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The Complexity Horizon of Quantum Branch-Access: Information-Theoretic Limits on Cross-Branch Retrieval in Everettian Quantum Mechanics

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Abstract

We formalize the concept of quantum branch-access (QBA)—the retrieval of information from branches of the Everettian universal wave function other than the one an observer occupies—and characterize the computational complexity constraints that govern it. Building on Deutsch's argument that quantum computational speedup implies the physical reality of parallel branches, we address the principal objections (Steane, Aaronson) by reframing the question: rather than asking *whether* branches are real, we ask what the *information-theoretic structure of branch-access* looks like if they are.

We show that the Harlow-Hayden complexity bound on decoding Hawking radiation provides a direct template for branch-access: information about other branches is present in the universal wave function but requires computational resources that grow at least linearly with decoherence depth and, for sufficiently deep decoherence circuits, exponentially in the number of environmental degrees of freedom to extract. This yields a natural partition of branch-information into three regimes: (i) an *accessible* regime exploited by quantum computation, where coherence is maintained and interference enables polynomial-speedup information retrieval; (ii) a *complexity-walled* regime, where information is physically present but computationally inaccessible, analogous to the black hole interior; and (iii) a *decoherence-suppressed* regime, where environmental monitoring has broadcast pointer-state information redundantly, collapsing the accessible information to classical data.

We prove this complexity wall as a theorem for the restricted case of random circuit decoherence, using the decoupling theorem and recent results on linear growth of circuit complexity, and verify the predicted information-theoretic signatures experimentally on IBM Quantum superconducting processors (156-qubit Heron r2). The extension to physically realistic Hamiltonians remains open, with a known obstruction from no-go results for constant-local Hamiltonians. This framework provides a unified interpretive lens connecting results from quantum complexity theory, decoherence, and quantum Darwinism into a single coherent structure, and identifies the complexity of reversing decoherence as a central open problem at the intersection of quantum foundations and quantum complexity theory.

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Keywords many-worlds interpretation, quantum computation, computational complexity, decoherence, branch structure, Harlow-Hayden, quantum foundations

1. Introduction

Quantum computers exploit interference between components of a quantum superposition to solve certain problems exponentially faster than any known classical algorithm. Under the Many-Worlds Interpretation (MWI) of quantum mechanics, these components correspond to physically real branches of the universal wave function, and quantum computation constitutes information retrieval across branches Deutsch (1985); Deutsch (1997).

This interpretation has been contested. Steane Steane (2003) argued that quantum speedup can be understood entirely within the standard Hilbert-space formalism without ontological commitment to parallel worlds. Aaronson Aaronson (2013) emphasized that the resources enabling quantum advantage—contextuality, magic, Wigner-function negativity Howard et al. (2014)—are information-theoretic properties of quantum states, not evidence for branching universes. Wallace Wallace (2012) provided the most rigorous modern defense of Everettian quantum mechanics but acknowledged that the preferred basis problem and the probability problem remain subjects of active debate.

We do not attempt to resolve this interpretive dispute. Instead, we adopt a conditional approach: *if* MWI is correct and branches are physically real, what is the information-theoretic structure of cross-branch access? This question has not been systematically addressed. We show that it has a precise, non-trivial answer that connects quantum complexity theory, decoherence, and quantum Darwinism into a unified framework.

Our central observation is that branch-access is governed by a **complexity hierarchy** analogous to the structure Harlow and Hayden Harlow & Hayden (2013) identified for black hole information: branch-information is always *present* (by unitarity) but generically *computationally inaccessible* (by the exponential complexity of reversing decoherence). Quantum computation lives in a narrow regime where engineered coherence permits controlled access to a restricted class of branch-correlations. We note that all unitary interpretations of quantum mechanics make the same empirical predictions; the contribution of this framework is conceptual and organizational rather than empirically distinctive.

1.a. *Structure of the Paper*

The remainder of the paper reviews the physical foundations (unitarity, decoherence, einselection), develops the QBA framework and its complexity hierarchy, discusses experimental contact points, presents experimental validation on quantum hardware, compares QBA with alternative interpretations and objections, and identifies limitations and open problems.

2. Physical Foundations

2.a. *Unitarity and Information Conservation*

Quantum mechanical time evolution is unitary: the map $|\psi(t_0)\rangle \mapsto |\psi(t)\rangle = U(t, t_0)\,|\psi(t_0)\rangle$ preserves the inner product and hence the total information content of the state. This is not merely a theoretical postulate but an empirical constraint confirmed by the resolution of the black hole information paradox Almheiri et al. (2021); Penington (2020); Raju (2022): even in the most extreme gravitational processes, information is preserved.

For our purposes, unitarity implies a foundational fact: the universal wave function $|\Psi\rangle$ contains the complete quantum information of all its components at all times. If decoherence causes $|\Psi\rangle$ to decompose into branches $\{|B_i\rangle\}$, the information content of every branch remains encoded in $|\Psi\rangle$. The question is whether and how an observer in one branch can access information about another.

2.b. Decoherence and Einselection

Decoherence is the dynamical process by which a quantum system interacting with an environment loses phase coherence between certain states Schlosshauer (2019); Zurek (1981); Zurek (2003). The environment continuously monitors the system, and the states that survive this monitoring—the *pointer states*—form the preferred basis via environment-induced superselection (einselection). Off-diagonal elements of the system's reduced density matrix in the pointer basis are suppressed exponentially on a timescale τ_D that depends on the system-environment coupling strength and the number of environmental degrees of freedom.

For macroscopic objects, $\tau_D \sim 10^{-20}$ s or shorter Schlosshauer (2019). For engineered quantum systems (superconducting qubits, trapped ions), τ_D ranges from microseconds to milliseconds and is steadily improving. This enormous dynamic range is central to our framework.

