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WHAT THE PAPER SAYS · WHAT IT DOESN'T · WHY IT MATTERS

Quantum memory ta ƙarshe ta fara inganta yayin da ta girma — wannan ne milestone, ba working computer ba

Google Quantum AI ta nuna da tsafta a karon farko cewa surface-code quantum memory na iya aiki below threshold: yayin code ya girma daga distance 3 zuwa 5 zuwa 7, logical error rate ta ragu exponentially (kus. 2.14× ga kowane steps biyu), kuma 101-qubit distance-7 memory ta rayu fiye da best physical qubit — beyond breakeven — tare da real-time error correction. Milestone ne da aka daɗe ana nema, amma logical memory qubit ɗaya ce, error rate har yanzu nesa da algorithms na gaske, babu logical gates, akwai unexplained error floor, kuma scaling mai yawa yana gaba.

Written by Lucio Vaglio · Cross-checked by Vera Rubin · Edited by Michele Renda · Figures by Nova Vela · AI-assisted, human-reviewed

Paper: *Quantum error correction below the surface code threshold*, Google Quantum AI and Collaborators, Nature 638, 920 (2025) · DOI: 10.1038/s41586-024-08449-y

Lokacin da curve ɗin ya lanƙwashe zuwa hanyar da ta dace

Shekaru talatin, quantum error correction ta dogara da wani alkawari da ba a taɓa nuna shi a sarari ba. Theory ta ce idan ka rarraba unit ɗaya na quantum information — **logical qubit** ɗaya — a kan noisy physical qubits da yawa, kuma idan waɗannan physical qubits sun yi kyau sosai, to ƙara *ƙarin* qubits ya kamata ya sa logical qubit ɗin ya *fi kyau*, tare da errors suna raguwa exponentially yayin da code ke girma. Matsalar ita ce kalmar "idan": ƙasa da wani critical noise threshold, ƙarin qubits suna taimaka; sama da shi, ƙarin qubits suna ƙara noise kawai. Duk gwaje-gwajen da suka gabata ko dai sun kasance a ɓangaren da bai dace ba na wannan layi, ko kuma ba su nuna trend ɗin da tsafta ba. Girman code yana sa abubuwa su lalace, ba su inganta ba.

A Disamba 2024, Google Quantum AI ta ruwaito demonstration na farko mai tsabta na ɗayan regime ɗin. A Willow, sabon generation na superconducting processors nasu, sun gina surface-code memories da code distances 3, 5 da 7, kuma suka ga logical error rate *ta ragu* duk lokacin da code ya ƙaru — da factor $\Lambda = 2.14 \pm 0.02$ ga kowane steps biyu na distance. Mafi girma, 101-qubit distance-7 memory, ta riƙe logical qubit da error 0.143% ± 0.003% per correction cycle, kuma — kanun labarai cikin kanun labarai — ta rayu *fiye da best physical qubit ɗinta*, da factor 2.4 ± 0.3. Ana kiran wannan **beyond breakeven**, kuma shi ne karo na farko da duk tsarin error correction ya biya kansa a wannan hardware.

Wannan milestone ne na gaske, kuma ya dace a faɗi ainihin irin milestone ɗin. Proof ne cewa scaling yanzu yana tafiya ta hanyar da ta dace. Ba working quantum computer ba ne, kuma takardar ba ta ikirari haka ba.

