Bandwidth Limits on Quantum Control

A Control-Theoretic Approach to Quantum Measurement

https://ignorantobserver.xyz

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January 2026
Version 1.1

DOI: 10.17605/OSF.IO/G5WRH

Abstract

We present a framework in which quantum measurement is treated as a control problem with finite bandwidth. An observer is defined as any physical system that tracks another system using finite channel capacity C_{eff}. When the observer's internal dynamics generate information faster than it can process—quantified by the ignorance rate $\kappa = h_{\text{KS}} - C_{\text{eff}} \ln 2$—the observer loses track of its own measurement basis θ. Since θ is a physical variable with causal history (not a free parameter), measurement independence (MI) is violated as a *consequence* of the control model—not as an assumption or as a claim that Bell's theorem is incorrect. The key prediction is *double-exponential* visibility decay $V(t) = \exp(-\frac{1}{2}\sigma_0^2 e^{2\kappa t})$, qualitatively different from standard Gaussian (e^{-t^2}) or exponential ($e^{-\gamma t}$) decoherence. The primary experimental signature is a sign reversal: increasing observer capacity should *extend* coherence time, opposite to standard thermal decoherence. The predicted timescale $\tau_{\text{loss}} \approx 1/\kappa$ overlaps with Penrose's objective reduction timescale τ_{OR} in the mesoscopic regime, but the two mechanisms make orthogonal predictions: τ_{loss} depends on observer bandwidth, τ_{OR} on mass geometry. We specify falsification criteria.

1 Introduction

The measurement problem in quantum mechanics has resisted solution for nearly a century. This paper presents a control-theoretic approach: rather than interpreting quantum mechanics, we ask *under what conditions can an embedded physical system maintain knowledge of its own measurement basis?*

We propose a minimal model in which the measurement basis θ is treated not as an abstract label chosen freely, but as a physical state variable with causal history—implemented by apparatus embedded in the same reality as the system being measured. An "observer" is any physical system that tracks another through a finite-capacity channel. When internal dynamics generate information faster than this capacity allows, knowledge of the basis degrades in a quantifiable way. The framework predicts a distinctive *double-exponential* visibility decay, qualitatively different from standard decoherence, with a sharp experimental discriminator: increasing observer capacity should *extend* coherence time—the opposite sign from thermal decoherence, where more power means more heating.

Sections 2–3 formalize the model; Sections 4–5 derive the dynamics; Section 6 presents testable predictions; Sections 7–8 compare with Penrose objective reduction and specify falsification criteria.

2 The Measurement Basis as Physical Variable

In standard treatments, the measurement basis θ is treated as a "free parameter"—something the experimenter chooses independently of the system being measured. But θ is not an abstract label; it is implemented by physical apparatus (a polarizer orientation, a magnetic field direction, a phase reference). The "choice" of θ is itself a physical process: neural activity $\rightarrow$ motor commands $\rightarrow$ servo actuation $\rightarrow$ apparatus configuration. This causal chain is not external to physics.

Bell's derivation assumes statistical independence between θ and λ (measurement independence, MI). The present framework does not assume MI violation; rather, MI violation *emerges as a consequence* of treating the measurement basis as a physical variable subject to control-theoretic constraints. When the observer is embedded in the same physical reality it measures, and when its capacity to track its own basis is limited, the "free choice" of θ becomes operationally constrained—θ and λ share common causal past, providing a natural route to correlations without fine-tuning or cosmic conspiracy. Palmer [1] formalizes a similar constraint geometrically as state-space admissibility (certain counterfactuals are "off-manifold"). The present framework arrives at the same constraint from the operational level: an embedded observer with finite capacity cannot enact arbitrary counterfactuals while holding internal variables fixed.

The following sections develop a quantitative framework: we first define the observer's capacity and the apparatus's information-generation rate, then show how their interplay determines when tracking fails and what observable consequences follow.

