Quantum Darwinism: An Attempted Solution To The Measurement Problem

Jaime Mok

Abstract

Quantum Darwinism is a theoretical framework that aims to explain the emergence of objective classical reality from the underlying quantum substrate. However, quantum Darwinism is also criticized due to many reasons; therefore, many argue that it does not resolve the full measurement problem. This essay outlines the foundational ideas behind Quantum Darwinism, beginning with the measurement problem and decoherence, and issues within Quantum Darwinism.

1 Introduction

The transition from quantum to classical physics remains one of the central puzzles in the foundations of quantum mechanics. While the quantum realm exhibits superposition and entanglement, the macroscopic world appears classical and objective. Quantum Darwinism, a theory proposed by Wojciech Zurek, attempts to bridge this gap by explaining how classical objectivity arises naturally from quantum principles via the selective proliferation of information. While Quantum Darwinism may be able to provide an explanation on classicality within quantum states most of the time, it fails in specially constructed quantum system; sometimes even the most fundamental quantum systems that we shall come across when quantum mechanics is introduced. This is due to the theory itself having a strong reliance on decoherence theory and it's lack of Universality; hence leading to failure within quantum systems that decoherence may not occur or apply, or quantum systems that are extremely complex.

2 Robustness of the predictions of quantum Darwinism

The essence of Quantum Darwinism is understanding how the system-environment information exchange leads to the emergence of classicality through the encoding of classical information of $\mathcal{S}$ in independent fragments of $\mathcal{E}$. Since Quantum Darwinism strongly relies on environmental interaction and decoherence, the theory is, in principle, experimentally accessible. Decoherence processes naturally occur in most realistic quantum systems due to their unavoidable coupling to the environment, and the redundant encoding of pointer state information in multiple parts of $\mathcal{E}$ offers a measurable signature of the emergence of objectivity. Specifically, the theory predicts a plateau in mutual information $I(\mathcal{S} : \mathcal{F})$ between the system and various environment fragments $\mathcal{F} \subset \mathcal{E}$, and a corresponding suppression of quantum discord. These information-theoretic quantities provide a framework for verifying when observers can independently extract the same classical information about $\mathcal{S}$ without perturbing it—thus revealing the classical world as an emergent, redundant record of the quantum one.

Moving onto experimental figures compared to simulations based on Darwinism, a team utilized 9 qubits on a superconducting processor to measure the plateau of mutual information and the vanishing quantum discord. In the 9-qubit experiment, the researchers prepared a quantum system $\mathcal{S}$ consisting of a single qubit, coupled to an environment $\mathcal{E}$ composed of four qubits directly interacting with $\mathcal{S}$, and another four qubits acting as auxiliary elements to simulate weak environmental scrambling. The initial state of $\mathcal{S}$ was set to a superposition $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, and entangling gates were applied between $\mathcal{S}$ and the environment using conditional unitaries of the form:

$$U^{\oslash}(\theta) = |0\rangle\langle 0| \otimes I + |1\rangle\langle 1| \otimes e^{-i\theta\sigma_y/2}.$$

This generated a *branching structure*, characteristic of quantum Darwinism, where the classical information about $\mathcal{S}$'s pointer states was redundantly recorded in multiple fragments $\mathcal{F} \subset \mathcal{E}$.

To analyze the emergence of classicality, the team performed *full quantum state tomography* on the relevant subsystems and computed key information-theoretic quantities: the mutual information $I(\mathcal{S} : \mathcal{F})$, the Holevo bound $\chi(\mathcal{S} : \check{\mathcal{F}})$, and the quantum discord $D(\mathcal{S} : \check{\mathcal{F}})$. They observed that when the interaction strength θ was tuned to approximately $\pi/2$—effectively mimicking ideal decoherence—the mutual information between $\mathcal{S}$ and small fragments $\mathcal{F}$ of the environment rapidly reached a *plateau*, matching the entropy $H_{\mathcal{S}}$. This indicates that each small fragment carried sufficient classical information about $\mathcal{S}$, consistent with the predictions of quantum Darwinism. Moreover, the *quantum discord* remained near zero across the plateau region, confirming that the accessible information was predominantly classical and redundantly encoded.

