



The CLEAN PAPER

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

Quantum memory kan nìkèhin dára síí bí ó ẹ̀ ń tóbi — milestone gidi náà, àti machine tí kò tū̀ jẹ̀

Google Quantum AI fi hàn ní kedere fún igba àkókó pé surface-code quantum memory lè run below threshold: bí code ẹ̀ ẹ̀ ló láti distance 3 sí 5 sí 7, logical error rate dín exponentially, largest 101-qubit distance-7 memory sì pé ju best physical qubit rẹ̀ ló — beyond breakeven — pẹ̀lú real-time error correction. Milestone engineering gidi ni. Sùgbón logical qubit kan ni tó ń ẹ̀ ẹ̀ bí memory, error rate rẹ̀ sì jìn sí ohun tí real algorithms nílò, kò sí logical gates, unexplained error floor sì wà.

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Àkókò tí curve náà bèrè sí í tẹ sí ọ̀nà tó tọ

Fún ọ̀dún oḡbòṇ, quantum àṣiṣe correction ti dúrò lórí ìlérí kan tí a kò tū fi hàn ní ọ̀nà tó tọ. Theory sọ pé tí o bá tan unit kan ti quantum information — *logical* qubit kan — káàkiri ọ̀pọ̀ noisy physical qubits, tí physical qubits náà sì dára tó, fífi *sí i* qubits kún un yẹ kí ó mú logical qubit náà *dára sí*, pẹ̀lú àṣiṣe tí ń ṣubú exponentially bí code ẹ́ ń tóbi. Catch náà wà nínú “if”: ní isalẹ̀ critical ariwo threshold, *sí i* qubits ń ràn lẹ́wọ̀; ní lókè rẹ̀, *sí i* qubits kan ń fi ariwo kún un. Gbogbo ìdánwò ṣáájú wà ní apa tó burú ti line náà, tàbí wọn kò fi trend náà hàn ní kedere. Nígbà code bá ń tóbi, nìkan máa ń buru, kì í ẹ́e dára.

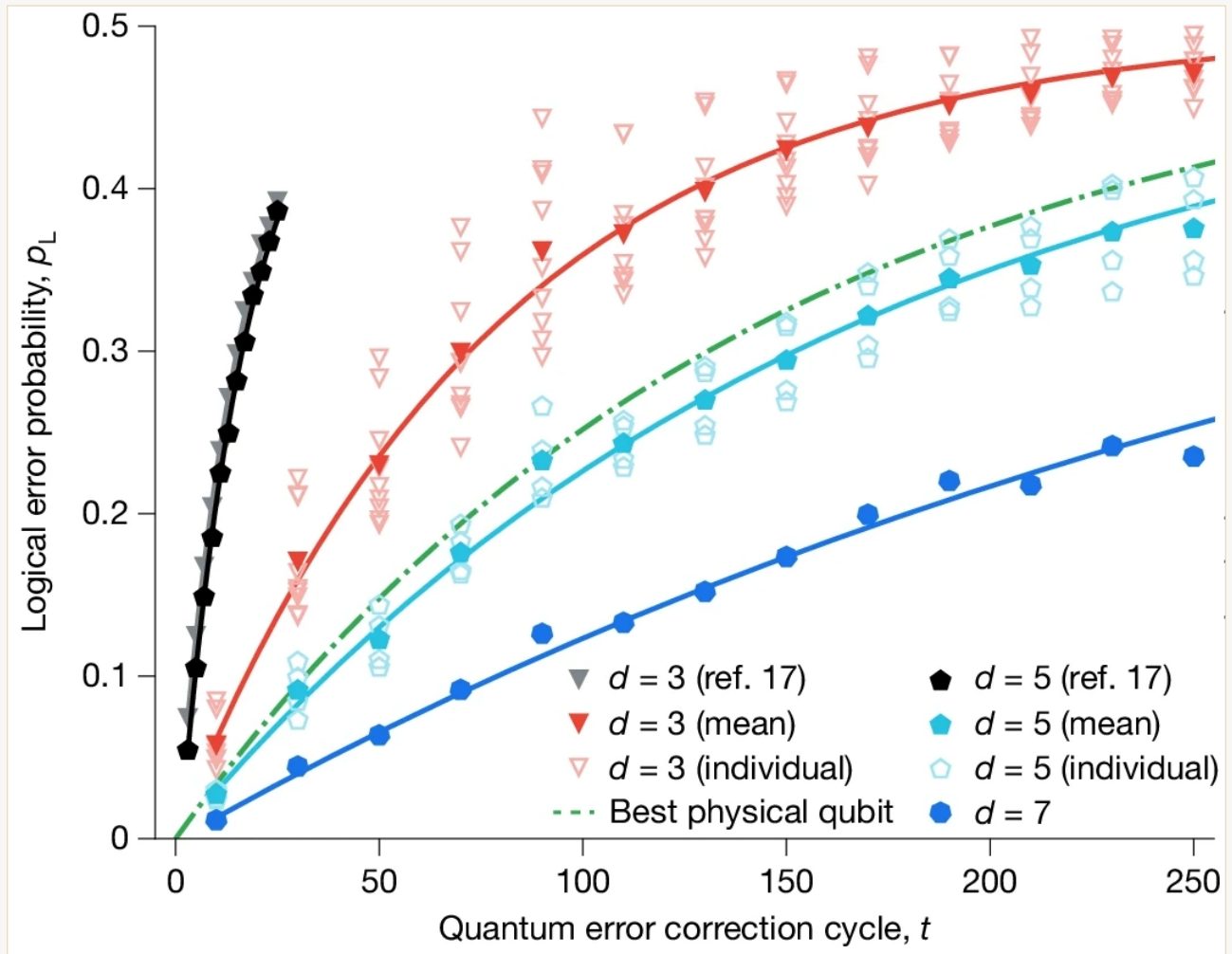
Ní December 2024, Google Quantum AI ròyìn demonstration tó mó àkókò tí regime kejì. Lórí Willow, generation tuntun ti superconducting processors wọn, wọn kọ surface-code memories ní code distances 3, 5 àti 7, wọn sì rí logical àṣiṣe rate *dín kù* ní gbogbo igba tí code bá tóbi — ní factor $\Lambda = 2.14 \pm 0.02$ fún gbogbo steps méjì tí ijìnnà bá ga. Largest wọn, 101-qubit distance-7 ìrántí, pa logical qubit mó pẹ̀lú àṣiṣe $0.143\% \pm 0.003\%$ per cycle of correction, àti — àkólé tó wà nínú àkólé — ó *pé ju best physical qubit tirẹ̀ lọ*, ní factor 2.4 ± 0.3 . Èyí ní a ń pè ní “beyond breakeven,” ó sì jẹ́ igba àkókò tí gbogbo apparatus àṣiṣe correction ti san owó complexity rẹ̀ padà lórí hardware yí.