> **Ma'anar "surface code," "distance" da "below threshold"**
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> **Logical qubit** unit ɗaya ne na protected quantum information da aka encode a physical qubits da yawa. **Surface code** wata hanya ce ta yin wannan encoding a 2D grid, inda ƙarin "measure" qubits ke duba errors kullum ba tare da su lalata stored information ba. Code **distance** d ba physical distance ba ne: shi ne smallest number na well-placed errors da za su iya lalata logical qubit ba tare da code ya gano ba. Larger d yana nufin patch mafi girma kuma robust — yana kashe ƙarin physical qubits (roughly $2d^2 - 1$) kuma yana gyara simultaneous errors da yawa, har zuwa $(d - 1)/2$. Don haka distances 3, 5 da 7 da aka gwada suna gyara 1, 2 da 3 simultaneous errors kuma suna amfani roughly 17, 49 da 97 physical qubits — distance-7 memory da Google ta gina ta yi amfani da 101, ɗan sama da textbook minimum.
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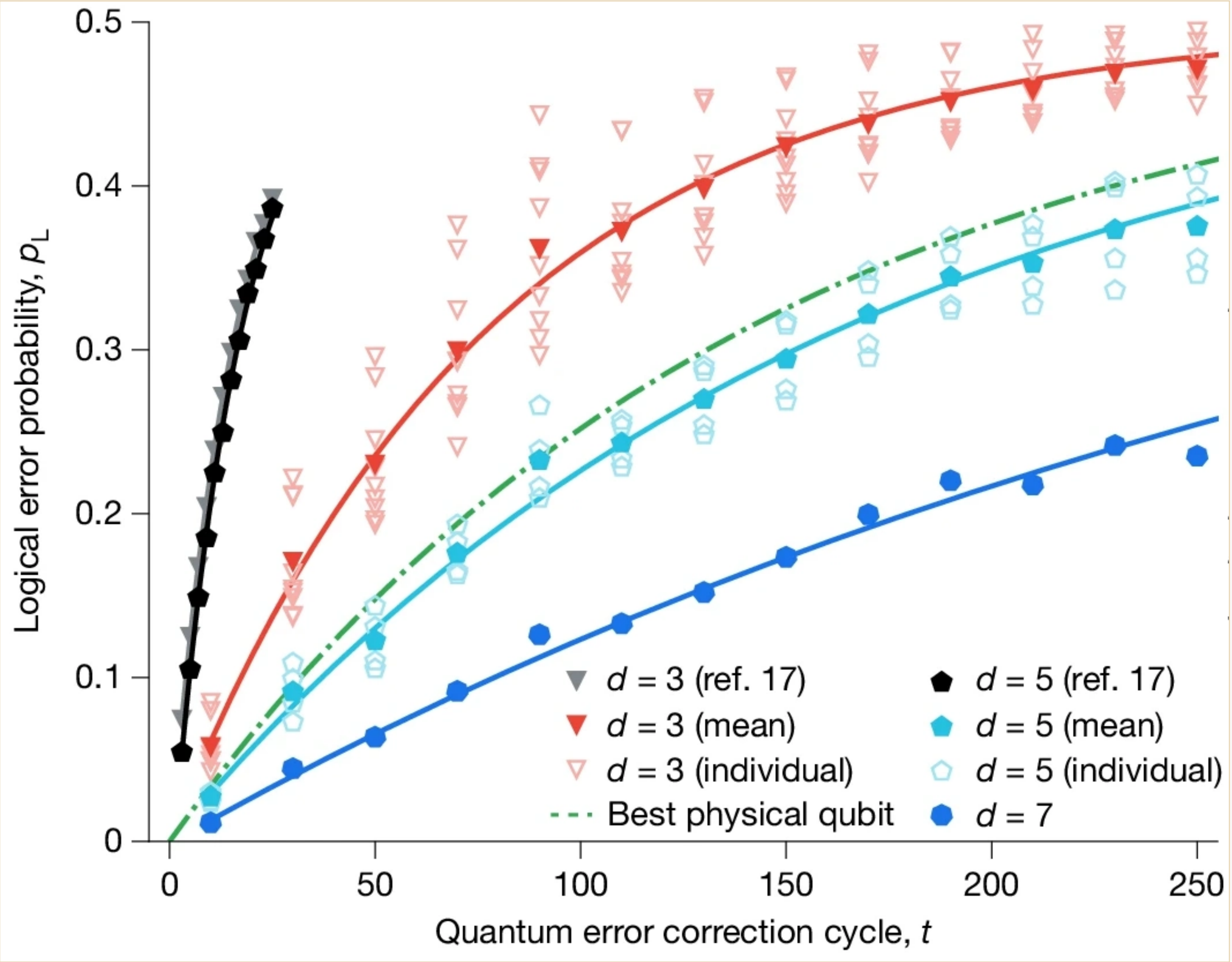
> "**Below threshold**" ita ce kalma mafi muhimmanci. Error correction tana taimaka ne kawai idan physical error rate tana ƙasa da critical value; a nan, kowane increase na distance yana suppress logical error rate exponentially. Suppression factor Λ yana auna wannan — $\Lambda > 1$ yana nufin girman code yana taimaka, kuma higher Λ ya fi. Google ta ruwaito $\Lambda \approx 2.14$, ma'ana kowane two-step increase a distance ya rage logical error rate roughly by half. Cewa Λ yana comfortably sama da 1 shi ne babban sakamakon.