3 The Tracking Problem

3.1 Definitions

We define an **observer** as any physical system that:

1. Uses energy to track or interact with another system
2. Has finite channel capacity C_{eff} (bits/s or nats/s)

The Landauer limit bounds the maximum achievable capacity given available power P and temperature T:

$$C = \frac{P}{kT \ln 2} \quad \text{(bits/s)} \tag{1}$$

Realistic systems achieve $C_{\text{eff}} = \eta C$ with efficiency $\eta \ll 1$ due to architectural overhead, latency, and dissipation. The operational definition of C_{eff} (Section 3.5) is what matters for the predictions.

3.2 Apparatus Dynamics: h_{KS}

We characterize the observer's apparatus by its Kolmogorov-Sinai entropy rate h_{KS}—the information-production rate of the classical degrees of freedom (voltage references, timing circuits, feedback loops) that define and maintain the measurement basis.

Even deterministic feedback loops can exhibit chaotic sensitivity: tiny untracked differences grow exponentially, characterized by positive Lyapunov exponents and quantified by h_{KS}. Measurement apparatus naturally tends toward high h_{KS} because amplification from microscopic quantum events to macroscopic records requires nonlinear or threshold dynamics, which generically produce chaos. In contrast, purely diffusive dynamics ($h_{\mathrm{KS}} \to 0$) produce only slow, linear growth of uncertainty—a limiting case where the framework predicts no capacity-dependent effects.

Quantum error correction can be understood as engineering that suppresses chaotic sensitivity, keeping h_{KS} low—though this suppression may ultimately fail at scale when controller bandwidth cannot keep pace with system entropy [9].

3.3 The Data-Rate Theorem: Scope and Application

The Data-Rate Theorem (DRT) establishes a necessary condition for mean-square stabilization: for a scalar unstable linear plant with Lyapunov exponent λ, stabilization over a finite-capacity channel requires $C > \lambda/\ln 2$ [2, 3].

Assumption/Extension: We model basis tracking as an estimation/control loop whose effective instability is characterized by the Kolmogorov-Sinai entropy rate h_{KS} (metric entropy). When $h_{\mathrm{KS}} > C_{\mathrm{eff}} \ln 2$, the DRT implies tracking error must exceed any fixed tolerance in finite time.

This extends the canonical DRT setting (linear plant, Gaussian noise). For nonlinear systems, analogous results exist: Nair et al. established topological conditions for feedback stabilization over finite-rate channels [3], and Kawan's invariance entropy framework [4] ties required data rates to Lyapunov-type quantities in general dynamical systems. We treat our application as a working hypothesis whose validity is tested by the experimental predictions below.

3.4 The Ignorance Rate

We define the **ignorance rate** κ as the gap between information generation and processing capacity:

$$\kappa = h_{\mathrm{KS}} - C_{\mathrm{eff}} \ln 2 \quad (2)$$

Following the DRT condition, this defines two regimes:

- **Capacity-wins** ($\kappa < 0$): Observer can in principle keep up with basis tracking
- **Chaos-wins** ($\kappa > 0$): Tracking error must grow without bound

3.5 Operational Estimators

For the framework to be testable, C_{eff} and h_{KS} must be operationally defined.

Effective capacity C_{eff}: We define C_{eff} as the effective information rate in the basis-tracking loop (not the whole device):

$$C_{\text{eff}} = r \cdot b \cdot f \tag{3}$$

where r is the update rate (Hz), b is the effective bits per update constraining θ, and $f \in (0, 1]$ is the fraction of updates that actually constrain θ after overhead and latency. In a controlled experiment varying C_{eff}, r would be the primary knob.

Metric entropy rate h_{KS}: For chaotic systems, h_{KS} equals the sum of positive Lyapunov exponents (Pesin identity). We estimate h_{KS} from the rate at which prediction error grows with prediction horizon: given controller state x_t, track how $|x_{t+n\Delta} - g^n(x_t)|$ increases with n, where g^n denotes n iterations of a fitted model. The exponential growth rate estimates λ_{max}, which provides a practical proxy (and lower bound) for h_{KS}. Standard algorithms apply to logged digital controller states (e.g., FPGA-based readout). The experiment should verify $h_{\text{KS}} > 0$ before testing capacity dependence.

4 Minimal Model

Having established when tracking fails ($\kappa > 0$), we now specify a minimal model to derive what happens to the observer's knowledge of its own measurement basis.