Èyí jẹ́ milestone gidi, ó sì yẹ ká sọ irú milestone wo ni pẹ̀lú precision. Ó jẹ́ proof pé scaling náà ti ń lọ sí ìtọ̀sọ̀nà tó tọ. Kì í ẹ́e working quantum computer, ìwé ìwádìí náà kò sì claim bèẹ̀.

Kí ni “surface code,” “distance” àti “below threshold” tùmọ̀ sí?

Logical qubit jẹ́ protected unit kan ti quantum information tí a encode kojá ọ̀pọ̀ physical qubits. **Surface code** jẹ́ ọ̀nà pàtó láti ẹ́e encoding yẹn lórí 2D grid, níbi tí extra “measure” qubits ti ń check àṣiṣe léraléra láì disturb stored information. Code **ijìnnà** d kì í ẹ́e physical ijìnnà: ó jẹ́ smallest number ti well-placed àṣiṣe tó lè corrupt logical qubit láì jẹ́ kí code mó. Larger d tùmọ̀ sí patch tó tóbi, robust síi — ó ń lo *sí i* physical qubits (roughly $2d^2 - 1$), ó sì correct *sí i* simultaneous àṣiṣe, tí tí dé $(d - 1)/2$. Nítorí náà sizes méta tí a ìdánwò níhìn-ín, distances 3, 5 àti 7, correct 1, 2 àti 3 simultaneous àṣiṣe, wọn sì lo roughly 17, 49 àti 97 physical qubits — distance-7 ìrántí Google lo 101, diẹ̀ lókè textbook minimum.

“Below threshold” ni phrase tó ẹ́e pàtàkì jù. Error correction máa ń ràn lẹ́wọ̀ nìkan tí physical àṣiṣe rate bá wà ní isalẹ̀ critical value; níbẹ̀, gbogbo mú pọ̀ *sí i* nínú ijìnnà máa ń suppress logical àṣiṣe rate exponentially. Suppression factor Λ ní ń wọn èyí — $\Lambda > 1$ tùmọ̀ sí pé growing code helps, higher Λ sì dára síi. Google ròyìn $\Lambda \approx 2.14$, tùmọ̀ sí gbogbo mú pọ̀ *sí i* two-step nínú ijìnnà dín logical àṣiṣe rate roughly ní idaji. Pé Λ wà comfortably above 1 ni gbogbo èsì.



