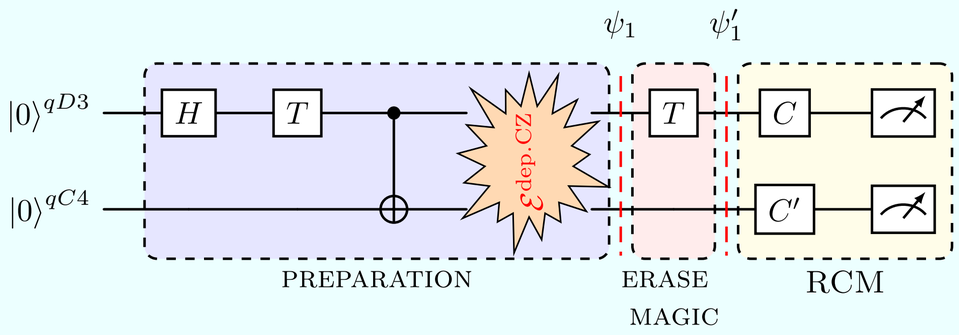


priča o sjedinjavanju teorije i eksperimenta

dvokraki pristup

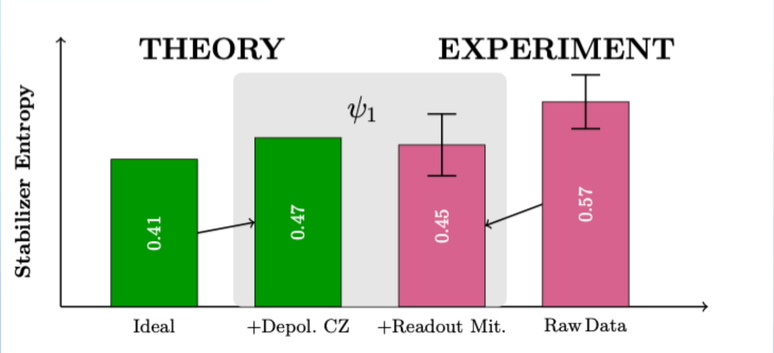
arXiv: 2511.15576

Klasa 1: Lokalna Magija



Circuit	State	Th. Purity	Exp. Purity	Th. Magic	Exp. Magic	NL-Magic (from RDM purity)
Preparation	ψ_1	0.92	**1.02** $\pm$ 0.04	0.47	**0.45** $\pm$ 0.06	
Prep.+Erasure	ψ_1'	0.92	**1.05** $\pm$ 0.06	0.11	**0.08** $\pm$ 0.08	**0.1176** $\pm$ 0.0007

Table 2: Local Magic (LM) state results. Comparison of Purity and Magic for states ψ_1 (before) and ψ_1' (after) the erasure , as well as the value of non-local magic obtained from subsystem purity. The theoretical predictions for purity and magic are calculated by considering the CZ depolarizing error and compared with the experimental results after readout error mitigation. Details on the errors are reported in *Methods*.



Alternativni metod

$$|\psi\rangle = \sqrt{\lambda}|\psi_1^A\rangle|\psi_1^B\rangle + \sqrt{1-\lambda}|\psi_2^A\rangle|\psi_2^B\rangle$$

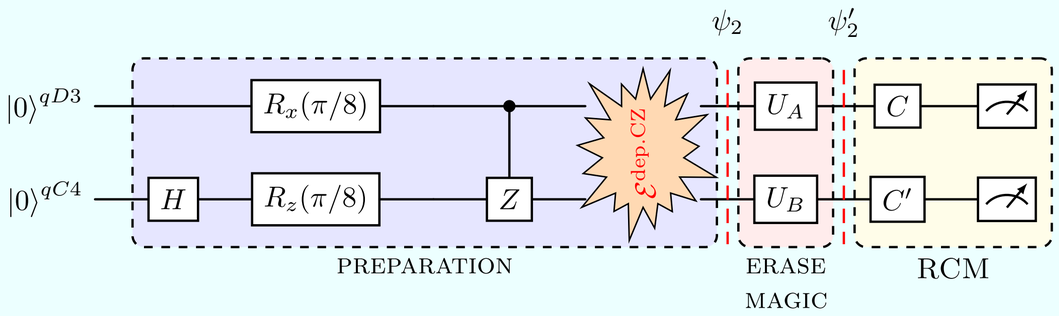
$$\psi_A := \mathrm{Tr}_B(|\psi\rangle\langle\psi|) \qquad \mathrm{Pur}(\psi_A) = \lambda^2 + (1-\lambda)^2 .$$