State variables:

- $\xi(t)$: hidden ontic state of the measured system
- $\theta(t)$: observer's internal measurement basis (a physical variable, not a free parameter)
- $x(t)$: additional apparatus degrees of freedom

Dynamics: Both ξ and θ evolve deterministically from initial conditions. The observer cannot fully reconstruct the causal history of its own θ. Since capacity limits can explain apparent randomness—tracking failure produces outcomes indistinguishable from fundamental noise—positing fundamental randomness in addition adds no explanatory power. By parsimony, we adopt the deterministic framework; the experiment below tests whether this is empirically correct.

Measurement independence: An embedded observer with finite capacity cannot set θ independently of its causal history. The process of "choosing" θ involves physical dynamics that share common past with ξ. When $h_{\text{KS}} > C_{\text{eff}} \ln 2$, the observer loses track of its own basis, making measurement independence operationally unachievable. This provides a natural mechanism for the correlations that Palmer's invariant set theory [1] formalizes geometrically: certain counterfactual measurement settings are dynamically inaccessible, not because of cosmic fine-tuning, but because of capacity constraints.

Measurement: At time t_m, the outcome is a deterministic function:

$$A = A(\xi(t_m), \theta(t_m), x(t_m)) \tag{4}$$

5 Basis Uncertainty

5.1 Basis Tracking Error

Due to finite capacity, the observer's estimate $\hat{\theta}$ of its own basis has uncertainty σ_θ. The realized $\theta(t_m)$ may differ from the intended value θ_0. The key distinction is between the frame the observer *believes* it has ($\hat{\theta}$) and the physical frame of the apparatus (θ). The observer records outcomes as if $\theta = \theta_0$, but the actual measurement was made in basis $\theta = \theta_0 + \delta\theta$. This mismatch, not environmental decoherence, is the source of visibility loss.

Conventionally, experimentalists treat θ as a known control parameter; unexpected outcomes are attributed to quantum randomness or detector noise, both of which produce exponential or Gaussian visibility decay. The present framework predicts a qualitatively different signature: double-exponential decay with breakdown time $t_{\text{break}} \propto 1/\kappa$. This distinctive structure—not the mere existence of noise—is what distinguishes tracking failure from standard decoherence, and explains why the effect has been overlooked: without looking for the specific functional form, the signature appears as ordinary noise and is discarded.

The framework does not require that capacity limits be uncircumventable in principle. It requires that *for a given observer with given capacity*, the limit exists and has predictable consequences. If C_{eff} increases, t_{break} should increase accordingly (Eq. 10). The claim is that *wherever* the capacity limit lies, it determines visibility loss via κ. Whether one labels this "fundamental" or "technical" is a terminological choice; the experimental predictions are identical.

5.2 Dynamics

In the chaos-wins regime ($\kappa > 0$), we model the basis estimation error as inheriting the exponential separation rate of the uncontrolled dynamics, reduced by the effective information rate of corrective updates. For a chaotic mode with Lyapunov exponent λ, uncorrected estimation error scales as $e^{\lambda t}$; therefore its *variance* scales as $e^{2\lambda t}$. Finite-rate correction reduces the effective exponent by $C_{\text{eff}} \ln 2$, yielding:

$$\frac{d}{dt} \ln \sigma_\theta^2 \approx 2(h_{\text{KS}} - C_{\text{eff}} \ln 2) = 2\kappa \tag{5}$$

This is a modeling claim, not a theorem. The experiment below tests this scaling directly: if visibility decay follows Eq. (8) with the predicted κ-dependence, the model is supported; if not, it is falsified.

Integrating Eq. (5):

$$\sigma_\theta^2(t) = \sigma_0^2 \, e^{2\kappa t} \tag{6}$$

The **threshold-crossing time** for uncertainty to grow from σ_0^2 to tolerance σ_{tol}^2 is:

$$\tau_{\text{loss}} = \frac{1}{2\kappa} \ln\left(\frac{\sigma_{\text{tol}}^2}{\sigma_0^2}\right) \quad (\kappa > 0) \tag{7}$$

5.3 Visibility Decay

When the observer has Gaussian uncertainty in its measurement basis, the observed visibility (fringe contrast) decays as:

$$V(t) = \exp\left(-\frac{\sigma_0^2}{2} e^{2\kappa t}\right) \tag{8}$$

where σ_0^2 is the initial basis uncertainty at $t = 0$, set by apparatus calibration and initialization quality.

