The role of redundant correlated records in the emergence of Objective Classical Reality

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Abstract

Quantum measurement inevitably involves a physical system, the observer, in which the result of the measurement procedure is stored. Therefore, in the context of unitary (reversible) quantum mechanics, one has to include the observer as a physical system operating within the limits of quantum mechanics. We argue that a physical quantity, correlation, is a resource used up in each quantum measurement. We put constraints on the nature of environmental/observer states which lead to redundant, classical record formation. A network of such measurements establishes a stable objective classical reality — the redundant agreement of several observers on the state of the measured quantum system. We verify our hypotheses by simulating the quantum measurement procedure — observer network states with a high amount of correlation gives rise to high fidelity measurement results.

Introduction

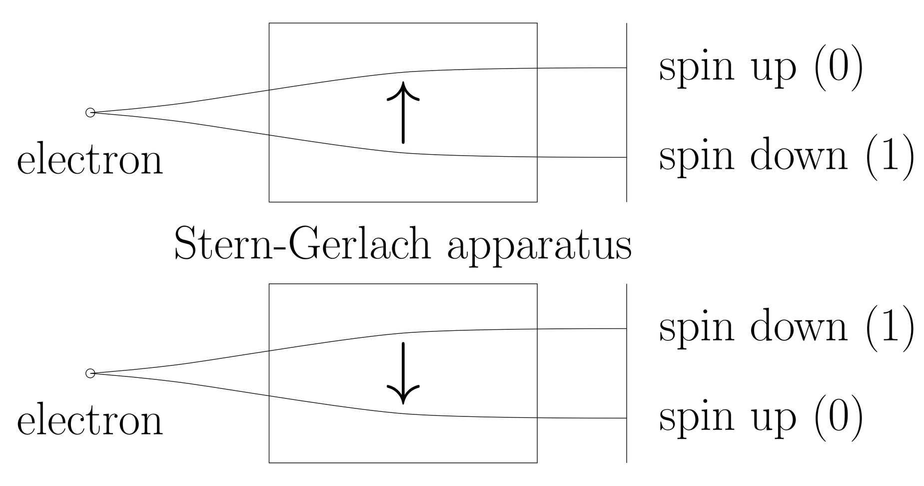

Fig. 1: An electron passes through a Stern-Gerlach apparatus.

- Stern-Gerlach experiment.
- Spin $^1/_2$ quantum system measured.
- Two spots on screen after Stern-Gerlach apparatus.
- Magnet acts as environment.
- Flipped environment → incorrect correlation. For example,

$$|\uparrow\rangle_{\mathrm{ele}}|\phi\rangle_{\mathrm{scr}}|\uparrow\rangle_{\mathrm{env}} \to |\uparrow\rangle_{\mathrm{ele}}|\uparrow\rangle_{\mathrm{scr}}|\phi\uparrow\rangle_{\mathrm{env}} \quad (1)$$

$$|\uparrow\rangle_{\mathrm{ele}}|\phi\rangle_{\mathrm{scr}}|\downarrow\rangle_{\mathrm{env}} \to |\uparrow\rangle_{\mathrm{ele}}|\downarrow\rangle_{\mathrm{scr}}|\phi\downarrow\rangle_{\mathrm{env}}. \quad (2)$$

Motivations

Definition 1 (Objectivity[1]) *A state of the system s exists objectively if many observers can find it out independently and without perturbing it.*

- Unitary quantum mechanics, generalised measurements, and finite dimensional Hilbert spaces $\implies$ arbitrary environmental states cannot lead to successful measurement.
- $\implies$ Environment has limited correlation capacity.
- Redundancy according to definition 1 restricts correlation capacity of environment.
- Correlation resource → observer network states (figure 3).

A Unitary Measurement Procedure

$|\psi\rangle_{\mathrm{s}} = \sum_i \psi_i |i\rangle_{\mathrm{s}}$ measured by correlated environment $|\chi\rangle_{\mathrm{e_1 \ldots e_N}} = \sum_j \chi_j |j\rangle_{\mathrm{e_1}} \ldots |j\rangle_{\mathrm{e_N}}$:

$$|\psi\rangle_{\mathrm{s}}|\chi\rangle_{\mathrm{e_1\ldots e_N}} \to \sum_i \psi_i |i\rangle_{\mathrm{s}}|i\rangle_{\mathrm{e_1}}|\chi\rangle_{\mathrm{e_2\ldots e_N}}. \quad (3)$$