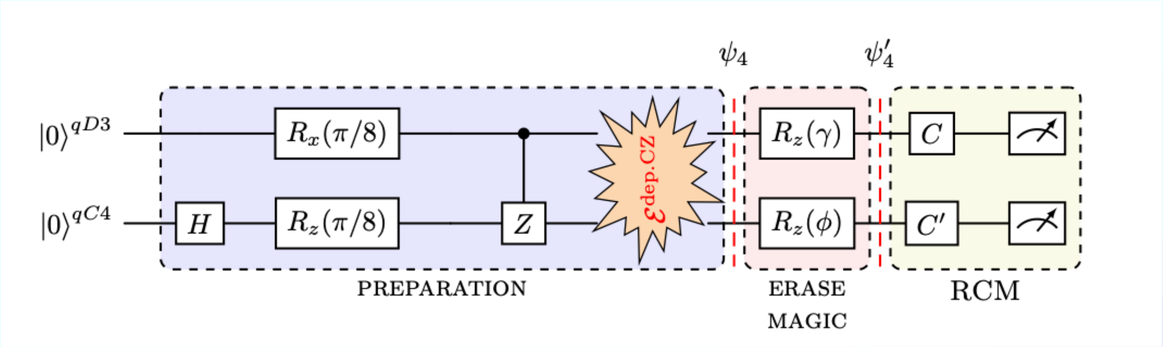
$$M^{\mathrm{NL}}(|\psi\rangle) = -\log_2\left(4\mathrm{Pur}(\psi_A)^2 - 6\mathrm{Pur}(\psi_A) + 3\right) .$$

Closed-form za slučaj 2 qubit-a

arXiv: 2511.15576

Klasa 2: Lokalna+Nelokalna magija (M)



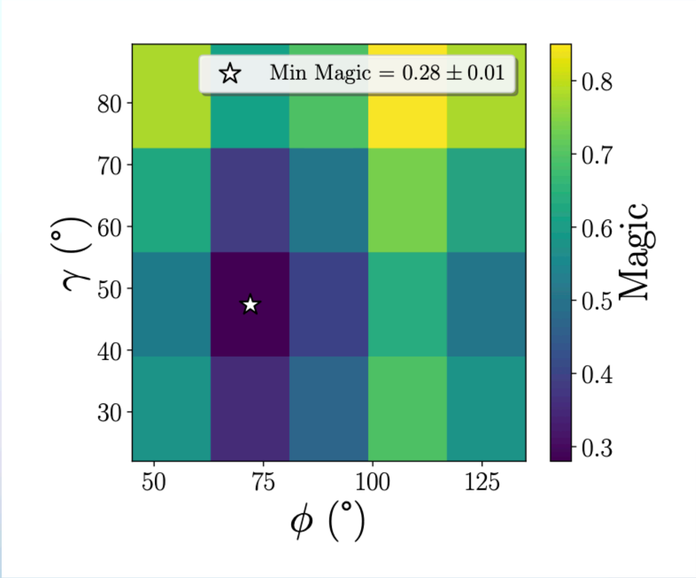


$$U_A = R_z(\alpha)R_y(\beta)R_z(\gamma)\ ,\ U_B = R_z(\delta)R_y(\eta)R_z(\phi)\ ,$$

$$\alpha = \beta = \gamma = \delta = \eta = 0, \phi = 67.61^\circ$$

Circuit	State	Th. Purity	Exp. Purity	Th. Magic	Exp. Magic	NL-magic (from RDM purity)
Preparation	ψ_2	0.95	**0.94** ± 0.04	0.44	**0.42** ± 0.09	
Prep.+Erasure	ψ_2'	0.95	**1.00** ± 0.05	0.3	**0.3** ± 0.1	**0.18** ± 0.07