Validity: This assumes Gaussian angle uncertainty and is accurate for $\sigma_\theta \lesssim 1$ rad. For larger uncertainties, higher cumulants contribute and suppression saturates.

Derivation: The observer intends basis θ_0 but realizes $\theta = \theta_0 + \delta\theta$ where $\delta\theta \sim \mathcal{N}(0, \sigma_\theta^2)$. Averaging the interference term $\cos(\phi - \theta)$ over this distribution:

$$\langle \cos(\phi - \theta) \rangle = \cos(\phi - \theta_0) \cdot e^{-\sigma_\theta^2/2} \tag{9}$$

5.4 Observable Breakdown Time

Define $V_* \in (0, 1)$ as a visibility threshold. The **breakdown time** t_{break} is when $V(t_{\text{break}}) = V_*$:

$$t_{\text{break}} = \frac{1}{2\kappa} \ln\left(\frac{-2\ln V_*}{\sigma_0^2}\right) \quad (\kappa > 0) \tag{10}$$

This is the primary experimental observable.

6 Consequences for Bell Correlations

Treating θ as a physical variable leads to MI violation as a *consequence* of the control model. This does not mean Bell's theorem is incorrect—the theorem is valid given its premises—but the premises are not satisfied for embedded observers with finite capacity. The result is *attenuated* correlations, not "Bell violation."

With Gaussian basis uncertainty σ^2, marginals remain exactly 50/50 (no signaling), but joint correlations are attenuated:

$$\langle E \rangle = -\cos(\theta_A - \theta_B) \cdot e^{-(\sigma_A^2 + \sigma_B^2)/2} \tag{11}$$

As uncertainty grows, the CHSH parameter $|S|$ decreases from $2\sqrt{2}$ toward zero—correlations fall *below* ideal QM predictions.

The novel prediction is the κ-dependent scaling: $\sigma^2(t) = \sigma_0^2 e^{2\kappa t}$, yielding double-exponential visibility decay $V(t) = \exp(-\frac{1}{2}\sigma_0^2 e^{2\kappa t})$ with breakdown time $t_{\text{break}} \propto 1/\kappa$. Figure 1 illustrates this.

7 Testable Predictions

The framework makes specific predictions that distinguish it from standard decoherence. The definitive test is the *sign* of the power dependence. Standard thermal decoherence predicts