Bí logical àṣiṣe ẹ̀ẹ́ ń kó jọ kọjá correction cycles, fún distance-3, -5 àti -7 memories (lókè sí isalẹ̀). Line tí o yẹ ká wo ni green dashed ọ̀kan — *best single physical qubit* lórí chip. Distance-7 ìrántí (blue, lowest) ń kó àṣiṣe jọ lóra ju line yẹn lọ, nítorí nàà encoded qubit ń pẹ̀ ju best physical qubit tí a fi kọ́ ọ́ — “beyond breakeven,” ní factor $2.4\times$. Èyí ni lifetime èsì; below-threshold suppression funra rẹ̀ ($\Lambda = 2.14$, bí code ẹ̀ẹ́ lọ láti ijinnà 3 sí 5 sí 7) wà nínú numbers text.

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Ohun tí àwọn olùkòwé ẹ̀

- Wọn kọ surface-code memories lórí Willow chips méjì: 105-qubit processor kan tó run distance-3, -5 àti -7 codes fún scaling ìdánwò (largest rẹ̀ jẹ́ 101-qubit, 49-data-qubit distance-7 ìrántí), àti 72-qubit processor kan tó run distance-5 ìrántí pèlú real-time decoder àti high-distance repetition codes.
- Wọn wọn bí logical àṣiṣe *per cycle* ẹ̀ẹ́ yí bí wọn ẹ̀ pọ̀ code ijinnà láti 3 sí 5 sí 7, wọn sì extract suppression factor Λ .
- Wọn fi lifetime logical qubit wé best individual physical qubit lórí chip kan nàà láti ìdánwò “breakeven.”
- Wọn run distance-5 code pèlú **real-time decoder** — classical hardware tó ń interpret àṣiṣe checks ní speed tí wọn ń jáde — fún títí dé million cycles, láti fi hàn pé àṣiṣe correction lè keep up pèlú machine.
- Wọn push simpler **repetition codes** títí dé ijinnà 29 láti wá rare, deep àṣiṣe orisun tó ń set floor lórí perfor-

mance.

Ohun tí wọn rí

- **Code náà wà below threshold.** Logical àṣiṣe per cycle dín kù ní $\Lambda = 2.14 \pm 0.02$ fún gbogbo mú pò sí i méjì nínú ijìnnà — clean exponential suppression, ìhùwàsí tí àbá-èkọ̀ ṣèlérí tí processor kankan kò tì fi hàn definitively.
- **Distance-7 irántí dé $0.143\% \pm 0.003\%$ àṣiṣe per cycle,** ó sì pè 2.4 ± 0.3 times longer ju best physical qubit rẹ — beyond breakeven.
- **Real-time decoding keep up.** Decoder ní average latency 63 microseconds ní ijìnnà 5, against 1.1-microsecond cycle àkókò, sustained kojá million cycles — àṣiṣe correction ní run live, kì í ṣe after-the-fact ìtupalẹ̀ nìkan.
- **Rare, deep àṣiṣe orísun kan sì wà.** Nínú repetition-code ìdánwò, performance ní ààlà níkehìn nípa correlated àṣiṣe bursts tí ní ṣẹlẹ̀ roughly **lẹ́ẹ́kan lówàákàtí** (nípa ọ̀kan in every 3×10^9 cycles), tó ní set àṣiṣe floor near 10^{-10} tí origin rẹ̀ ònḱòwé sọ pé **a kò tì lóye**.

Ohun tí èyí kò fi ẹrí múlẹ̀

- Kì í ṣe quantum computer tó ní ṣe computation. Èyí jẹ quantum *irántí*: ó ní store, ó sì protect logical qubit kan. Kò perform logical operations (gates) láàárín logical qubits, kò sì run algorithm.
- Kì í ṣe pé qubit kan ṣoṣo ló kù sí useful machines. Distance-7 logical qubit lo nípa 101 physical qubits; 0.1%-per-cycle àṣiṣe rate sì ga gan-an ju roughly 10^{-6} sí 10^{-10} tí gidi algorithms nílò. Closing gap yẹn tùmọ̀ sí much larger distances — sí i physical qubits per logical qubit — useful algorithms sì nílò *thousands* of logical qubits at once. Physical-qubit budget yẹn lè lọ sí millions.
- Ọ̀rọ̀ **“if scaled” ṣe iṣẹ̀ gidi.** Conclusion iwé iwádíí fúnra rẹ̀ ní pé device performance, *if scaled*, lè meet requirements of large algorithms. Fífi trend tó tò hàn lórí logical qubit kan kì í ṣe ohun kan náà pèlú scaled machine, kò sì sí ohun nìhìn-ín tó guarantee pé trend yẹn yóò survive larger sizes.
- **Unexplained àṣiṣe floor jẹ live iṣòro.** Correlated bursts tó cap repetition-code performance jẹ, ní ọ̀rọ̀ ònḱòwé, orders of magnitude larger than expected, wọn sì máa preclude larger fault-tolerant applications tití a fi lóye wọn — open flaw, tí a sọ kedere, kì í ṣe solved detail.
- Kò sọ nḱan nípa **breaking encryption tàbí “quantum supremacy” fún useful iṣẹ̀-ṣiṣe.** Wọn nílò full fault-tolerant machine tí èsì yí jẹ foundation stone fún, kì í ṣe demonstration náà funra rẹ̀.

