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Original Article

Classical Event Anchoring in Quantum Measurement: A Scale-Relative Record Criterion for the State-to-Record Transition

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Abstract: *Quantum measurement involves a transition from a quantum description containing superposed alternatives to physical configurations that can function as stable classical records. Although measurement interaction, decoherence, environmental encoding, and Quantum Darwinism explain important aspects of this quantum-to-classical transition, they do not by themselves provide a unified criterion for determining when measurement information becomes a sufficiently stable and accessible physical record. This paper introduces Classical Event Anchoring (CEA), a record-centred conceptual framework that organizes the state-to-record transition through system–apparatus correlation, decoherence, record stability, communicability, and practical irreversibility. The framework further develops a scale-relative perspective in which classical record formation depends on physical scale, temporal resolution, environmental conditions, measurement resolution, and the persistence of recorded information. Stability, persistence, distinguishability, accessibility, environmental imprinting, and redundancy are identified as key conditions supporting classical event formation. A review of recent research on generalized measurements, Quantum Darwinism, quasi-probability, information encoding, and continuous quantum measurements highlights the absence of an explicit scale-relative record criterion. CEA therefore provides an integrative conceptual basis for describing how quantum information becomes physically anchored as a robust, distinguishable, and communicable classical record.*

Keywords: *Classical Event Anchoring, Quantum Measurement, Quantum-To-Classical Transition, Decoherence, Classical Records, Environmental Encoding.*

I. INTRODUCTION

Quantum mechanics describes physical systems through quantum states that can contain multiple possible states simultaneously, with each alternative associated with a probability amplitude [1]. During measurement, interaction between a quantum system and an apparatus establishes correlations between possible system states and corresponding apparatus configurations. Although this interaction connects microscopic alternatives with measurable physical states, the resulting description can remain entangled and may contain multiple correlated components. Consequently, measurement interaction alone does not fully explain how a particular outcome becomes a stable and accessible classical record.

The transition toward classical behaviour involves environmental interactions that influence the information contained in the quantum system and measurement apparatus [2]. Decoherence suppresses accessible interference between alternative states and allows effectively distinguishable configurations to emerge. Environmental interactions can also encode information about system states across surrounding physical degrees of freedom. When related information becomes distributed across multiple environmental fragments, redundancy can increase the robustness and accessibility of the resulting information [3][4]. These processes provide important foundations for understanding the emergence of classical information, but they do not alone specify when a physical configuration becomes sufficiently persistent and distinguishable to function as a classical record.

Classical Event Anchoring (CEA) provides a record-centred framework for organizing the state-to-record transition [5]. It considers system–apparatus correlation, decoherence, record stability, communicability, and practical irreversibility as interconnected conditions. The framework also distinguishes quantum states, physical events, and classical records, emphasizing that a record can exist physically before direct human observation. A scale-relative perspective is therefore important because record formation depends on physical scale, temporal resolution, environmental conditions, measurement resolution, and the persistence of recorded information. Stability, distinguishability, accessibility, environmental imprinting, and redundancy provide additional conditions for determining whether measurement information remains available as a physical record. This perspective establishes the basis for examining how quantum information becomes physically anchored as a stable, accessible, and communicable classical event.

A. Structure of the Paper

The remainder of this paper is organized as follows. Section II discusses quantum measurement. Section III introduces Classical Event Anchoring and examines the transition from measurement outcomes to physical records. Section IV develops the scale-relative criterion for the state-to-record transition. Section V reviews recent literature and compares existing approaches with CEA. Finally, Section VI presents the conclusion and identifies directions for future research.

II. QUANTUM MEASUREMENT AND THE EMERGENCE OF CLASSICAL OUTCOMES

This section explains measurement interaction, system–apparatus correlation, environmental effects, decoherence, and information encoding that contribute to the emergence of stable classical alternatives.

A. Quantum State and Measurement Interaction

Quantum mechanics describes physical systems through quantum states that encode the possible outcomes of measurements and their associated probability amplitudes [6]. When a quantum system interacts with a measurement apparatus, the interaction establishes correlations between states of the system and distinguishable states of the apparatus. An idealized measurement interaction can be represented in Equation (1):

$$|\psi\rangle|A_0\rangle \rightarrow \sum_i c_i|s_i\rangle|A_i\rangle \qquad (1)$$

where $|\psi\rangle$ represents the initial system state, $|A_0\rangle$ represents the initial apparatus state, $|s_i\rangle$ denotes possible system states, $|A_i\rangle$ denotes corresponding apparatus states, and c_i represents the associated probability amplitudes. The interaction therefore produces a correlation between microscopic system alternatives and macroscopic apparatus states.