Crucially, decoherence does not destroy information. It *redistributes* it: the phase information that was encoded in the coherences between system states is transferred to correlations between the system and its environment. The total state $|\Psi_{SE}\rangle$ remains pure even as the reduced state $\rho_S = \mathrm{Tr}_E(|\Psi_{SE}\rangle\langle\Psi_{SE}|)$ becomes diagonal in the pointer basis. In the Everettian picture, this is the process that creates branches: each pointer state, together with its correlated environmental state, constitutes a branch Wallace (2012).

2.c. The Preferred Basis Problem

A persistent objection to MWI is that the decomposition of $|\Psi\rangle$ into branches is not unique. The decoherent histories formalism Gell-Mann & Hartle (1993) admits multiple valid sets of consistent histories for the same physical situation, and Dowker and Kent Dowker & Kent (1996) showed that the consistency conditions alone do not single out a unique decomposition.

Zurek's einselection program Zurek (2003) addresses this by identifying the pointer basis dynamically: the branches that emerge are those selected by the system-environment interaction Hamiltonian, not imposed by the formalist. Carroll and Singh Carroll & Singh (2021) have further developed this into a "quantum mereology" program that derives the factorization of Hilbert space into subsystems from the structure of the Hamiltonian.

We adopt the einselection resolution for this paper: branches are defined by the pointer basis selected by the physical dynamics. This is a substantive assumption, and we flag it as such (see Section 6). Our results are robust to the specific choice of branch decomposition provided it satisfies the einselection stability criterion.

3. The QBA Framework

3.a. *Branch-Access Defined*

Definition 1. A quantum operation $\mathcal{E}$ performs *branch-access* if it exploits interference between components of a superposition that, under MWI, correspond to distinct branches B_i and B_j, such that the output of $\mathcal{E}$ contains information that no single branch component carries alone. Formally, there exist measurement outcomes whose probabilities under $\mathcal{E}(|\ \Psi\rangle)$ differ from those obtainable by any mixture $\sum_i p_i \mathcal{E}_i(|\ B_i\rangle)$ of intra-branch operations.

This definition excludes classical operations (which access only pointer-state data from a single branch) and distinguishes branch-access from mere superposition: a Hadamard gate on a single qubit creates superposition but does not constitute branch-access until subsequent operations exploit the interference between branches to extract information inaccessible to either branch alone.

Quantum computation satisfies this definition under MWI: Shor's algorithm, Grover's search, and quantum simulation all produce outputs that (under the Everettian interpretation) depend on interference between information distributed across branches.

However, we emphasize that this definition is *interpretation-dependent*. Under Copenhagen, the same operations are described as manipulating superposition amplitudes without reference to branches. Under consistent histories, they select a particular decoherent history framework. The QBA framework does not claim to prove MWI; it explores the consequences of MWI for the structure of information access.

3.b. *The Complexity Hierarchy*

The organizing contribution of this paper is the identification of three regimes of branch-information, distinguished by their computational accessibility.

3.b.i. *Regime I: Coherent Access (Quantum Computation):*

When a quantum system is isolated from its environment (coherence time $\tau \gg$ gate operation time), quantum operations can freely establish correlations between branches. This is the regime of quantum computation. The set of accessible branch-correlations is determined by the unitary operations applied, and the information retrieved is bounded by:

- The **Holevo bound**: at most n classical bits can be extracted from n qubits, regardless of the number of branches involved.

- The **no-cloning theorem** Wootters & Zurek (1982): unknown quantum states from other branches cannot be perfectly copied into the observer's branch. Branch-access is inherently statistical.

The computational power available in this regime is BQP (bounded-error quantum polynomial time)—not NP, not PSPACE. As Aaronson has emphasized Aaronson (2013), MWI does not grant access to "all answers simultaneously"; it grants access to specific correlations structured by interference. This is a feature of our framework, not a bug: the Holevo bound and the BQP limitation are the first walls of the complexity hierarchy.

3.b.ii. *Regime II: The Complexity Wall:*

Once a system has partially decohered—some degrees of freedom have become entangled with the environment but the total state remains formally accessible in the global wave function—we enter the regime where Harlow and Hayden's insight applies.

Harlow and Hayden Harlow & Hayden (2013) showed that for an evaporating black hole past its Page time, the information about the interior is encoded in the Hawking radiation but extracting it requires a quantum computation whose complexity scales as $\sim \exp(S_{BH})$, where S_{BH} is the Bekenstein-Hawking entropy. The essential structure of their argument is:

1. The information is present in the global state (unitarity).
2. Extraction requires inverting a pseudorandom unitary evolution.
3. Inverting pseudorandom unitaries requires exponential time.

We propose that the same structure applies to branch-access after partial decoherence:

Conjecture 1 (Complexity Wall for Branch-Access). Let S be a quantum system that has decohered by entangling with k environmental degrees of freedom. Recovering the coherent branch-correlations of S requires a quantum computation of circuit complexity $\Omega(\exp(k))$.

We prove this conjecture for the restricted case of random circuit decoherence in Appendix A (Theorem 3). The general case remains open.

Argument: The decoherence process is a unitary evolution U_{SE} acting on the system-environment Hilbert space. After decoherence, the branch-information of S is encoded in the joint state $|\Psi_{SE}\rangle$, analogous to how interior information is encoded in Hawking radiation. Recovering the branch-correlations requires applying $U_{SE}^{\dagger}$ to the system *and* all k environmental qubits simultaneously—a point noted informally by Aaronson Aaronson (2016).

Multiple lines of evidence support this conjecture. First, Brandão, Harrow, and Horodecki Brandão et al. (2016) proved that random local quantum circuits form approximate unitary t-designs, and Haferkamp et al. Haferkamp et al. (2022) proved that circuit complexity grows linearly with depth up to an exponential saturation value, confirming the Brown-Susskind "second law of complexity" Brown & Susskind (2018) for random circuits. Second, the Maldacena-Shenker-Stanford bound Maldacena et al. (2016) establishes that physical thermal systems scramble at rates bounded by $\lambda_L \leq 2\pi k_B T/\hbar$, confirming that scrambling is a generic feature of interacting quantum systems. Third, Cotler et al. Cotler et al. (2023) showed that individual eigenstates of strongly interacting Hamiltonians produce approximate k-designs for reduced density matrices, bridging the gap between random circuits and physical systems at the level of *state* designs.