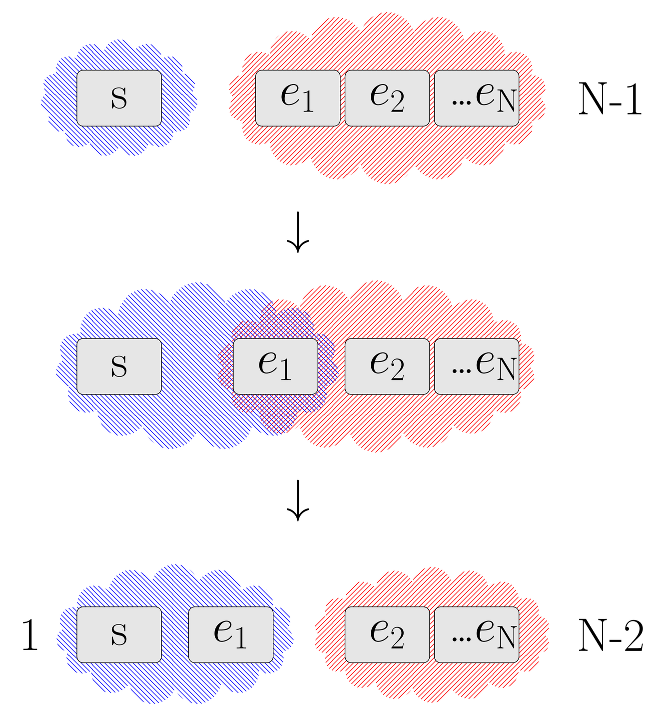

Fig. 2: An example of a measurement procedure

1. s interacts with correlated environment $e_1 \ldots e_N$.
2. A complex consisting of s and $e_1 \ldots e_N$ forms.
3. Correlation transferred from environment to observer network.

Observer Network State

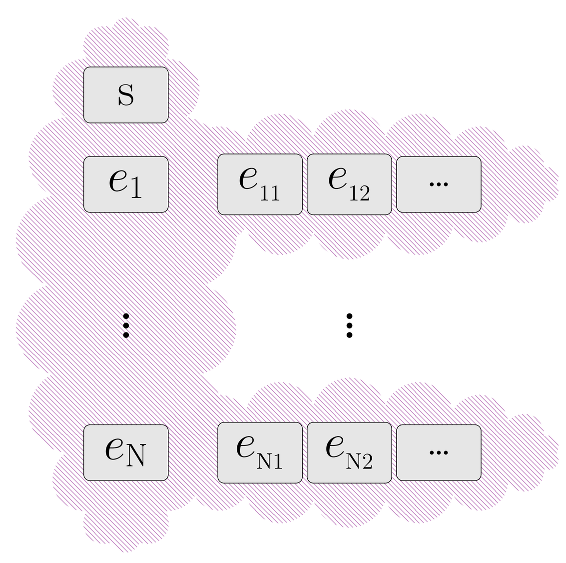

Fig. 3: Several measurements such as in figure 2 give rise to an observer network state.

- Quantum system s measured by environmental systems e_i (figure 2).
- Environmental systems e_i measured by other environmental systems e_{ij} and so on.
- → observer network states.

Correlation Proxy for Qubits

- Correlation C_α: average (signed) number of systems that agree with state of system α, $C_\alpha = Z_\alpha \sum_{\mu \neq \alpha} Z_\mu$. Z is the Pauli Z matrix.
- Correlation C_0: average (signed) number of systems that agree with state of system s (index 0).
- Correlation C_E: $C_E = \sum_{i \in \{1,\ldots,N\}} C_i$.

Simulation

- System s (index 0) interacts with correlated environment (index 1 to N) through measurement procedure as in equation (3).
- Interaction events are Poisson distributed.
- Each interaction is at random system-environment or environment-environment.
- System-environment: increase C_0 (observer network size).
- Environment-environment: increases or decreases C_0.
- **Large initial environmental correlation (C_E) → large observer network states (C_0).**

