

Thermodynamic Veto

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Correlated

Noise and the Phase Transition of Scalable Quantum Computing

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The realization of commercially viable, fault-tolerant quantum computing is precluded not by engineering immaturity but by a fundamental percolation phase transition driven by correlated noise and thermodynamic constraints, which render the required system scales physically uncorrectable.

Deconstructing

the Foundational Myth of Shor's Algorithm

The status of integer factorization within quantum information theory rests on a conflation of mathematical validity with physical realizability. While the derivation holds within the standard quantum circuit model, it necessitates axioms of ideal unitary evolution and infinite precision that violate the thermodynamic constraints of open systems. This formalism treats quantum amplitudes as continuous variables capable of infinite resolution, a premise challenged by Levin, who observes that physical laws are not verified to the precision required to sustain such states against environmental degradation. Concurrently, the underlying complexity model assumes a constant operational cost independent of system size, ignoring the argument that the thermodynamic resources required to maintain coherence must scale with the non-degeneracy of the state space. The resulting discord creates an asymptotic projection where theoretical efficiency diverges from engineering feasibility. Empirical evidence reflects this ontological gap, as the massive overhead required for quantum error correction expands the resource requirements for cryptographically relevant factorization by orders of magnitude beyond current capabilities. Consequently, the algorithm serves as an abstract attractor that prioritizes formal elegance over the energetic realities governing information storage and retrieval.

Landauer's

Principle and the Three-Legged Stool of Constraints

The presumption that qubit volume, coherence fidelity, and circuit depth function as independent variables ignores the physical grounding of information processing. Landauer's principle dictates that logical states are inseparable from physical degrees of freedom, binding computational metrics to the laws of thermodynamics. This coupling creates a system where optimizing for quantity, correlation, or duration necessarily degrades the remaining parameters through increased entropy production. A large-scale quantum processor constitutes a low-entropy assembly requiring precise phase relationships across a high-dimensional state space. Expanding the physical array steepens the thermodynamic gradient relative to the thermal environment, increasing the cross-section for interaction and noise injection. The maintenance of macroscopic order demands an energetic cost that scales non-linearly, as the density of states facilitates rapid thermalization. Consequently, the linear addition of physical units accelerates the degradation of global correlation. Temporal extension through error correction relies on irreversible

operations, specifically syndrome measurement and ancilla reset, which mandate energy dissipation. This local entropy generation introduces thermal fluctuations that propagate as correlated noise, effectively recycling the disorder the system attempts to excise. The mechanism intended to preserve logical lifetimes thereby functions as a thermodynamic load, imposing a cycle-time constraint where the rate of heat extraction must exceed the rate of logical erasure to prevent thermal runaway. These coupled constraints destabilize the fault tolerance threshold as the system scales. Increased device density promotes correlated error mechanisms, leading to percolation events where noise clusters span the lattice and defeat topological protection. The divergence between the energy required for error suppression and the thermal capacity of the substrate indicates a phase transition in device physics. The mutual exclusivity of maximizing isolation and control limits system utility when the thermodynamic penalty of error correction overwhelms the gain in logical fidelity.

The Percolation

Phase Transition Mechanism

Fault tolerance relies on threshold theorems guaranteeing logical error suppression, provided physical errors remain local, uncorrelated, and below a critical density. Thermodynamic constraints challenge this independence assumption, as correlated noise in large-scale systems drives a percolation phase transition rather than asymptotic suppression. Conventional error correction models map to random bond Ising models or site-percolation on two-dimensional lattices, where independent failures allow logical error rates to decay exponentially with code distance. However, environmental radiation deposits energy into substrates, generating phonon cascades and quasiparticle poisoning that manifest as spatially correlated error bursts. This phenomenology shifts the statistical failure model from Bernoulli percolation to continuum percolation, defined by a characteristic correlation length corresponding to the macroscopic radius of the error cluster. A critical geometric threshold emerges when the code distance fails to span this burst diameter, allowing a single event to topologically connect logical boundaries and bypass correction mechanisms. Empirical measurements indicate this geometric limit lies orders of magnitude below the physical qubit count required for practical algorithms. By expanding the lattice to useful scales, the system increases its interaction cross-section for these macroscopic events, entering a super-critical regime. The processor effectively undergoes a phase transition from an ordered, correctable state to a disordered, percolating state where the probability of catastrophic logical failure approaches unity.

Empirical

Divergence of Required versus Critical Scales

Operational constraints for cryptographic quantum utility are defined by the resource overhead of surface code implementations, necessitating approximately 20 million physical qubits to factor standard integers given current gate fidelities. This theoretical trajectory presumes that noise processes remain local and uncorrelated as system dimensions expand. Empirical characterization of superconducting arrays contradicts this independence, identifying environmental ionizing radiation as a mechanism for correlated entropy generation. High-energy particle impacts deposit energy into the substrate, triggering phonon-mediated cascades that break Cooper pairs and induce simultaneous quasiparticle poisoning across a characteristic radius of ten lattice sites.

The robustness of topological error correction is governed by continuum percolation statistics, where logical validity relies on the sparsity of error chains. The experimentally observed correlation length establishes a specific critical threshold for system size, estimated at 400 qubits, beyond which the processor exits the correctable subcritical phase. The divergence between the algorithmic requirement of 20 million qubits and this stability limit places the target architecture deep within the supercritical percolation regime. In this thermodynamic domain, single

ionization events generate error clusters that exceed the code distance, bridging the logical lattice and neutralizing fault tolerance. This discrepancy indicates that scaling requires not merely linear engineering optimization but the resolution of a fundamental phase transition where macroscopic quantum states are dismantled by correlated environmental coupling.

Toward a

Paradigm of Physically Grounded Computation

The segregation of logical architecture from its thermodynamic substrate rests on the assumption that physical noise remains perturbative and statistically independent. However, correlated high-energy events and material defects drive percolation phase transitions that disrupt the separability of information and medium. A quantum processor operates as a non-equilibrium thermodynamic system subject to entropy production and quasiparticle dynamics, not as an approximation of ideal vector geometry. A physically grounded computational model must therefore position statistical mechanics and condensed matter physics as axioms rather than engineering constraints.

The operational envelope of any device is bounded by a critical system size defined by the percolation threshold of correlated error clusters. Empirical evidence indicates that error correction codes fail in the supercritical regime, suggesting that the pursuit of unbounded fault tolerance is ill-posed. Computational capacity depends on effective thermodynamic free energy and the correlation length of the noise environment rather than nominal qubit count. The inability to execute arbitrarily deep circuits constitutes a fundamental boundary condition similar to Carnot efficiency, prohibiting the realization of asymptotic fidelity through resource scaling alone.

This thermodynamic reality necessitates a transition from universal algorithmic objectives to bounded-advantage architectures designed for the sub-critical regime. By prioritizing analog Hamiltonian simulation and variational approaches, such systems exploit the natural dynamics of the substrate and the physical isomorphism between the processor and target applications in chemistry or materials science. Progress requires abandoning the teleological commitment to specific end-states in favor of empirical exploration consistent with the energetic costs of information processing and the hard limits imposed by the scaling phase transition.