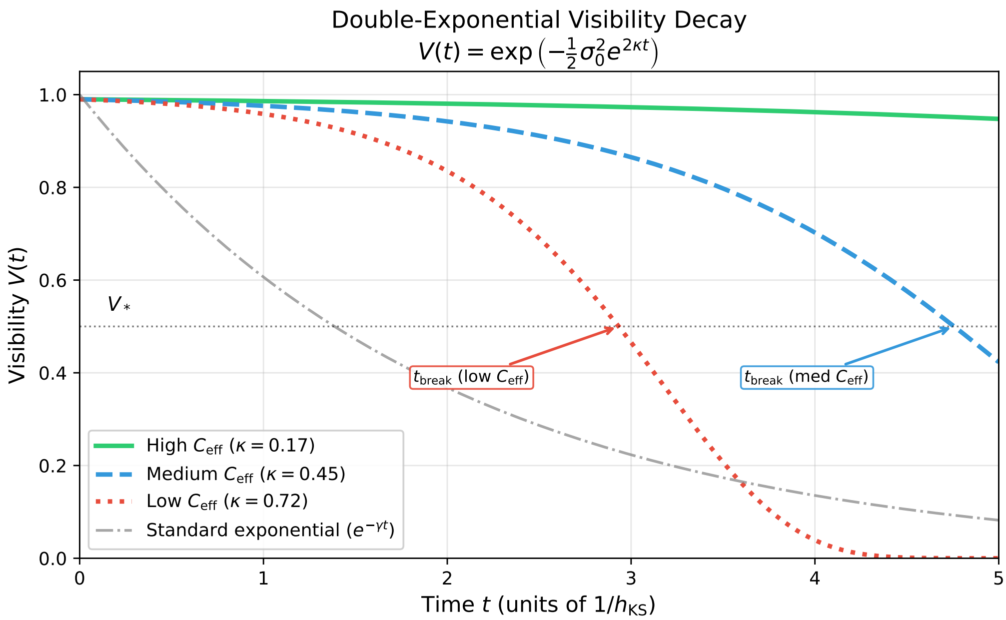

Figure 1: **Double-exponential visibility decay for three capacity levels.** Visibility $V(t) = \exp(-\frac{1}{2}\sigma_0^2 e^{2\kappa t})$ is plotted for high capacity (green, $\kappa = 0.17$), medium capacity (blue, $\kappa = 0.45$), and low capacity (red, $\kappa = 0.72$). Lower observer capacity C_{eff} yields higher $\kappa = h_{\text{KS}} - C_{\text{eff}} \ln 2$, causing earlier breakdown. The arrows mark t_{break}, the time when visibility crosses the threshold $V_* = 0.5$. For comparison, standard exponential decoherence ($e^{-\gamma t}$, gray dash-dot) decays steadily from $t = 0$, whereas the double-exponential curves remain near unity before collapsing—a qualitatively distinct signature. The prediction: reducing C_{eff} shifts t_{break} leftward.

$\partial V/\partial P < 0$: increasing controller power increases heat load, which reduces coherence. The present framework predicts the opposite—$\partial V/\partial P > 0$: increasing observer power increases C_{eff} via the Landauer bound, which *extends* coherence time. This sign reversal is the primary falsification signature.

The sign reversal is only observable when environmental temperature T is actively stabilized. Without constant T, any power increase will also increase temperature, and the standard thermal effect ($\partial V/\partial T < 0$) will mask the information-theoretic effect. The experiment requires varying P while clamping T via active feedback.

Visibility should follow the double-exponential decay $V(t) = \exp(-\frac{1}{2}\sigma_0^2 e^{2\kappa t})$, qualitatively distinct from standard exponential ($e^{-\gamma t}$) or Gaussian (e^{-t^2}) decoherence. The characteristic timescale satisfies $t_{\text{break}} \propto 1/\kappa$ where $\kappa = h_{\text{KS}} - C_{\text{eff}} \ln 2$. Higher apparatus entropy rate h_{KS} should produce faster visibility loss (smaller t_{break}), independent of environmental decoherence channels.

A comprehensive experimental protocol specifying platform requirements, statistical analysis plans, and detailed procedures is available separately [5]. The QGEM collaboration's pathfinder apparatus [8], designed for extreme isolation and cryogenic operation with mesoscopic masses, may provide a near-term platform for testing the sign-reversal prediction under controlled conditions.

8 Connection to Penrose Objective Reduction

The framework's predictions can be compared with other approaches to quantum state reduction. Penrose's gravitational Objective Reduction (OR) provides a natural comparison because both predict characteristic timescales that depend on measurable system parameters—enabling experimental discrimination.

Penrose proposes that quantum superpositions become unstable due to gravitational self-energy, giving a characteristic timescale [6]:

$$\tau_{\text{OR}} = \frac{\hbar}{E_G} \sim \frac{\hbar s}{Gm^2} \tag{12}$$

where m is the mass in superposition and s is the spatial separation. For mesoscopic masses ($m \sim 10^{-15}$ kg) with separations of 100 nm–1 μm, this gives $\tau_{\text{OR}} \sim$ 10–100 ms.

The present framework predicts a tracking-loss timescale in the chaos-wins regime:

$$\tau_{\text{loss}} \approx \frac{1}{\kappa} = \frac{1}{h_{\text{KS}} - C_{\text{eff}} \ln 2} \tag{13}$$

For apparatus parameters $h_{\text{KS}} \approx 50$ nats/s and $C_{\text{eff}} \approx 10$ bits/s ($C_{\text{eff}} \ln 2 \approx 7$ nats/s), we obtain $\kappa \approx 43$ nats/s and $\tau_{\text{loss}} \approx 1/\kappa \approx 23$ ms. Including the log factor from Eq. (7) for 1–5% visibility thresholds contributes a factor of 2–3, giving $\tau_{\text{loss}} \approx$ 50–70 ms.