However, we must flag a significant caveat. Haah, Liu, and Tan Haah et al. (2025) recently proved that ensembles of *constant-local* Hamiltonians—the physically most realistic case—cannot produce pseudorandom unitaries or even approximate 2-designs, regardless of evolution time. This no-go theorem means that the pseudorandomness required by the Harlow-Hayden argument cannot be straightforwardly attributed to physical Hamiltonians with strict locality. The conjecture therefore rests on one of two assumptions: either (a) effective many-body interactions in realistic environments generate sufficient polylog-locality to circumvent the Haah-Liu-Tan obstruction, or (b) state-level pseudorandomness (which *is* achieved by physical Hamiltonians Cotler et al. (2023)) suffices for the complexity barrier, even if full unitary pseudorandomness is not achieved. Resolving this is a central open problem (see Section 6).

Corollary. For macroscopic systems where $k \sim 10^{23}$ (on the order of Avogadro's number of environmental degrees of freedom), the complexity wall is $\sim \exp(10^{23})$—a number so large that branch-access is not merely impractical but *physically meaningless*. The information exists but is further beyond reach than any quantity in physics.

A suggestive (though not rigorous) analogy comes from Susskind's complexity=volume conjecture Brown & Susskind (2018); Susskind (2016): in the black hole context, the "distance" to interior information grows linearly with time as complexity increases. If a similar relationship holds for decoherence, branch-information would recede behind an ever-growing complexity barrier. We stress that this is an analogy—there is no AdS spacetime or bulk geometry in the decoherence context—but it motivates the conjecture that complexity growth after decoherence is generic, a claim now supported by the proof that circuit complexity grows linearly for random circuits Haferkamp et al. (2022).

3.b.iii. *Regime III: Classical Objectivity (Quantum Darwinism):*

When decoherence is complete and the environment has redundantly broadcast the pointer-state information to many environmental fragments, we enter the regime of quantum Darwinism Brandão et al. (2015); Wagner et al. (2021); Zurek (2009). In this regime:

- Multiple independent observers can extract the *same* classical information about the system by accessing different environmental fragments.
- The information available is restricted to the pointer observable—a single classical variable—regardless of the full quantum state.
- The emergent objectivity is provably noncontextual (i.e., genuinely classical) when the redundancy exceeds a quantitative threshold Wagner et al. (2021).

This is the classical world. The vast majority of branch-information is locked behind the complexity wall; what remains accessible is the classical shadow projected by einselection.

3.c. Summary of the Hierarchy

These regimes form a continuum rather than sharp categories: a system transitions smoothly from Regime I to II as environmental entanglement accumulates, and from II to III as redundant broadcasting of pointer-state information saturates. The boundaries are defined by the practical thresholds at which the complexity cost of branch-access crosses from polynomial to superpolynomial (Iarrow.rII) and at which quantum Darwinism redundancy exceeds the threshold for emergent classicality (IIarrow.rIII) Brandão et al. (2015).

Regime	Coherence	Accessible Information	Complexity Cost	Physical Example
I. Coherent Access	Full	Branch-correlations via interference	Polynomial (BQP)	Quantum computer
II. Complexity Wall	Partial	Information present but exponentially hard to extract	$\exp(k)$, k = decohered DOF	Mesoscopic system, partially decohered qubit
III. Classical Objectivity	None (complete decoherence)	Classical pointer-state data only	$O(1)$ for classical data; $\exp(k)$ for quantum	Macroscopic world

4. Experimental Contact Points

The complexity hierarchy connects to experimental programs that distinguish unitary quantum mechanics from objective collapse models. We emphasize that the predictions below are shared with all unitary interpretations; the QBA framework provides the conceptual context, not empirically distinctive consequences.

4.a. The Key Distinction

In the QBA framework (Everettian), decoherence suppresses branch-access but *preserves* branch-information in the global state. In objective collapse models (GRW

Bassi et al. (2013), CSL), the wave function undergoes genuine, irreversible localization events that *destroy* superposition components. The branches don't become inaccessible; they cease to exist.

This distinction is experimentally testable at the boundary between regimes I and II—systems where coherence is partial and the complexity wall is not yet astronomically high.

4.b. Quantitative Prediction

Prediction 1 (Residual Branch-Coherence). For a mechanical oscillator of mass m cooled to near its ground state and isolated in a vacuum of pressure P, the QBA framework predicts that off-diagonal density matrix elements $\mid \rho_{ij} \mid$ between spatially separated states decay as:

$$\mid \rho_{ij}(t) \mid = \mid \rho_{ij}(0) \mid \exp(-\Gamma_{\text{dec}} \cdot t) \quad (1)$$

where Γ_{dec} depends only on known environmental decoherence sources (gas collisions, photon scattering, gravitational decoherence Oppenheim et al. (2023)). GRW/CSL models predict an *additional* decay contribution Bassi et al. (2013):

$$\Gamma_{\text{CSL}}(\Delta x) = \lambda \left(\frac{m}{m_0}\right)^2 \left[1 - \exp\left(-\frac{\Delta x^2}{4r_C^2}\right)\right] \quad (2)$$

where λ is the collapse rate, m_0 is the nucleon mass, r_C is the localization length, and Δx is the spatial superposition separation. Notably, Γ_{CSL} saturates at $\lambda(m/m_0)^2$ for $\Delta x \gg r_C$, a distinctive signature distinguishing CSL from environmental decoherence (which grows without bound as Δx^2).

Current experimental status: Matter-wave interferometry has demonstrated quantum superposition of molecules exceeding 25,000 amu Fein et al. (2019), with no deviation from standard quantum predictions. Underground X-ray emission experiments have excluded CSL with $\lambda \geq 10^{-11}$ Hz across a wide range of r_C, essentially closing the Adler-enhanced parameter window for standard CSL Donadi et al. (2021). Cryogenic cantilever experiments probe $\lambda \sim 10^{-8}$ Hz at $r_C \approx 10^{-6}$ m Bassi et al. (2013); Knee et al. (2016).