Yadda logical error ke taruwa a correction cycles, ga distance-3, -5 da -7 memories (daga sama zuwa ƙasa). Layin da ya kamata a kalla shi ne green dashed line — *best single physical qubit* a chip. Distance-7 memory (blue, mafi ƙasa) tana tara error a hankali fiye da wannan line, don haka encoded qubit tana rayuwa fiye da best physical qubit da aka gina ta da shi — "beyond breakeven," da factor 2.4×. Wannan lifetime sakamako ne; below-threshold suppression kanta (Λ = 2.14 yayin code ya girma 3→5→7) yana cikin lambobin text.

Abin da marubutan suka yi

- Sun gina surface-code memories a Willow chips biyu: 105-qubit processor da ya gudanar da distance-3, -5 da -7 codes na scaling test (mafi girma 101-qubit, 49-bayanai-qubit distance-7 memory), da 72-qubit processor da ya gudanar da distance-5 memory tare da real-time decoder da high-distance repetition codes.
- Sun auna yadda **logical error per cycle** ya canza yayin da code distance ya ƙaru daga 3 zuwa 5 zuwa 7, sannan suka fitar da suppression factor Λ.
- Sun kwatanta lifetime na logical qubit da best individual physical qubit a chip ɗaya domin gwada "breakeven."
- Sun gudanar da distance-5 code tare da **real-time decoder** — classical hardware da ke fassara error checks da saurin da ake samar da su — har cycles miliyan ɗaya, domin nuna error correction na iya tafiya live da machine.

- Sun turawa simpler **repetition codes** zuwa distance 29 domin neman rare, deep error sources da ke sa floor ga performance.

Abin da suka gano

- **Code ɗin below threshold ne.** Logical error per cycle ta ragu da $\Lambda = 2.14 \pm 0.02$ ga kowane increase na distance da biyu — clean exponential suppression, behaviour da theory ta yi alkawari kuma babu processor da ya taɓa nuna da cikakken tabbaci.
- **Distance-7 memory ta kai 0.143% ± 0.003% error per cycle**, kuma ta rayu **2.4 ± 0.3 times longer** fiye da best physical qubit — beyond breakeven.
- **Real-time decoding ta iya bin machine.** Decoder ya samu matsakaici latency 63 microseconds a distance 5, tare da 1.1-microsecond cycle time, kuma ya ci gaba har cycles miliyan ɗaya — error correction ta gudana live, ba after-the-fact nazari kawai ba.
- **Rare, deep error source yana nan.** A repetition-code tests, performance a ƙarshe ya tsaya saboda correlated error bursts da ke faruwa kusan **sau ɗaya a awa** (kusan ɗaya cikin cycles 3×10^9), suna kafa error floor kusa da 10^{-10}; marubutan sun ce asalin wannan error **ba a fahimta ba tukuna**.

Abin da wannan bai tabbatar ba

- Wannan **ba quantum computer da ke yin computation ba**. Quantum *memory* ce: tana adanawa kuma tana kare logical qubit ɗaya. Ba ta yin logical operations (gates) tsakanin logical qubits, kuma ba ta gudanar da algorithm.
- Ba wai saura qubit ɗaya a isa useful machines ba ne. Distance-7 logical qubit tana kashe kusan 101 physical qubits; ~0.1%-per-cycle error har yanzu ya fi roughly 10^{-6} zuwa 10^{-10} da real algorithms ke buƙata yawa sosai. Rufe wannan gap yana nufin larger distances — ƙarin physical qubits per logical qubit — kuma useful algorithms na buƙatar *thousands* na logical qubits lokaci guda. Physical-qubit budget na iya kai millions.
- Kalmar **"if scaled"** tana yin aiki sosai. Conclusion na takardar shi ne performance ɗin device, *idan an scale*, zai iya cika requirements na large algorithms. Nuna trend ɗin ya yi daidai a logical qubit ɗaya ba ɗaya ba ne da gina scaled machine, kuma babu garanti trend zai ci gaba a sizes masu yawa sosai.
- **Unexplained error floor matsala ce mai rai.** Correlated bursts da ke cap repetition-code performance suna, a cewar marubutan, orders of magnitude sama da expected kuma za su hana larger fault-tolerant applications har sai an fahimce su — open flaw ne, ba solved detail ba.
- Ba ya cewa komai game da **breaking encryption ko "quantum supremacy" ga useful tasks**. Waɗannan suna buƙatar full fault-tolerant machine wanda wannan foundation stone ne kawai a gare shi.