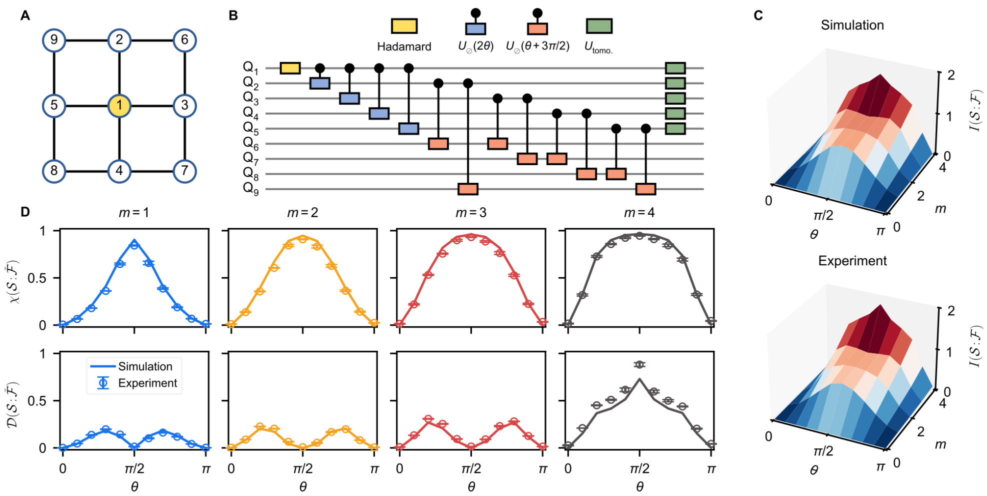

Figure 1: **Robustness of the predictions with comparison to experimental data.** Mutual information $I(\mathcal{S} : \mathcal{F})$ shows a plateau as fragment size m increases.

Importantly, this plateau vanished when the interaction strength deviated significantly from the ideal value, and quantum discord increased—highlighting the sensitivity of objectivity to decoherence quality.

These results provide compelling experimental evidence that classical objectivity can emerge from quantum dynamics via decoherence and redundancy, thus supporting the core claims of quantum Darwinism. This 9-qubit implementation not only validated theoretical predictions but also showcased the power of *superconducting circuits* as controllable platforms for exploring foundational quantum phenomena.

3 Infinite Square Well

While experimental data supporting Quantum Darwinism are both compelling and precise, a satisfactory solution to the measurement problem must ultimately be universal in its applicability. However, when Quantum Darwinism is extended to systems $\mathcal{S}$ that are isolated from their environment $\mathcal{E}$, core principles of standard quantum mechanics tend to fail at this point. Most notably, the Born Rule, which assigns probabilities via the squared magnitude of the wavefunction,

$$P(x) = |\psi(x)|^2.$$

This breakdown arises due to Quantum Darwinism attempts to derive the Born Rule from the theory's decoherence and redundancy-based framework rather than postulating it axiomatically as in traditional formulations. An illustration of this issue is the **Infinite Square Well**, one of the most elementary systems introduced in undergraduate quantum mechanics. In such closed systems, where no environment is present to "select" pointer states or cause decoherence, the assumptions of Quantum Darwinism no longer apply, and thus its derivation of probabilistic outcomes becomes questionable.

For instance the eigenstates and eigenvalues of the Infinite Square Well are:

$$\psi_n(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right), \quad n = 1, 2, 3, \ldots$$

with the potential function,

$$V(x) = \begin{cases} 0, & 0 < x < L \\ \infty, & \text{otherwise} \end{cases}$$

and the general state of superposition is given by:

$$|\psi_s\rangle = \sum_{n}^{\infty} c_n |n\rangle,$$

where $|n\rangle$ corresponds to $\psi_n(x)$ for the sake of simplicity, e.g.

$$|\psi_s\rangle = \alpha|1\rangle + \beta|2\rangle, \quad |\alpha|^2 + |\beta|^2 = 1$$

Here, decoherence will not occur, as decoherence requires the density matrix to be in a mixed state:

$$\rho_s = \sum_k p_k |\psi_k\rangle\langle\psi_k|, \quad \sum_k p_k = 1$$

But the density matrix of the Infinite Square Well remains pure:

$$\rho_{\mathcal{S}} = |\psi\rangle\langle\psi|$$

This leads to failure in Envariance, as it requires a transformation $U_{\mathcal{E}}$ to counter swap the transformation $U_{\mathcal{S}}$, so that there is a symmetry in probability between different states to generate a branching structure and maintain invariance under U_s.