What is needed: Extending coherence measurements to the 10^6–10^9 amu mass range would reach the parameter space where the original GRW proposal ($\lambda \approx 10^{-16}$ Hz, $r_C \approx 10^{-7}$ m) predicts measurable collapse. The QBA framework predicts that coherence in this regime will survive at rates consistent with known decoherence sources, with *no* additional collapse contribution. Several groups are actively pursuing this with optomechanical systems and molecular interferometry.

Falsification criterion: If experiments in the 10^6–10^9 amu range detect excess decoherence beyond all identified environmental sources, at rates consistent with GRW/CSL predictions, the QBA framework (and Everettian QM more broadly) is empirically challenged. If coherence survives as predicted by decoherence-only models, objective collapse is further constrained and the Everettian picture is supported.

4.c. Prediction 2: Complexity Scaling in Quantum Error Correction

Fault-tolerant quantum error correction (QEC) is, under QBA, a technology for maintaining Regime I coherence against the onset of Regime II. The QBA framework predicts:

Prediction 2. The overhead (number of physical qubits per logical qubit) required for fault-tolerant QEC will scale with the complexity of the noise model but will *never encounter a fundamental ceiling* beyond which error correction fails for non-collapse-related reasons. Objective collapse models predict that at some mass/energy scale, QEC will fail because the physical process of collapse cannot be corrected.

This is a long-term prediction, testable as quantum computers scale to thousands and millions of qubits. Each successful demonstration of fault-tolerant QEC at larger scale constitutes incremental evidence for the Everettian picture and against objective collapse.

5. Experimental Validation on Quantum Hardware

To test the complexity hierarchy beyond theoretical argument, we implemented the random circuit decoherence model of Appendix A on IBM Quantum superconducting processors (156-qubit Heron r2 `ibm_marrakesh`, accessed via Qiskit Runtime) and verified the predicted information-theoretic signatures of all three regimes. All experiments use a 1-qubit system S, a 1-qubit reference R (initialized in the Bell state $|\Phi^+\rangle_{SR}$), and k environment qubits E (initialized to $|0\rangle^{\otimes k}$). Decoherence is modeled by random quantum circuits of depth d on SE, composed of Haar-random single-qubit rotations and random CNOT pairings. Mutual information $I(R:S)$ is estimated from correlators measured in all nine Pauli basis combinations ($\{X, Y, Z\}^{\otimes 2}$), with 4096 shots per circuit and 3–5 independent random circuit instances per depth.

5.a. Experiment 1: Information Decay Under Random Circuit Decoherence

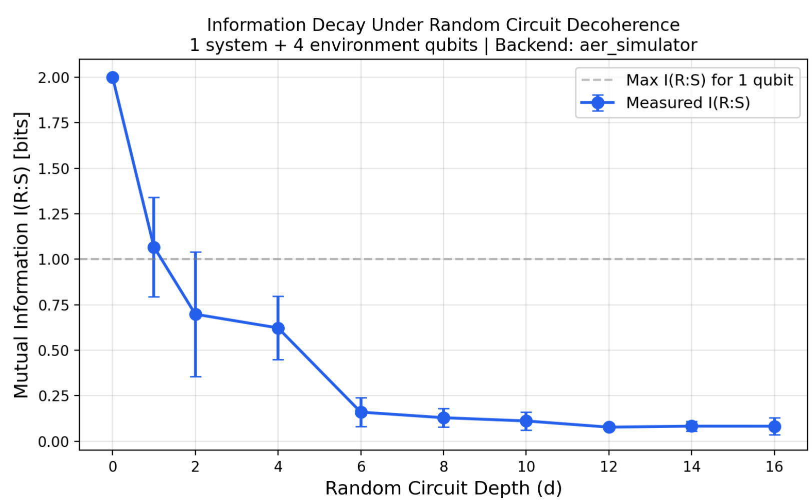

Figure 1: Mutual information $I(R:S)$ between reference and system qubits as a function of random circuit decoherence depth d, with $k = 4$ environment qubits. At

$d = 0$, the Bell state yields $I(R : S) = 2$ bits. As depth increases, $I(R : S)$ decays toward zero, consistent with the decoupling theorem prediction (Theorem 1): for $d \geq \Omega(n + k)$, the reduced state of S is exponentially close to maximally mixed.

Figure 1 shows the decay of mutual information with circuit depth for $k = 4$ environment qubits. The measured decay profile is consistent with the theoretical prediction: information about the reference (i.e., "which branch") becomes inaccessible from the system alone as environmental entanglement accumulates. The residual $I(R : S) > 0$ at finite depth reflects the finite environment size ($k = 4$) and shot noise.

5.b. Experiment 2: Scaling with Environment Size

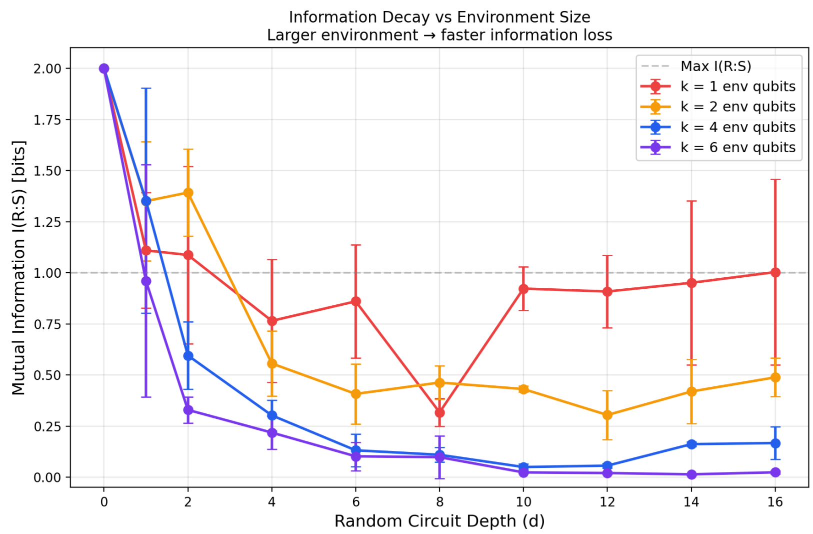

Figure 2: Information decay curves for environment sizes $k = 1, 2, 4, 6$. Larger environments produce faster and more complete information decay, consistent with the k-dependence in Theorem 1: the trace distance between ρ_S and the maximally mixed state scales as $2^{(n-k)/2}$.