Simulation Results

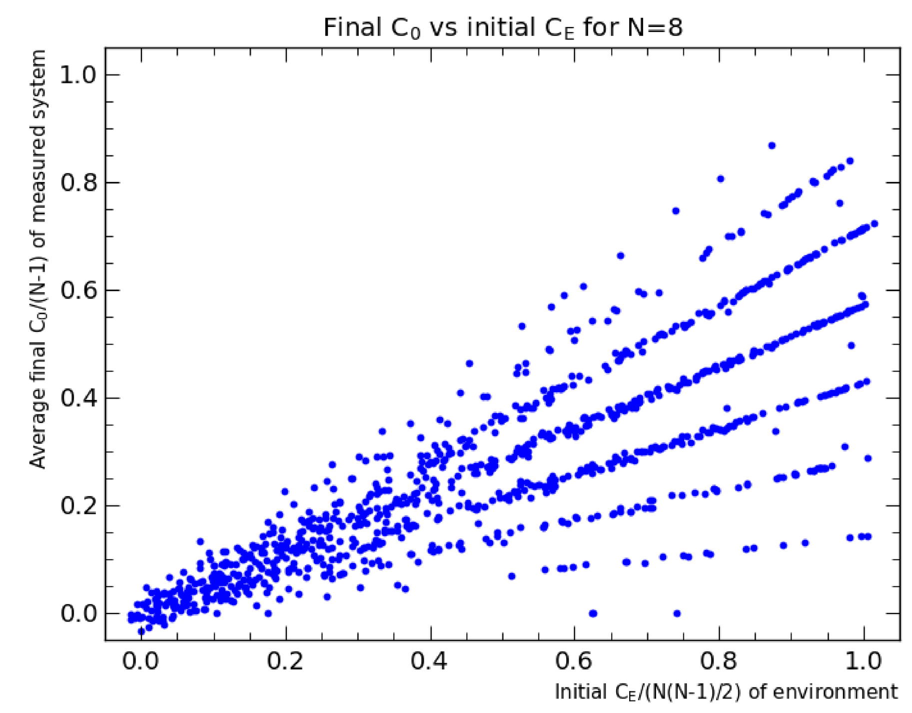

Fig. 4: Final C_0 metric vs initial environmental C_E. Low env-env interactions.

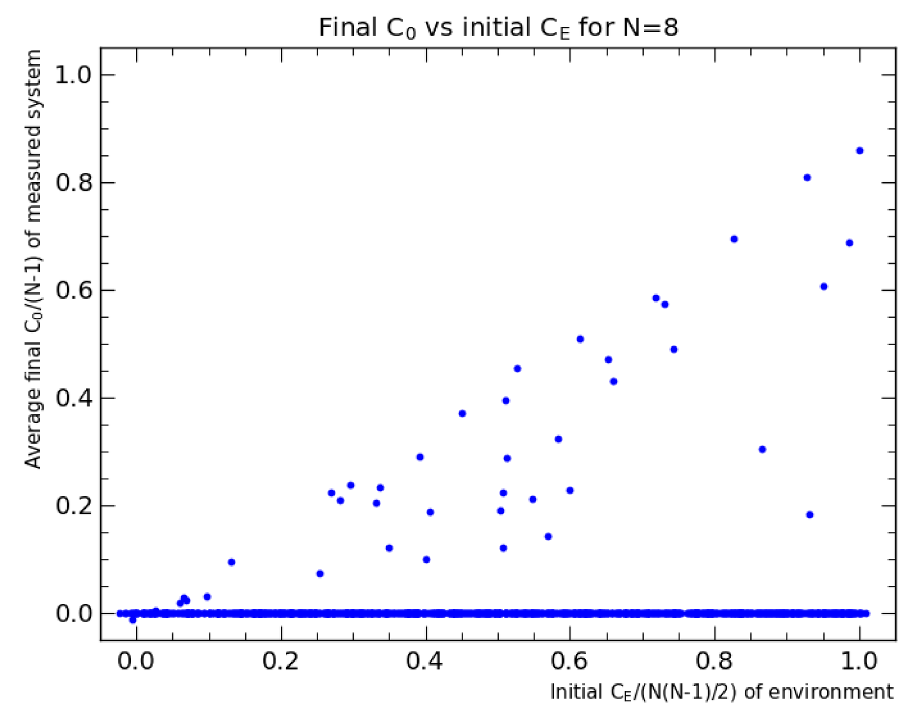

Fig. 6: Final C_0 metric vs initial environmental C_E. High env-env interactions.