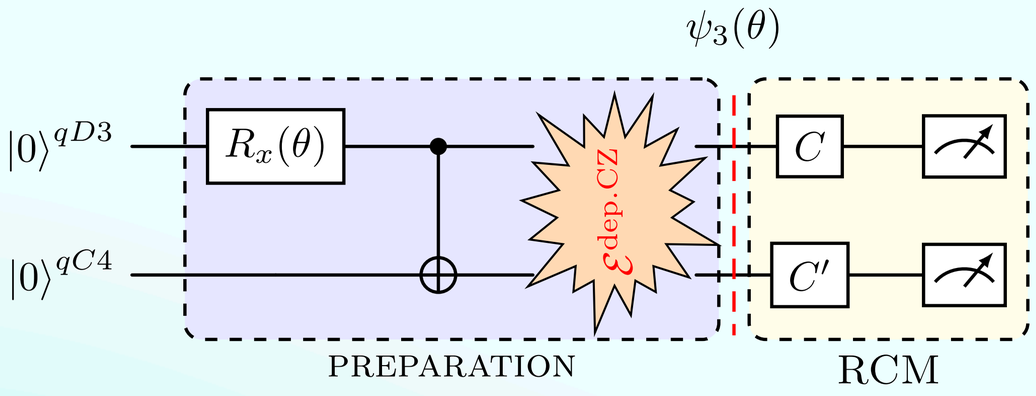
Table 3: Local + Non-Local (M) magic quantum state results. Comparison of Purity and Magic for states ψ_2 (before) and ψ_2' (after) the erasure protocol, as well as the value of non-local magic obtained from subsystem purity. The theoretical predictions for purity and magic are calculated by considering the CZ depolarizing error and compared with the experimental results after readout error mitigation. Details on the errors are reported in *Methods*.