Numerical proximity: For the apparatus parameters above, τ_{loss} falls near the Penrose-predicted τ_{OR} range for mesoscopic systems.

Different predictions: Despite this proximity, the frameworks make orthogonal predictions:

- Penrose OR: gravitational instability; τ_{OR} depends on mass and geometry, independent of observer bandwidth
- Present framework: information-theoretic tracking limits; τ_{loss} depends on observer bandwidth, independent of spatial geometry

This enables experimental discrimination:

Test	**Penrose OR**	**This framework**
Vary power P at fixed mass	No effect on τ	τ_{loss} increases
Vary temperature T at fixed mass	No effect on τ	τ_{loss} decreases
Vary separation s at fixed C_{eff}	τ_{OR} increases	No effect on τ_{loss}

The power/temperature test is the primary discriminator: if increasing observer bandwidth (via $C_{\text{eff}} \leq P/(kT \ln 2)$) extends coherence time, the information-theoretic mechanism is operative. If coherence time depends only on mass and geometry, gravitational OR dominates.

Penrose OR is considered foundational because it connects collapse to gravity—a universal physical phenomenon. The present framework connects collapse to information-theoretic limits—equally universal, as all physical observers are subject to thermodynamic constraints (Landauer bound). Thermodynamic approaches to gravity—notably Jacobson's derivation of Einstein's equations from local horizon thermodynamics [7]—suggest these domains may be more deeply connected than their separate formulations imply. If gravitational and information-theoretic scales are fundamentally linked, the numerical proximity of τ_{loss} and τ_{OR} might reflect structure rather than coincidence—a possibility the discriminating experiments above could illuminate.

9 Falsification Criteria

The framework is falsified if any of the following hold:

1. **Wrong sign (primary test)**: At constant temperature, increasing observer power P fails to extend coherence time, i.e., $\partial t_{\text{break}}/\partial P \leq 0$. This sign reversal is the definitive discriminator from standard thermal decoherence.
2. **No chaos dependence**: t_{break} independent of apparatus chaos rate h_{KS}
3. **Wrong functional form**: $V(t)$ fits ordinary exponential or power-law decoherence but *not* the double-exponential structure $V(t) = \exp(-\frac{1}{2}\sigma_0^2 e^{2\kappa t})$
4. **Gravitational scaling**: Coherence timescale tracks mass/geometry ($\propto m^{-2}$ or $\propto s$) rather than observer bandwidth—gravitational OR dominates
5. **Marginal violation**: Single-party statistics deviate from 50/50, indicating signaling or systematic bias

10 Conclusion

We have presented a framework in which measurement is treated as a control problem. The observer must maintain knowledge of its own measurement basis $\theta(t)$ while its apparatus generates chaotic dynamics. When the apparatus entropy rate exceeds processing capacity, basis uncertainty grows exponentially.

The key prediction is operational: in the chaos-wins regime, visibility decays as $V(t) = \exp(-\frac{1}{2}\sigma_0^2 e^{2\kappa t})$, with breakdown time inversely proportional to κ. Because treating θ as a physical variable leads to MI violation as a consequence (not an assumption), the framework operates where Bell's premises are not satisfied—this is not a claim that Bell's theorem is incorrect. The testable claim is that observed correlations should fall *below* ideal QM predictions when bandwidth is limited, with the specific functional form distinguishing this from standard decoherence. Controlled variation of observer capacity would provide a direct experimental test. These predictions are falsifiable.

The framework's timescale $\tau_{\text{loss}} \approx 1/\kappa$ overlaps with Penrose's τ_{OR} in the mesoscopic regime ($\sim$50–70 ms), but predicts different dependences—bandwidth vs. mass geometry—enabling experimental discrimination.

If the predicted capacity dependence is observed, the deterministic interpretation becomes parsimonious: the capacity mechanism already explains apparent randomness, leaving no explanatory role for fundamental randomness. The conspiracy objection does not apply because measurement independence fails due to physical constraints, not cosmological fine-tuning.

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