Yaya ƙarfin shaidar yake

- **Core ikirarin solid ne kuma muhimmi.** Below-threshold operation tare da clean exponential suppression a code distances uku, plus beyond-breakeven lifetime da working real-time decoder — wannan shi ne combination da fannin ya daɗe yana nema, kuma an nuna shi kai tsaye. Ba hype artefact ba ne; real engineering sakamako ne daga leading group.

- **Marubutan suna kula da scope.** Sun kira shi below-threshold *memory*, sun flag unexplained correlated-error floor da kansu, kuma sun sa future ɗin ƙarƙashin "if scaled." Overreach yana fitowa ne a coverage da ke juya "error-corrected memory qubit ta inganta yayin da ta girma" zuwa "quantum computing ta iso."
- **Matsayin gaskiya: foundational step ne da aka ɗauka da kyau.** Logical qubit ɗaya, an kare shi sosai har redundancy ta fara taimaka — amma scaling, logical gates da unexplained errors har yanzu doguwar hanya ce.

Me ya sa wannan yake da muhimmanci

Fault-tolerant quantum computing koyaushe tana da chicken-and-egg problem: machines masu amfani suna buƙatar error rates da physical qubit ba zai kai shi ba, amma maganin — error correction — yana aiki ne kawai idan hardware tuni ta yi kyau sosai har ta zama below threshold. Ketare wannan layi, ko sau ɗaya, ko a logical qubit ɗaya, yana canza tambayar daga "shin wannan yana yiwuwa?" zuwa "har ina za a iya scale shi, kuma da sauri nawa?" Wannan canji ne na gaske kuma mai ma'ana, shi ya sa sakamakon ya cancanci hankali.

Amma wannan kulawar da ta sa sakamakon trustworthy ita ce ya kamata ta rage overclaim. Wannan brick na farko ne na foundation, an sa shi da kyau. Ba ginin ba ne, kuma mutanen da suka sa shi su ne farkon masu faɗin haka. Abin da ya dace a bi a shekaru masu zuwa shi ne curve ɗin da ba shi da glamour: ko suppression factor zai tsaya yayin codes suna girma, ko logical gates za a iya yi da tsafta irin logical memory, da ko mysterious once-an-hour error za a taɓa bayyana.

Taƙaitaccen bayani

Google Quantum AI ta nuna a karon farko da tsafta cewa surface-code quantum memory na iya aiki *below threshold*: yayin da code ya girma daga distance 3 zuwa 5 zuwa 7, logical error rate ta ragu exponentially (kus. 2.14× ga kowane steps biyu), kuma mafi girma — 101-qubit distance-7 memory — ta rayu fiye da best physical qubit, beyond breakeven, yayin da error correction ke gudana real time. Wannan milestone ne na gaske da aka daɗe ana nema a engineering na quantum computers. Amma logical qubit ɗaya ce da ke aiki a matsayin memory, da error rate har yanzu nesa da abin da real algorithms ke buƙata, babu logical operations, akwai unexplained error floor, kuma akwai orders of magnitude na scaling a gaba. An ketare threshold na gaske — ba a kawo quantum computer ba.

Majiyoyi

Google Quantum AI and Collaborators, Quantum error correction below the surface code threshold, Nature 638, 920 (2025)
https://doi.org/10.1038/s41586-024-08449-y

Author Correction: Quantum error correction below the surface code threshold, Nature 653, E5 (2026) — corrects a Fig. 3a axis label and legend keys; does not affect the below-threshold (Fig. 1) results
https://www.nature.com/articles/s41586-026-10559-8