However, system–apparatus correlation alone does not explain why a particular measurement result becomes a stable classical outcome. The resulting state is an entangled quantum description that has several correlated components. Thus, the measurement problem is not limited to the first interaction but continues to manifest in the physical processes that lead to the suppression of observable interference and the production of good measurement records. This constitutes the starting point for the discussion of the role of decoherence and environmental effects in the quantum-to-classical transition.

B. From Superposition to Measurement Outcome

A system can be in a state of superposition of several states prior to measurement in quantum mechanics. The system is measured in an apparatus, so that correlations among the possible quantum states and the different configurations of the apparatus are set up during the measurement [7]. There are steps to understand in the transition towards classical outcome as follows:

- Quantum superposition: Multiple possible states coexist within the quantum description.
- Measurement interaction: The system becomes correlated with distinguishable apparatus states.
- Environmental interaction: Information about these states becomes encoded in the surrounding environment.
- Suppression of interference: Environmental interactions reduce accessible interference between alternative states, making them effectively distinguishable.
- Formation of robust alternatives: Stable apparatus configurations emerge that can preserve information about the measurement.

Decoherence is needed to suppress interference and to create robust states but is not sufficient to account for the selection of a particular definite outcome. From the Classical Event Anchoring (CEA) perspective, the measurement outcome will therefore be considered as part of a broader transition from quantum superposition to a stable and accessible physical record. This distinction between the quantum state, measurement interaction, and resulting record will provide the basis for the subsequent discussion of classical event formation.

C. Decoherence and Environmental Encoding

Decoherence occurs when interactions between a quantum system and its environment correlate different system states with different environmental states [8]. A simplified representation of this process is Equation (2):

$$\sum_i c_i|s_i\rangle|A_i\rangle|E_0\rangle \rightarrow \sum_i c_i|s_i\rangle|A_i\rangle|E_i\rangle \qquad (2)$$

where $|E_i\rangle$ represents an environmental state correlated with the corresponding system–apparatus state. When environmental states associated with different alternatives become approximately orthogonal, shown in Equation (3):

$$\langle E_j|E_i\rangle \approx 0 \qquad (i \neq j) \qquad (3)$$

the off-diagonal coherence terms in the reduced density matrix become strongly suppressed. The resulting reduced state can therefore exhibit effectively classical alternatives even though the overall system remains described quantum mechanically.

Environmental encoding is particularly important because the environment can function as an information-bearing medium [9]. Information concerning selected system states can become distributed across many environmental degrees of freedom. This observation provides a foundation for quantum Darwinism, which emphasizes the proliferation of information about selected states into multiple environmental fragments. Environmental encoding therefore connects decoherence with the emergence of robust and potentially accessible classical information.

III. CLASSICAL EVENT ANCHORING: FROM MEASUREMENT OUTCOMES TO PHYSICAL RECORDS

This section introduces Classical Event Anchoring as a record-centred framework connecting quantum measurement, decoherence, stability, communicability, and practical irreversibility in classical record formation.

A. Concept of Classical Event Anchoring

Building on the concepts of quantum measurement, decoherence, environmental encoding, and redundant information, this paper introduces Classical Event Anchoring (CEA) as a record-centred conceptual framework for describing the transition from a quantum-state description to a stable and communicable classical record [10]. CEA organizes this transition around five interconnected conditions:

- System–apparatus correlation: The quantum system is physically correlated with a measuring device, establishing a correlation between the quantum state and a measurable physical configuration.
- Decoherence: The experimentally available interference between alternative states is diminished by interactions with the surrounding environment.
- Record stability: The physical arrangement that results lasts for a relevant period and is sufficiently resistant to disturbance.
- Communicability: Information that is stored in the physical record is accessible, repeatable, comparable, and physically transferable.
- Practical irreversibility: The reconstruction of the physical coherent state becomes impractical in the above-mentioned range of experiments.

CEA is not suggested as a modification of quantum mechanics. Rather, it offers an all-inclusive structure to structure these processes around the transition from quantum state description to a stable physical record. The framework thus highlights the issue of how the quantum information is physically embedded in a way that can then be used as a classical record.

