Quantum Error Correction Below The Surface Code Threshold

Quantum computing threshold for this milestone. Quantum computations exploit phenomena such as superposition, interference, and entanglement. Quantum computers have the potential to complete some calculations exponentially faster than classical computers. Quantum computing increasingly focused on controlling decoherence through quantum error correction. For example, a large-scale quantum computer could break widely used encryption schemes and aid physicists in performing physical simulations. In 2024, researchers demonstrated A quantum computer is a computer that represents and processes information using quantum states. However, current hardware implementations of quantum computation are largely experimental and suitable for only certain specialized tasks 627f02647a

Surface code It is also the simplest example of topological order—Z2 topological order. These conditions give the model translational invariance, which is useful for analytic study. The toric code is the simplest and most well studied of the quantum double models. The first type of surface code introduced by Alexei Kitaev in 1997 was the toric code, which gets its name from its periodic boundary conditions, giving it the shape of a torus. The surface code is a topological quantum error correcting code, and an example of a stabilizer code, defined on a two-dimensional spin lattice. The first The surface code is a topological quantum error correcting code, and an example of a stabilizer code, defined on a two-dimensional spin lattice 627f02647a

Quantum error correction Quantum error correction (QEC) comprises a set of techniques used in quantum memory and quantum computing to protect quantum information from errors arising Quantum error correction (QEC) comprises a set of techniques used in quantum memory and quantum computing to protect quantum information from errors arising from decoherence and other sources of quantum noise. QEC schemes that employ codewords stabilized by a set of commuting operators are known as stabilizer codes, and the corresponding codewords are referred to as quantum error-correcting codes (QECCs) 627f02647a

== History == 627f02647a == Definition... == 627f02647a == Explanation == 627f02647a

Threshold theorem This result was proven independently (for various error models) by the groups of Dorit Aharonov and Michael Ben-Or; Emanuel Knill, Raymond Laflamme, and Wojciech Zurek; and Alexei Kitaev. These results built on a paper of Peter Shor, which proved a weaker version of the threshold theorem. This shows that quantum computers can be made fault-tolerant, as an analogue to von Neumann's threshold theorem for classical computation. In quantum computing, the threshold theorem (or quantum fault-tolerance theorem) states that a quantum computer with a physical error rate below a certain In quantum computing, the threshold theorem (or quantum fault-tolerance theorem) states that a quantum computer with a physical error rate below a certain threshold can, through application of quantum error correction schemes, suppress the logical error rate to arbitrarily low levels 627f02647a

According to Microsoft Azure Quantum's scheme, NISQ computation is considered level 1, the lowest of the quantum computing implementation levels. 627f02647a In October 2023, the 1,000 qubit mark was passed for the first time by Atom Computing's 1,180 qubit quantum processor. However, as of 2024, only two quantum processors have over 1,000 qubits, with sub-1,000 quantum processors still remaining the norm. 627f02647a == 1930s == 627f02647a However, on many quantum computation platforms, experimental realization of a surface code is much easier if the code can be embedded on a 2D plane. This motivated the design of another type of surface code with open boundary conditions, the planar code. As of 2025, Google Quantum AI has implemented a distance-7 planar code on their newest generation of superconducting quantum processors, Willow processor, demonstrating a below-threshold physical error rate. 627f02647a Willow is announced on December 9, 2024 via an article published in Nature, succeeding the Sycamore, the company's previous quantum processor. Google claimed improved quantum error correction. The processor completed a random circuit sampling (RCS) benchmark task in 5 minutes, and claimed the task will take 10 septillion (1025) years to complete on the fastest traditional supercomputer at the time. 627f02647a Surprisingly, the quantum threshold... 627f02647a

Noisy intermediate-scale quantum computing The NISQ era is the current state of quantum computer technology, and the term was coined by John Preskill in 2018. This intermediate-scale is defined by the quantum volume, which is based on a moderate number of qubits and gate fidelity. 638 (8052): 920–926. "Quantum error correction below the surface code threshold". (February 2025). Ballard, Brian; Bardin, Joseph C. 13687 Noisy intermediate-scale quantum (NISQ) computing is characterized by quantum processors containing up to 1,000 qubits which are not advanced enough yet for fault-tolerance or large enough to achieve quantum advantage. These processors, which are sensitive to their environment (noisy) and prone to quantum decoherence, are not yet capable of continuous quantum error correction. Nature. arXiv:2408 627f02647a

== Overview == 627f02647a == Education == 627f02647a Hartmut Neven studied Physics and Economics in Brazil, Köln, Paris, Tübingen and Jerusalem. He wrote his Master thesis on a neuronal model of object recognition at the Max Planck Institute for Biological Cybernetics under Valentino Braitenberg. In 1996 he received his Ph.D. in Physics from the Institute for Neuroinformatics at the Ruhr University in Bochum, Germany, for a thesis on "Dynamics for vision-guided autonomous mobile robots" written under the tutelage of Christoph von der Malsburg. He received a scholarship from the Studienstiftung des Deutschen Volkes, Germany's most prestigious scholarship foundation. 627f02647a Willow is constructed with a square grid of superconducting transmon physical qubits. Improvements over past work were attributed to improved fabrication techniques, participation ratio engineering, and circuit parameter optimization. 627f02647a The service was... 627f02647a The basic unit of information in quantum computing, the qubit (quantum bit), serves a similar function as the bit in ordinary or "classical" computing. Unlike a classical bit, which can be in one of two states (a binary), a qubit can exist in a linear combination of states known as a quantum superposition. The result of measuring a qubit is one of the two states, given by a probabilistic rule. If a quantum computer manipulates the qubit in a particular way, wave interference effects amplify the probability of the desired measurement result. Quantum algorithm design involves creating procedures that allow a quantum... 627f02647a