Báwo ni ẹrí ṣe lágbára tó?

- **Core claim náà solid, ó sì ṣe pàtàkì.** Below-threshold operation pèlú clean exponential suppression kojá code distances méta, plus beyond-breakeven lifetime àti working real-time decoder, ní combination tí field tí í lé fún ọ̀dún, a sì demonstrate rẹ̀ taara dípò inference. Kì í ṣe hype artefact; engineering èsì gidi ní láti leading egbé.

- **ònkòwé sọra nípa scope.** Wọn frame rẹ gégé bí below-threshold *irántí*, wọn flag unexplained correlated-error floor fúnra wọn, wọn sì hedge future lórí conspicuous “if scaled.” Overreach, níbi tí ó bá wà, sàbà wá láti coverage tó yí “error-corrected *irántí* qubit improved as it grew” sí “quantum computing is here.”
- **Honest status ni foundational step tí a ẹẹ cleanly.** Logical qubit kan, protected tó bẹẹ tí adding redundancy fi ní ràn án lẹwọ níhẹhin — ẹ̀gbọn long, hard, not-guaranteed road ti scaling, logical gates àti unexplained àṣiṣe sì wà níwájú.

Kí nìdí tí ó fi ẹẹ pàtàkì?

Fault-tolerant quantum computing ti ní chicken-and-egg feel láti ìbèrẹ̀: machines tí yóò wúlò nílò àṣiṣe rates tí physical qubit kankan kò lè dé, solution nàà — àṣiṣe correction — sì ní ẹ́ṣẹ̀ nìkan tí hardware bá ti dára tó láti wà below threshold. Crossing line yẹn, paápàá lẹ̀ẹ̀kan, paápàá lórí single logical qubit, yí ìbèèrẹ̀ kúrò ní “sẹ̀ èyí ẹ́e ẹ́e rara?” sí “báwo ni a ẹ́ lè scale rẹ̀ jìn, báwo sì ni a ẹ́ lè ẹ́ yára?” Èyí jẹ́ meaningful shift gidi, ìdí nìyẹn tí èsì yẹ attention.

Ẹ̀gbọn ìṣọra kan nàà tó mú èsì trustworthy ni yẹ kí ó temper itàn tó yí i ká. Èyí ni brick àkókò ti foundation, tí a fi sílẹ̀ dáadàa. Kì í ẹ́ building, àwọn tó fi brick nàà sílẹ̀ sì jẹ́ ẹ̀ni àkókò láti sọ bẹ́. Ọ̀nà tó tọ láti tẹ̀lé quantum computing ní ọ̀dún tó ní ẹ̀ni curve tí kò ní glamour yí: bóyá suppression factor dúró bí codes ẹ́ ní tóbi, bóyá logical gates lè ẹ́ cleanly bí logical *irántí*, àti bóyá mysterious once-an-hour àṣiṣe yẹn yóò ní explanation.

Àkótán kedere

Google Quantum AI fi hàn fún igba àkókò ní ọ̀nà tó mó pé surface-code quantum *irántí* lè ẹ́ṣẹ̀ *below threshold*: bí wọn ẹ́ pọ̀ code láti jìnnà 3 sí 5 sí 7, logical àṣiṣe rate dín exponentially (ní ayíká $2.14\times$ fún every méjì steps), largest — 101-qubit distance-7 *irántí* — sì pé ju best physical qubit rẹ̀ lọ, beyond breakeven, nígbà tí àṣiṣe correction ní run gidi àkókò. Èyí jẹ́ milestone gidi, tí field ti ní retí, nínú engineering of quantum computers. Ẹ̀gbọn logical qubit kan ni tó ní ẹ́ṣẹ̀ bí *irántí*, àṣiṣe rate rẹ̀ sì jìn sí ohun tí gidi algorithms nílò, kò sí logical operations, unexplained àṣiṣe floor wà, scaling road sì tún gùn lópò orders of magnitude. Threshold gidi ni a kojá — kì í ẹ́ quantum computer tí a ti fi lé wa lẹwọ̀.

Àwọn orísun

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>