B. From Measurement Outcome to Physical Event

The result of a measurement can be viewed in various integrated aspects. The quantum description of the system is represented by a quantum state with amplitudes and phase relations at the quantum level. In the case of the measurement interaction, the correlations are made between the possible states of the system and the distinguishable configurations of the apparatus. On the environmental level, information about these configurations may get scattered around through interactions with degrees of freedom in the immediate environment. The resulting physical configuration can be used as a record at the macroscopic level.

CEA will therefore be a distinction between quantum states, physical events, and classical records [11]. A quantum state is a mathematical description of the system, a physical event is an interaction or an occurrence in a well-defined physical context and a classical record is the physical information that persists after the occurrence. This is significant because a record doesn't need to be seen by humans at the moment. The information can be stored in a detector, memory device, photographic medium, or freedom of an environment prior to being seen by a human observer. The key issue is then whether the information is now stable enough, clearly distinguishable, and easily accessible to act as a physical record.

C. Persistence, Stability, and Environmental Redundancy of Classical Records

A measure is operationally meaningful if information related to a physical interaction is fairly durable, stable, distinguishable, and retrievable from the previous observation or comparison. The creation of such a record is not just a system–apparatus correlation, but the encoded information must persist through the measurement timescale and be known subsequent to the interaction. An additional contribution to the process of recording can be made by environmental interactions, which imprint information on other physical degrees of freedom surrounding the measured state. The redundancy in the preservation of related information across environmental fragments can enhance the robustness and accessibility of the record. In the Classical Event Anchoring (CEA) framework, these processes will be viewed as a group of mechanisms that make information related to a measurement physically anchored and accessible as a classical record. A summary of the main conditions needed for the classical formation of records within the CEA is presented in Table I.

Table 1: Conditions Supporting Classical Record Within the Classical Event Anchoring

Condition	Physical Meaning	Role in Classical Record Formation
Persistence	Information remains available over a relevant time interval.	Allows the record to survive beyond the initial measurement interaction.
Stability	The recorded configuration remains sufficiently resistant to physical disturbance.	Preserves the identity and integrity of the measurement record.
Distinguishability	Alternative record states can be physically discriminated.	Enables different measurement outcomes to be identified reliably.
Accessibility	Recorded information can be physically retrieved, observed, or compared.	Allows the record to support subsequent observation and communication.
Environmental Imprinting	Information about the measurement becomes encoded in surrounding physical degrees of freedom.	Extends the physical presence of the record beyond the measurement apparatus.
Redundancy	Related information is retained across multiple physical carriers or environmental fragments.	Enhances the robustness, accessibility, and communicability of the record.

Table I shows that classical record formation needs to be stable, distinguishable, accessible, environmentally imprinted and redundant. CEA thus sees record formation as a process of information stabilization, preservation and access, and not as a process of decoherence alone.

IV. A SCALE-RELATIVE CRITERION FOR THE STATE-TO-RECORD TRANSITION

The physical scale, temporal resolution, environmental conditions, measurement properties, and persistence of the records are discussed in this section.

A. Scale and Stability of Classical Records

The transitions to a classical record are dependent on the physical size, temporal resolution and environmental conditions of a measurement process. To be physically meaningful, a recorded configuration should last long enough to be recognizable as such and be different from possible alternative configurations [12]. Decoherence plays a role in this process by eliminating interference accessible to the system and driving towards strong states that can preserve stable physical structures. Environmental interactions, properties of measurement apparatus and the timescale on which the recorded information is needed also affect the stability and persistence of a record. Two properties are particularly important for understanding the persistence of a physical record:

- Stability: The recorded configuration is still sufficiently resistant to the relevant physical disturbance factors.
- Persistence: The recorded information is kept for an adequate time to facilitate subsequent observation or interaction.

The following properties offer a link between decoherence and classical record formation. Decoherence accounts for the lack of interference and formation of stable states, but the physical structure has to hold for long enough to serve as a recording. Even with this persistence, environmental interactions can play a further role in supporting the persistence, enabling information related to a measurement to be encoded beyond the immediate system–apparatus interaction. Thus, the emergence of a classical record can be understood as a scale-dependent physical process in which information becomes sufficiently stable and persistent to remain available as an observable event.

B. Conditions Associated with Classical Record Formation

There are a number of physical conditions that help to create classical records. The decoherence may happen in a time scale fast enough that the interference between relevant alternatives is effectively unobservable at the scale of the observation. The measurement device also needs to have a resolution high enough to distinguish the resulting configurations [13]. The physical configuration must then hold for sufficiently long period to enable subsequent retrieval or comparison to be made, and environmental encoding can be used to offer other means of access to the information.