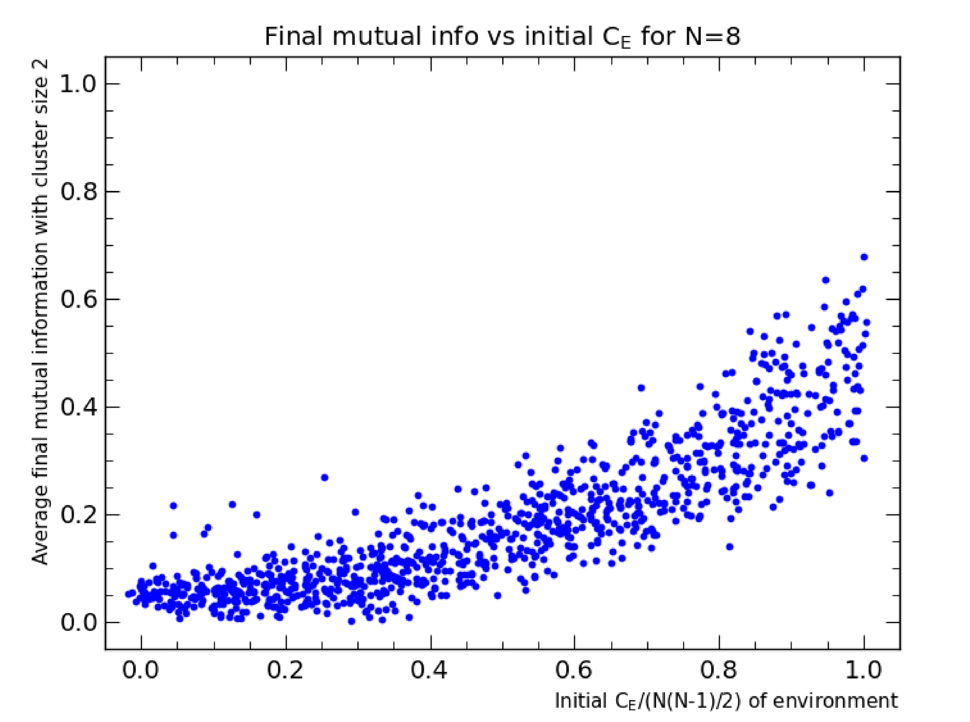

Fig. 5: Final mutual information vs initial environmental C_E. Low env-env interactions.

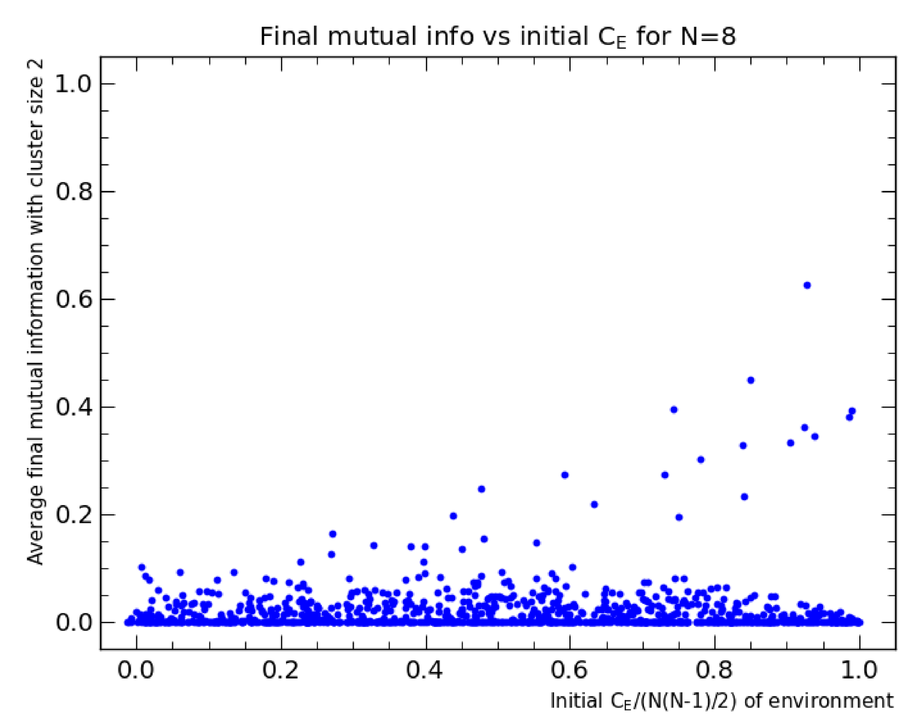

Fig. 7: Final mutual information vs initial environmental C_E. High env-env interactions.

- Low env-env interactions (figures 4 5): larger initial env correlation → larger observer network states for s.
- High env-env interactions (figures 6,7): overall correlation low.

Conclusions

- Correlation capacity of an environment is a finite resource.
- Correlation as a resource is used up for every measurement event.
- Objective classical reality results from the formation of observer network states.
- Early conclusion: simulations confirm our intuition.

[1] J. K. Korbicz. "Roads to objectivity: Quantum Darwinism, Spectrum Broadcast Structures, and Strong quantum Darwinism – a review". In: *Quantum* 5 (Nov. 2021), p. 571. DOI: 10.22331/q-2021-11-08-571. URL: https://doi.org/10.22331%2Fq-2021-11-08-571.