Willow processor Nature. (2024-12-09). 13687 The Willow processor is a 105-qubit superconducting quantum processor developed by Google's Quantum AI division, manufactured in Santa Barbara, California, and announced in 2024. "Quantum error correction below the surface code threshold". arXiv:2408. 638 (8052): 920–926. Ballard, Brian; Bardin, Joseph C 627f02647a

Much of the terminology in QEC is derived from its classical counterpart, the classical error-correcting code. In classical coding theory, a code is commonly denoted by the notation 627f02647a IBM's quantum processors are made up of superconducting transmon qubits, located in dilution refrigerators at the IBM Research headquarters at the Thomas J. Watson Research Center. Users interact with a quantum processor through the quantum circuit model of computation, typically through code written in Qiskit. This code can be compiled down to OpenQASM for execution on real quantum systems. 627f02647a == Algorithms == 627f02647a Willow prompted optimism in accelerating applications in pharmaceuticals, material science, logistics, drug discovery, and energy grid allocation. Popular media responses discussed its risk in breaking cryptographic systems, but a Google spokesman said that they were still at least 10 years out from breaking RSA. Hartmut Neven, founder and lead of Google Quantum AI, told... 627f02647a The key question that the threshold theorem resolves is whether quantum computers in practice could perform long computations without succumbing to noise. Since a quantum computer will not be able to perform gate operations perfectly, some small constant error is inevitable; hypothetically, this could mean that quantum computers with imperfect gates can only apply a constant number of gates before the computation is destroyed by noise. 627f02647a NISQ algorithms are quantum algorithms designed for quantum processors in the NISQ era. Common examples are the variational quantum eigensolver (VQE) and quantum approximate... 627f02647a

Fault tolerant quantum computing Full-FTQC In quantum information, fault-tolerant quantum computing (FTQC) is a regime of quantum processors that are both large-scale and that effectively incorporate quantum error correction to achieve arbitrarily low error rates (i. e. their logical error rate is much lower than their physical error rate). incorporate quantum error correction to achieve arbitrarily low error rates (i. e. their logical error rate is much lower than their physical error rate) 627f02647a

Full-FTQC processors are theoretically possible, but have not yet been realized experimentally. They are often seen as the primary end goal of quantum processor development, and are used to contrast with existing noisy intermediate-scale quantum (NISQ) quantum processors, which are subject to noise and decoherence preventing scalable error correction. 627f02647a The transition from NISQ-era devices to the FTQC regime is an open research topic in quantum information. It is likely that advances at both the hardware and algorithm level are... 627f02647a

Hartmut Neven He is best known for his work in face and object recognition and his contributions to quantum machine learning. Co-awarded to Neven and the Google Quantum AI team for implementing quantum error correction below the surface code threshold using the Willow processor. Most Hartmut Neven (born 1964) is a German American scientist and entrepreneur working in quantum computing, computer vision, robotics and computational neuroscience. He is currently Vice President of Engineering at Google where he leads the Quantum Artificial Intelligence Lab, which he founded in 2012 627f02647a

(first studied in the context of Z2 spin liquid in 1991). The toric code can also be considered to be a Z2 lattice gauge theory in a particular limit. 627f02647a == Overview == 627f02647a

Timeline of quantum computing and communication arXiv:2408. 13687 This is a timeline of quantum computing and communication. Acharya, Rajeev; et al. (December 9, 2024). "Quantum error correction below the surface code threshold". 638 (8052): 920–926. Nature 627f02647a

Circuits can be created either graphically with the Quantum Composer, or programmatically through Jupyter notebooks on IBM's approved platforms for cloud-based quantum computing: qBraid and OVHCloud. 627f02647a Conceptually, to use a quantum error-correcting code, one can append ancilla qubits to qubits that need protection, and apply a unitary encoding circuit to rotate the global state into a subspace of a larger Hilbert space. This highly entangled, encoded state corrects for local noisy errors. A quantum error-correcting code makes quantum computation and quantum communication practical by providing a way for a sender and receiver to simulate a noiseless qubit channel given a noisy qubit channel whose noise conforms to a particular error model. 627f02647a One way FTQC devices can be realized is by grouping together multiple physical qubits to create a single logical qubit, and using error correction methods such as the surface code so that the combined system is fault-tolerant. Proposed FTQC devices generally include hundreds of logical (error-corrected) qubits, which would mean thousands of physical qubits at minimum. 627f02647a

IBM Quantum Platform This includes access to a set of IBM's quantum processors, a set of tutorials on quantum computation, and access to interactive courses. As of June 2025, there are 12 devices on the service, all of which are freely accessible by the public. "IBM Quantum Devices". 2024-05-15 IBM Quantum Platform (previously known as IBM Quantum Experience) is an online platform allowing public and premium access to cloud-based quantum computing services provided by IBM. found here. The first demonstration of quantum error correction circuit using flag qubits on IBM quantum hardware was reported. This service can be used to run algorithms and experiments, and explore tutorials and simulations around what might be possible with quantum computing 627f02647a