The principal conditions can be summarized as follows:

- Effective decoherence: Relevant alternatives' interference is almost eliminated in the process of environmental interaction.
- Physical distinguishability: Subsequently, alternative measurement settings are sufficiently differentiated at the appropriate observation level.

- Record persistence: The resulting physical information is stable for the relevant observation and retrieval time period.
- Information accessibility: The encoded information can be physically retrieved, compared or communicated.
- Environmental redundancy: Information about the relevant state can be stored over multiple environmental degrees of freedom, making it more robust and accessible.

These conditions and responses are not to be taken as a generic threshold for physical systems. Each system may have a different decoherence time, an environmental coupling, a resolution of the measurement and a lifetime of the record [14]. Classical record formation can then be seen as an operational process with features that are defined by the physical system, the measurement setup and the observational scale.

C. State-to-Record Transition: A Conceptual Perspective

The processes of moving from a quantum state to a classical record include ones where information becomes correlated, stabilized, and accessible. System–apparatus interactions create system–apparatus correlations, and environment–apparatus interactions create decoherence by decreasing accessible interference. This information can then be coded into the environment and across multiple degrees of freedom, making it more robust and accessible. Therefore, a record is a physical configuration in which there is information about the measurement that is stable, retrievable, and communicable. It can therefore be conceptually represented as follows in Fig. 1.

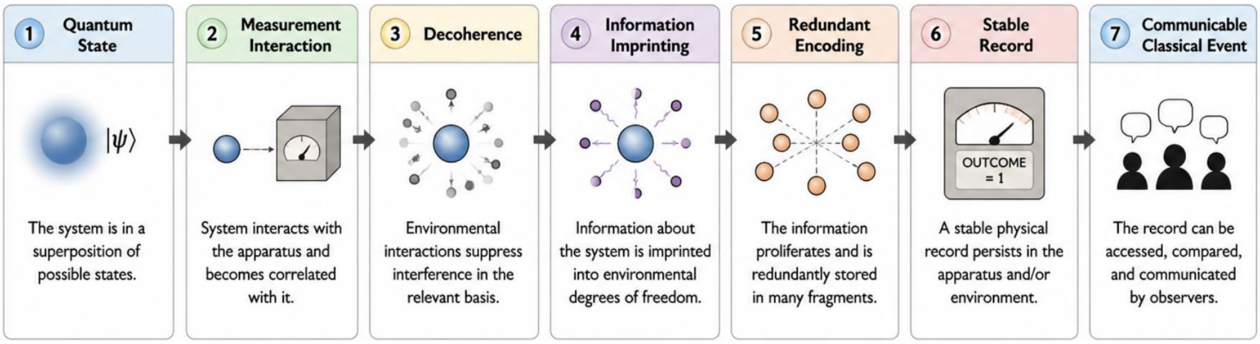

Figure 1: Conceptual Illustration of The State-To-Record Transition

V. LITERATURE REVIEW

Recent studies investigate quantum-to-classical transitions through generalized measurements, quantum Darwinism, quasiprobabilities, information encoding, and measurement dynamics, but classical record formation remains insufficiently defined.

Z. Xu (2026) established an operational connection between discrete generalized measurements and continuous-time decoherence. The study revealed that quasiprobability negativity could be eliminated in finite-dimensional systems by a single round of the generalized measurement and that the loss of nonclassicality can happen before the usual decoherence time [15].

A. Touil, B. Yan, and W. H. Zurek (2025) compared the redundant environmental records that allow observers to reach a consensus in Quantum Darwinism. They found that informative enough environmental fragments enable independent observers to independently determine the same pointer state, thus connecting redundancy and classical objectivity [16].

E. Doucet and S. Deffner (2025) established a connection between Kirkwood-Dirac quasiprobability and Quantum Darwinism. They demonstrated that dynamics that enable Quantum Darwinism link two views of the origin of classicality, by showing that the corresponding quasiprobability distributions become classical [17].

B. Ferté and X. Cao (2024) proposed a solved Quantum Darwinism model based on random Clifford circuits and uncovered unique phases and transitions of information encoding. They applied their ideas to information spreading and measurement-induced phase transitions in Quantum Darwinism [18].