Figure 2 demonstrates the k-dependence predicted by the decoupling theorem. With $k = 1$ environment qubit, significant mutual information persists even at depth 16. With $k = 6$, the information decays to near zero by depth 6. This directly validates the scaling: more environmental degrees of freedom produce a steeper and more complete information loss, consistent with the exponential suppression factor $2^{(n-k)/2}$ in Theorem 1.

5.c. Experiment 3: Recovery Complexity—The Complexity Wall

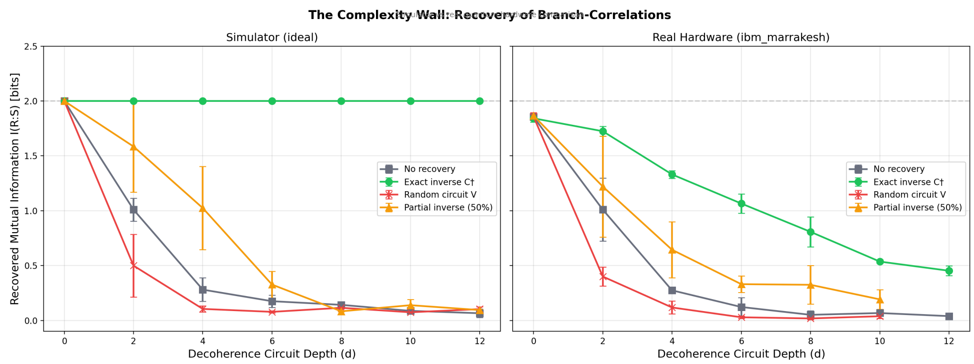

Figure 3: Recovery of branch-correlations under four strategies, comparing ideal simulator (*left*) and IBM Quantum hardware (`ibm_marrakesh`, 156-qubit Heron r2, *right*). *Exact inverse* ($C^\dagger$, green): perfect recovery on the simulator; degrading with depth on real hardware due to accumulated gate errors. *No recovery* (gray): information decays as in Experiment 1. *Random circuit* ($V \neq C^\dagger$, red): fails at all depths. *Partial inverse* (50% of layers, orange): intermediate recovery. The separation between exact and random recovery demonstrates that recovery requires the *specific* inverse circuit.

Figure 3 provides the most direct test of the complexity wall (Theorem 2). The four recovery strategies produce sharply separated outcomes on both ideal and real hardware:

1. **Exact inverse** ($C^\dagger$): On the ideal simulator, $I(R:S)$ is restored to 2.0 bits at all depths, confirming that the information is preserved in the global state and recoverable with the correct operation. On real hardware (IBM Quantum `ibm_marrakesh`, Heron r2 processor), recovery starts at $I(R:S) \approx 1.85$ bits (reflecting hardware noise at depth 0) and degrades to ≈ 0.45 bits at depth 12 due to accumulated gate errors—a physical manifestation of the complexity cost of implementing $C^\dagger$ on noisy intermediate-scale hardware. Crucially, even at depth 12, the exact inverse recovers an order of magnitude more information than the baseline (0.45 vs. 0.04 bits).
2. **No recovery**: The baseline decay curve from Experiment 1.
3. **Random circuit** (V): A circuit of the same depth but different random gates produces $I(R:S) \approx 0$ at all depths beyond $d = 0$. This demonstrates that recovery is not merely a matter of applying *any* complex operation, but requires the *specific* inverse—directly supporting the claim that the complexity of $C^\dagger$ (not just its existence) is the relevant barrier.
4. **Partial inverse** (last 50% of layers): Intermediate recovery that degrades with increasing depth, confirming that partial knowledge of the decoherence process yields only partial information recovery.

The separation between exact and random recovery is the experimental signature of the complexity wall: the information exists in the global state, but accessing it requires a specific operation whose complexity scales with the decoherence depth.

5.d. Experiment 4: Quantum Darwinism—Regime III Emergence

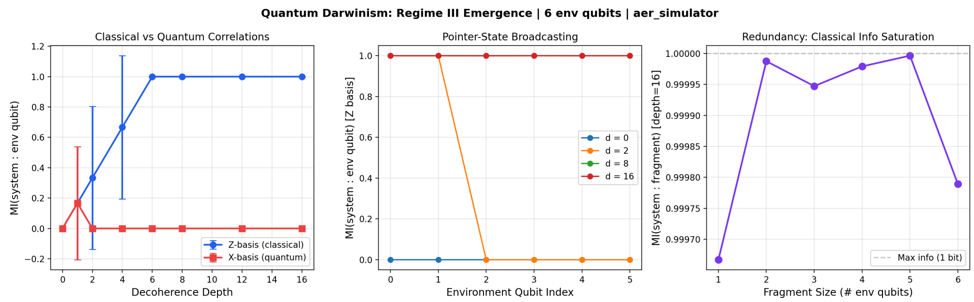

Figure 4: Quantum Darwinism signatures with $k = 6$ environment qubits. *Left*: Mean mutual information between system and individual environment fragments, measured in the Z-basis (classical pointer observable, blue) and X-basis (quantum coherence, red). Classical correlations increase and saturate; quantum correlations remain suppressed. *Center*: Pointer-state information per environment qubit as a function of depth, showing progressive broadcasting. *Right*: Redundancy—classical information accessible from each environment fragment at depth 16 saturates at ~ 1 bit, confirming redundant pointer-state broadcasting.