The unitary swap U_s is defined to be:

$$U_{\mathcal{S}}|\psi_s\rangle = \alpha|2\rangle + \beta|1\rangle$$

but,

$$\langle\psi_s|U_{\mathcal{S}}|\psi_s\rangle \neq 1, \quad (\alpha \neq \beta)$$

And hence with no environmental unitary counter swap to maintain symmetry, we have:

$$U_s|\psi_s\rangle \neq |\psi_s\rangle$$

Thus, the state is not invariant under $U_{\mathcal{S}}$ and no symmetry enforces equal probability $\rightarrow$ no valid eigenfunction for any observable. This causes contrast because for an operator to be valid, the only boundary is that it should be Hermitian:

$$\langle\hat{Q}\psi|\psi\rangle = \langle\psi|\hat{Q}\psi\rangle^*$$

4 Decoherence Without Entanglement

One important factor which Quantum Darwinism heavily rely on is decoherence, which is caused by entanglement. The action of entanglement between the quantum system and the environment is significant due to the mechanism of shared information between $\mathcal{S}$ and $\mathcal{E}$. However, recent break through show that entanglement may not be always necessary in order for decoherence to happen.

Consider a single qubit with Hamiltonian,

$$H_s = \frac{\omega}{2}\sigma_z$$

and an environment $\mathcal{E}$ constructed of many un-entangled qubit ancillae, where their density matrix is, $\rho_a = |0\rangle\langle 0|$. And that the system collides with ancillae at random times with an interaction time of almost instantaneous; following a Poisson process with rate λ (i.e. the time between collisions is exponentially distributed). Since the interaction time is instantaneous, the unitary transformation will solely be defined by the interaction strength

$$\theta = \lim_{t\to 0} t\eta$$

and thus,

$$U_\theta = e^{-i\frac{\theta}{2}\sigma_x^a \otimes \sigma_z^S},$$

with the interaction Hamiltonian,

$$H_I = \frac{\eta}{2}\sigma_x^a \otimes \sigma_z^S.$$

Where η is the parameter that determines how strongly the system and ancilla interact during each collision. After each collision, the system changes according to the collision channel :

$$\Phi_c[\rho_S] = \mathrm{Tr}_a\left[U_\theta(\rho_a \otimes \rho_S)U_\theta^\dagger\right].$$

In the eigenbasis of H_I, this can be written as :

$$\Phi_c[\rho_S] = K\rho_S K^\dagger + K^\dagger \rho_S K,$$

where

$$K = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{pmatrix}$$

This simply means that after each collision, the off diagonal elements of the density matrix ρ_s are multiplied by $\cos\theta$. (keep in mind that $\theta = \lim_{t\to 0} t\eta$). And the dynamics of the system is provided by :

$$\dot{\rho}_S(t) = -i[H_S, \rho_S(t)] + \lambda \left(\Phi_c[\rho_S(t)] - \rho_S(t)\right).$$

solving this yields the solution - decoherence factor,

$$c(t) = \exp\left[-\lambda(1-\cos\theta)t\right].$$

However, this decoherence can happen without entanglement as in the case $\theta = \pi$, where U_θ preserves separability and maximally entangled for $\theta = \frac{\pi}{2}$. Contrastingly, in Quantum Darwinism entanglement is necessary in order for information to be encoded. The mutual information between $\mathcal{S}$ and fragments $\mathcal{F}$ is

$$I_s = H_{\mathcal{S}} + H_{\mathcal{E}_f} - H_{\mathcal{S}\mathcal{E}_f},$$

where H is the Vonn Neumann Entropy given by, $H(\rho) = -\mathrm{Tr}(\rho\log\rho)$. After precise calculations, it is shown that information encoding requires entanglement to occur in the Context of Quantum Darwinism. Thus, it fails in this specially constructed yet realistic system.

5 Conclusion

While predictions of Quantum Darwinism is generally accurate and robust, it's universality still require development, as previously mentioned, a satisfactory solution to the measurement problem should be universal on its applicability. And as Quantum Mechanics evolves, it is likely to encounter more systems where Quantum Darwinism and decoherence theory fails (perhaps one day a truly isolated quantum system like the infinite square well will be feasible.) This leads to a conclusion that while Quantum Darwinism fails in certain aspect and it's certain that it's limitations will be even more apparent as quantum mechanics progress, it does not necessary mean that Quantum Darwinism is incorrect. Rather it's failure in some context might indicate that it is incomplete. Thus, Quantum Darwinism might be a step in the right direction, but it will likely need refinement and expansion as new insights into quantum systems emerge.

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