Y. O. Nakagawa et al. (2024) proposed adaptive quantum-classical algorithm for the construction of input states for quantum-selected configuration interaction (QSCI). The methodology was shown to be correct and to yield a good approximation of the ground-state energies for small molecular systems under noisy quantum-device conditions[19].

C. Carisch, A. Romito, and O. Zilberberg (2023) studied entanglement evolution in the presence of ongoing quantum measurements, via quantum trajectories and mixed-state descriptions. The results of their simulations revealed similar qualitative dynamics for both descriptions and related measures of strength of coherence-length dynamics[20].

The approaches, major findings, limitations, and directions for further investigations are summarized in Table II. The studies together provide various different aspects of measurement, decoherence, information redundancy and quantum-to-classical transition, but they do not directly provide a scale-relative criterion for the sufficiency of the stability, distinguishability and accessibility of the physical record in order to qualify it as a classical record. This gap is what drives the record-centred perspective that is developed in CEA.

Table 2: Comparative Assessment of Recent Approaches to Quantum-To-Classical Transition and Classical Event Anchoring

References	Approaches	Key Findings	Limitation	Future Work	Recommendations
Xu, Z. (2026)	Generalized measurements, decoherence, and quasiprobability negativity.	A single measurement can eliminate nonclassicality before conventional decoherence time.	Does not define when the state becomes a stable classical record.	Link nonclassicality loss with record stability and accessibility.	Develop a scale-relative record criterion beyond decoherence time.
Touil, A., Yan, B., & Zurek, W. H. (2025)	Quantum Darwinism, mutual information, environmental redundancy, and observer consensus.	Redundant records enable independent observers to agree on pointer states.	No unified threshold for classical event formation or observational scale.	Combine redundancy, accessibility, persistence, and scale.	Use consensus and redundancy as components of a record criterion.
Doucet, E., & Deffner, S. (2025)	Kirkwood–Dirac quasiprobability and quantum Darwinism.	Connects quasiprobability classicality with the emergence of quantum Darwinism.	Does not explicitly define an observable classical record or scale threshold.	Combine KDQ behaviour with redundancy and distinguishability.	Develop a multidimensional measure of classical record formation.
Ferté, B., & Cao, X. (2024)	Random Clifford circuits, information encoding, quantum Darwinism, and MIPTs.	Shows distinct Darwinism and encoding phases with different information-recovery properties.	Focuses on many-body encoding rather than individual measurement events.	Test record formation under realistic noise, scale, and measurement conditions.	Use information recoverability to establish a scale-dependent record threshold.
Nakagawa, Y. O. et al. (2024)	ADAPT-QSCI, iterative state preparation, and measurement sampling.	Measurement sampling can produce accurate results even with substantial noise.	Does not examine measurement outcomes as persistent classical records.	Study stability, reproducibility, and accessibility of measurement records.	Treat measurement outcomes as candidate records under realistic noise.
Carisch, C., Romito, A., & Zilberberg, O. (2023)	Continuous measurements, quantum trajectories, entanglement, and coherence dynamics.	Measurement strength affects coherence length and quantum-to-classical dynamics.	Does not incorporate redundancy, observer consensus, or record formation.	Connect measurement strength and coherence decay with record persistence.	Include measurement strength and coherence as variables in a record criterion.

VI. CONCLUSION & FUTURE WORK

The transition from quantum states to classical records involves interconnected physical processes rather than measurement interaction or decoherence alone. System–apparatus correlation establishes the relationship between quantum alternatives and measurable configurations, while decoherence suppresses accessible interference and environmental encoding distributes information across surrounding physical degrees of freedom. Within Classical Event Anchoring (CEA), stability, persistence, distinguishability, accessibility, environmental imprinting, redundancy, communicability, and practical irreversibility collectively characterise the formation of a physical record. The scale-relative perspective further indicates that classical record formation depends on the physical system, environmental coupling, measurement resolution, temporal scale, and required record lifetime rather than a single universal threshold. Existing research on generalized measurements, Quantum Darwinism, quasiprobability, information encoding, and continuous measurements addresses important components of the quantum-to-classical transition, but a unified criterion for identifying when information becomes a stable, distinguishable, and accessible classical record remains insufficiently defined. Future work should aim at defining quantitative quantities that combine the decoherence time, record lifetime, distinguishability, information recoverability, environmental redundancy and measurement strength. These can be evaluated experimentally and through computations under realistic noise conditions and at various scales of observation. Based on these results, cross-platform studies can be conducted to investigate the consistency, applicability and limitations of the CEA framework in various quantum measurement environments.

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