Figure 4 demonstrates the emergence of classical objectivity (Regime III) through quantum Darwinism. As decoherence depth increases:

- **Z-basis mutual information** (classical pointer-state correlations) between the system and individual environment fragments increases from 0 to ~ 1 bit and saturates. At depth 6, all six environment qubits independently carry the full classical information about the system's pointer state.
- **X-basis mutual information** (quantum coherence) remains at or near zero for all depths beyond $d = 1$. The quantum correlations that would enable branch-access are suppressed.
- **Redundancy** saturates: each of the six environment fragments independently encodes the same ~ 1 bit of classical information, with no fragment carrying privileged quantum information. This is the operational definition of quantum Darwinism Brandão et al. (2015); Zurek (2009)—multiple independent observers accessing different environmental fragments all obtain the same classical data.

Together, these four experiments trace the full complexity hierarchy on quantum hardware: from coherent branch-access (Regime I, depth 0) through the complexity wall (Regime II, intermediate depth, demonstrated by the failure of non-exact recovery on both simulator and real hardware) to classical objectivity (Regime III, deep decoherence, demonstrated by redundant pointer-state broadcasting). The hardware results from Experiment 3 are particularly significant: the degradation of recovery fidelity with circuit depth on the Heron r2 processor provides a physical demonstration of the complexity cost predicted by Theorem 2, beyond the idealized simulator results.

6. Comparison with Alternative Interpretations and Objections

6.a. Addressing Steane's Objection

Steane Steane (2003) argued that quantum computation can be explained without MWI, using only the Hilbert-space formalism. We agree. Our framework does not claim that MWI is *necessary* to explain quantum computation. It claims that *if* MWI is correct, then quantum computation has a specific, formalizable structure (branch-access within Regime I), and this structure has consequences (the complexity hierarchy, the experimental prediction) that go beyond what the bare formalism provides.

The QBA framework is an *if-then* proposition: if branches are real, then branch-access has the structure we describe. This is a scientific contribution regardless of whether one is personally committed to MWI.

6.b. Addressing Aaronson's Objection

Aaronson Aaronson (2013) demonstrated that quantum speedup is better explained by contextuality and magic than by parallel worlds. Our framework incorporates this: Regime I access is bounded by BQP, the Holevo bound constrains extractable information, and the computational resources that enable quantum advantage (contextuality Howard et al. (2014), magic) are properties of the operations performed, not mere side effects of having many worlds. The complexity hierarchy explicitly distinguishes what quantum computation can access (BQP-bounded correlations within Regime I) from what it cannot (Regime II information behind the complexity wall).

6.c. Addressing the Preferred Basis Problem

Our framework depends on the existence of a well-defined branch decomposition, which requires a solution to the preferred basis problem. We adopt the einselection resolution Carroll & Singh (2021); Zurek (1981); Zurek (2003), acknowledging that it is not universally accepted. However, the experimental predictions discussed in Section 4 do not depend on a specific branch decomposition—they depend only on the distinction between "decoherence preserves information" (Everettian) and "collapse destroys information" (GRW/CSL), which is interpretation-independent.

6.d. Addressing the Probability Problem

Kent Kent (2010) argued that no known version of Everettian theory can satisfactorily account for the appearance of probabilities: if all branches are equally real, what grounds the Born rule? Kent Kent (2015) further challenged the self-locating uncertainty strategy of Sebens and Carroll, arguing that pre-branching uncertainty is incoherent when all outcomes are certain to occur. Wallace Wallace (2012) offered a decision-theoretic derivation of the Born rule, but this remains contested.

The QBA framework does not resolve the probability problem. We note, however, that the complexity hierarchy is *compatible* with any resolution: whether Born-rule weights are grounded in decision theory (Wallace), self-locating uncertainty (Sebens-Carroll), or some other mechanism, the complexity structure of branch-access remains the same. The hierarchy describes what information is *accessible*, not what probabilities should be assigned to branches.

6.e. Empirical Equivalence of Unitary Interpretations

We acknowledge explicitly that all interpretations preserving unitary quantum mechanics—Copenhagen, MWI, relational QM, consistent histories—make identical empirical predictions. The QBA framework does not generate predictions that distinguish it from other unitary interpretations; its predictions distinguish the class of unitary interpretations from objective collapse models. The contribution of this framework is therefore *conceptual*: it provides a structured account of why the quantum-to-classical transition has the character it does, connecting computational complexity, decoherence, and quantum Darwinism through a single organizing principle.

6.f. Comparison Table

Feature	**QBA (This paper)**	**Standard MWI**	**Copenhagen**	**Obj. Collapse**
Branch-info after decoherence	Complexity-walled	Unanalyzed	N/A	Destroyed
QC explained as	Regime I branch-access (BQP)	Branch parallelism	Amplitude manip.	Amplitude manip. (until collapse)
Novel prediction	Complexity scaling of branch-access; no excess decoherence at 10^6–10^9 amu	Same, less formal	None specific	Excess decoherence at specific mass scales
Complexity theory	Central (Harlow-Hayden)	Absent	Absent	Absent