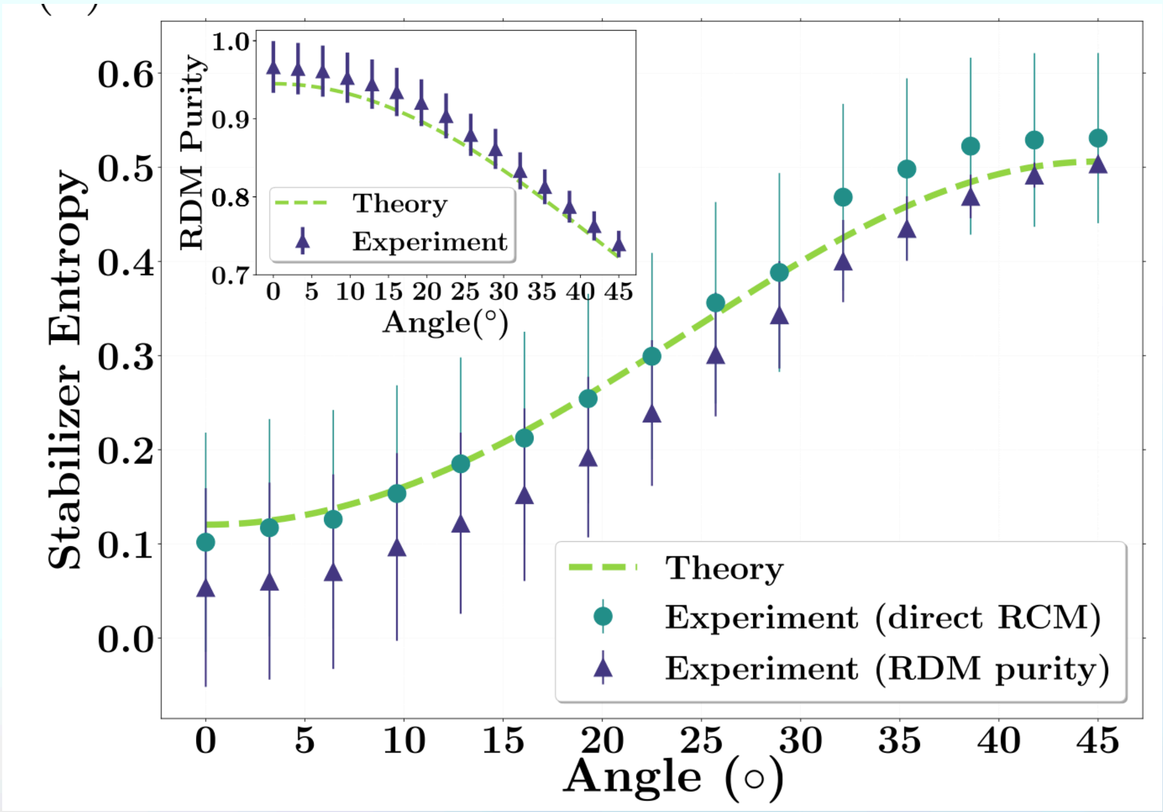


Ono što ostane je nelokalna magija!

arXiv: 2511.15576

Klasa 3: Nelokalna magija (NLM)





Sveukupno —> smoking gun eksperimentalne nelokalne magije

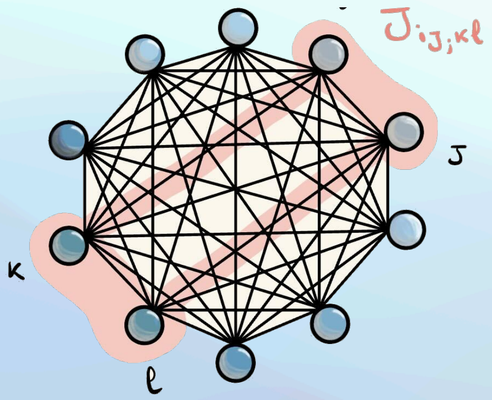
arXiv: 2511.15576

Perspektiva i budući rad

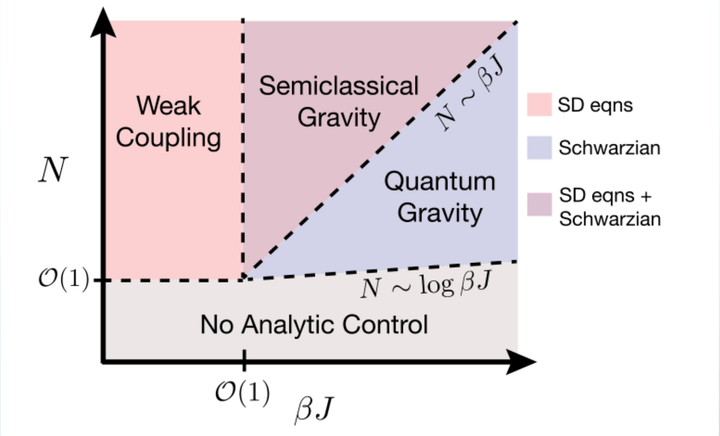
- Neki aspekti nelokalne magije imaju interpretaciju u AdS/CFT dualnosti? (Gravitational back-reaction is magical, arXiv:2403.07056)

- Simulacija strogo korelisanih sistema poput Sachdev-Ye-Kitaev (SYK) modela na kvantnim računarima. SYK kvantno haotičani model koji opisuje neke aspekte crnih rupa.

- SYK model ima slično ponašanje niskodimenzionima teorijam gravitacije (Jackiw-Teitelboim (JT) theory and nearly-AdS2 spaces)



SYK model



Solvable limits of the SYK-4 model - PRL **126**, 030602 (2021)

Stabilizer entropy and entanglement complexity in the Sachdev-Ye-Kitaev model

Barbara Jasser [1,2,*], Jovan Odavić [2,3,†], and Alioscia Hamma [1,2,3,‡]

Show more

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Novi rad na ovu temu!