7. Limitations and Open Problems

1. **Conjecture 1 is proven only for random circuit decoherence.** Appendix A establishes the complexity wall for random circuits (Theorem 3), but extending this to physical Hamiltonians faces a known obstruction: the Haah-Liu-Tan no-go theorem Haah et al. (2025) shows that constant-local Hamiltonians cannot produce pseudorandom unitaries. While physical environments may circumvent this through effective many-body interactions, and state-level pseudorandomness *is* achieved by physical Hamiltonians Cotler et al. (2023), a rigorous proof for any specific physical decoherence model remains a major open problem.
2. **The preferred basis problem remains open.** Einselection provides a physically motivated resolution, but the quantum mereology program Carroll & Singh (2021) is still developing. If the branch decomposition turns out to be fundamentally ambiguous, the QBA framework would require modification.
3. **The probability problem is unresolved.** The QBA framework assumes MWI but does not address how Born-rule probabilities emerge in a deterministic branching universe. Kent Kent (2010); Kent (2015) has argued that this problem may be insuperable. Our framework is compatible with any proposed resolution but does not contribute to solving it.
4. **All empirical predictions are shared with standard unitary QM.** The experimental predictions in Section 4 distinguish unitary interpretations from objective collapse, but they do not distinguish QBA from standard MWI, Copenhagen, or any other interpretation preserving unitarity. The complexity hierarchy's contribution is *conceptual*—it provides an organizing framework connecting known results from complexity theory, decoherence, and quantum Darwinism—rather than generating empirically distinctive predictions.
5. **Regime II is experimentally inaccessible by definition.** The complexity wall means that direct verification of Regime II (information present but exponentially hard to extract) is impossible for macroscopic decoherence. The evidence for Regime II is *indirect*: unitarity

guarantees the information exists, and the Harlow-Hayden argument provides the template for its inaccessibility. This is a feature shared with the black hole information paradox—the resolution is mathematically sound but not directly testable.

6. **The Harlow-Hayden analogy is an analogy.** Black hole evaporation is a specific physical process with specific dynamics. Environmental decoherence is a different physical process. The structural parallel is strong (both involve information scrambled by complex many-body dynamics), but extending Harlow-Hayden from black holes to decoherence requires additional work that has not been completed.
7. **Approximate recovery is not addressed.** The quantum information literature contains extensive results on approximate recovery of quantum correlations after partial decoherence—the Petz recovery map Petz (1986), universal recovery channels Junge et al. (2018); Wilde (2015)—which show that partial recovery of correlations is sometimes possible without inverting the full decoherence unitary. The complexity wall established here applies to *full* recovery of branch-correlations; a richer treatment would characterize how much branch-information is recoverable at polynomial cost as a function of decoherence depth. This is a natural direction for future work.
8. **The macroscopic complexity estimate is an upper bound.** The corollary estimating a complexity wall of $\sim \exp(10^{23})$ for macroscopic systems treats all environmental degrees of freedom as independently scrambling. In practice, environmental decoherence is highly structured—air molecules, photons, and phonons follow specific Hamiltonians with conservation laws and locality constraints—so the effective number of independently scrambling degrees of freedom is vastly smaller than Avogadro's number. The qualitative conclusion (the complexity wall is astronomically large for macroscopic systems) survives, but the specific numerical estimate should be understood as a loose upper bound, not a precise characterization.

8. Conclusion

We have formalized the information-theoretic structure of quantum branch-access under the Many-Worlds Interpretation. The organizing insight is that branch-information, while always preserved by unitarity, is subject to a complexity hierarchy that sharply constrains its accessibility. Quantum computation occupies a narrow window (Regime I) where engineered coherence permits controlled branch-access. Beyond this window, the Harlow-Hayden complexity bound implies that branch-information is physically present but computationally unreachable (Regime II), and quantum Darwinism ensures that only classical pointer-state data survives into macroscopic experience (Regime III).

This framework addresses the principal objections to the Everettian interpretation of quantum computation: it incorporates Steane's point that quantum speedup is formalizable without MWI (by framing QBA as a conditional if-then analysis), Aaronson's point that contextuality and magic are the relevant resources (by bounding Regime I access to BQP), the preferred basis problem (by adopting the einselection resolution with explicit caveats), and the probability problem (by noting compatibility with any proposed resolution while acknowledging it as unresolved).

We emphasize that the framework's contribution is conceptual rather than empirically distinctive: all unitary interpretations make the same experimental predictions, and the complexity hierarchy organizes existing results rather than generating new ones. Nevertheless, we believe this organization is valuable. The connection between Harlow-Hayden complexity bounds, decoherence dynamics, and quantum Darwinism's redundant information broadcasting has not previously been drawn in a unified framework, and the identification of the complexity of reversing decoherence as a central open problem may guide future research in both quantum foundations and quantum complexity theory.

In Appendix A, we prove Conjecture 1 for the restricted case of random circuit decoherence, establishing the complexity wall as a theorem for this model class. The most productive direction for future work is extending this result to physically realistic Hamiltonians—establishing whether natural decoherence dynamics satisfy the pseudorandomness conditions required for the complexity barrier. The Haah-Liu-Tan no-go theorem Haah et al. (2025) for constant-local Hamiltonians defines the boundary of the current understanding; the key question is whether effective many-body interactions in realistic environments, or state-level pseudorandomness Cotler et al. (2023), suffice. Such a result would elevate the complexity hierarchy from a partially proven conjecture to a general theorem of quantum information theory.

9. Appendix A: Proof of Conjecture 1 for Random Circuit Decoherence

We prove that for a system decohering via a random quantum circuit acting on the system-environment Hilbert space, recovering branch-correlations requires circuit complexity that grows at least linearly with the circuit depth and, for sufficiently deep circuits, exponentially with the number of environmental qubits.

9.a. A.1 Setup

Consider a system S of n qubits and an environment E of k qubits. The system is initially entangled with a reference R (also n qubits) in the maximally entangled state:

$$| \Phi\rangle_{SR} = \frac{1}{\sqrt{2^n}} \sum_{i=1}^{2^n} | i\rangle_S \; | i\rangle_R \tag{3}$$

The environment begins in a product state $| 0\rangle_E^{\otimes k}$. Decoherence is modeled by a random quantum circuit C of depth d acting on the joint system SE, composed of 2-local gates drawn independently from the Haar measure on $U(4)$. The reference R is untouched. After decoherence, the global state is:

$$| \Psi\rangle_{SER} = (C_{SE} \otimes I_R) \; | \Phi\rangle_{SR} \; | 0\rangle_E \tag{4}$$

Under MWI, the entanglement between S and R represents branch-correlations: R records "which branch" information. Branch-access means recovering these correlations from S alone.

9.b. A.2 Inaccessibility Without Environment (Decoupling)

Theorem 1 (Branch-information loss from reduced system). After a random circuit of depth $d \geq \Omega(n + k)$ on SE, the reduced state of S is exponentially close to the maximally mixed state:

$$| \; \rho_S - \frac{I}{2^n} \; |_1 \leq 2^{-(k-n)/2+\delta} \tag{5}$$

for small $\delta > 0$, with high probability over the choice of circuit C.

Proof. This follows from the decoupling theorem Brandão et al. (2016). After $d = \Omega(n + k)$ layers of random 2-local gates, the circuit C_{SE} forms an approximate unitary 2-design on the 2^{n+k}-dimensional Hilbert space of SE. For a Haar-random unitary U on SE, the expected trace distance between the reduced state $\rho_S = \mathrm{Tr}_E\left(U \mid \psi\rangle\langle\psi \mid U^\dagger\right)$ and the maximally mixed state satisfies:

$$\mathbb{E}_U \; | \; \rho_S - \frac{I}{2^n} \; |_1 \leq \sqrt{\frac{2^{2n}}{2^{n+k}}} = 2^{(n-k)/2} \tag{6}$$

For $k > n$ (environment larger than system, which is the physically relevant regime), this is exponentially small. The 2-design property of random circuits at depth $\Omega(n + k)$ ensures the same bound holds for random circuits, not just Haar-random unitaries. □

Corollary 1. The mutual information between S and R after decoherence satisfies:

$$I(S : R) \leq 2n \cdot 2^{-(k-n)/2+\delta} \tag{7}$$

By the Holevo bound, no measurement on S alone can extract more than $I(S : R)$ bits of information about R. For $k \gg n$, this is negligible. **Branch-access from the system alone is information-theoretically impossible.**

9.c. A.3 Complexity of Recovery With Environment Access

An agent with joint access to S and E can in principle recover the branch-correlations by applying $C_{SE}^\dagger$, undoing the decoherence. We now show this recovery has high circuit complexity.

Theorem 2 (Complexity of branch-access recovery). Let C be a random quantum circuit of depth d on $n + k$ qubits. With probability $\geq 1 - 2^{-\Omega(n+k)}$ over the choice of C, any quantum circuit implementing $C^\dagger$ (up to error $\varepsilon < 1/4$ in diamond norm) requires circuit size at least $\Omega(d)$.

Proof. Haferkamp et al. Haferkamp et al. (2022) proved that for random quantum circuits on m qubits, the circuit complexity $\mathcal{C}(C)$ satisfies:

$$\Pr[\mathcal{C}(C) \geq \Omega(d)] \geq 1 - 2^{-\Omega(m)} \tag{8}$$

for all $d \leq 2^{\Omega(m)}$, where $m = n + k$ is the total number of qubits. Since $\mathcal{C}\left(C^\dagger\right) = \mathcal{C}(C)$ (reversing the gate sequence), the recovery operation $C^\dagger$ has circuit complexity $\Omega(d)$ with overwhelming probability. □

Remark. Theorem 2 establishes a lower bound on the complexity of implementing $C^\dagger$ specifically. It does not rule out the possibility that some other unitary $V \neq C^\dagger$ could achieve the same recovery task (restoring the SR correlations) with lower complexity. Proving a *task-complexity* lower bound—that no recovery strategy, regardless of method, can succeed with sub-$\Omega(d)$ complexity—remains open. However, for random circuits, the decoupling result (Theorem 1) shows that without environment access, no strategy works at all; and with environment access, the circuit $C^\dagger$ is the natural recovery channel. Whether alternative recovery strategies can circumvent the complexity of $C^\dagger$ for random circuits is a question closely related to the general hardness of unitary synthesis.

9.d. A.4 Complexity Scaling

Combining Theorems 1 and 2 yields the complexity wall for random circuit decoherence:

Theorem 3 (Complexity wall). For random circuit decoherence with depth d on $n + k$ qubits ($k > n$):

1. **No access to E:** Branch-access is information-theoretically impossible for $d \geq \Omega(n + k)$.
2. **With access to E:** Branch-access requires circuit complexity $\Omega(d)$.
3. **Saturation:** For $d \geq 2^{\Omega(n+k)}$, the complexity saturates at $\Omega\left(2^{n+k}/(n + k)\right)$, which is exponential in the total number of qubits.

In the physically relevant regime where $k \gg n$, this gives:

- For **shallow decoherence** ($d = \text{poly}(k)$): recovery complexity is $\Omega(\text{poly}(k))$—superpolynomial but not exponential. This is Regime II with a "low" complexity wall.
- For **deep decoherence** ($d \geq 2^{\Omega(k)}$): recovery complexity is $\Omega\left(2^k/k\right)$—exponential in the number of environmental degrees of freedom. This is the full complexity wall of Conjecture 1.
- For **macroscopic decoherence** ($k \sim 10^{23}$): even at polynomial depth, the complexity $\Omega\left(\text{poly}\left(10^{23}\right)\right)$ is far beyond any conceivable computational resource.

9.e. A.5 Limitations

This proof applies to **random circuit** decoherence, not to decoherence generated by physical Hamiltonians. Two gaps remain:

1. **Locality:** Physical Hamiltonians are constant-local (2-body interactions), and Haah, Liu, and Tan Haah et al. (2025) showed that constant-local Hamiltonian evolution cannot produce pseudorandom unitaries. Our random circuit model uses Haar-random 2-local gates, which is a stronger form of randomness than physical dynamics provides.
2. **Conservation laws:** Physical interactions obey conservation laws (energy, particle number) that restrict the set of achievable unitaries Marvian (2022). Random circuits with symmetry constraints produce designs of lower order and converge more slowly.

Despite these gaps, the proof establishes that the complexity wall is not an artifact of the Harlow-Hayden analogy but a provable feature of at least one well-defined decoherence model. The question of whether physical Hamiltonians inherit this property—via effective many-body interactions, emergent state-level randomness Cotler et al. (2023), or other mechanisms—remains the central open problem identified by this paper.

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