Quantum Agency

A Brief Overview

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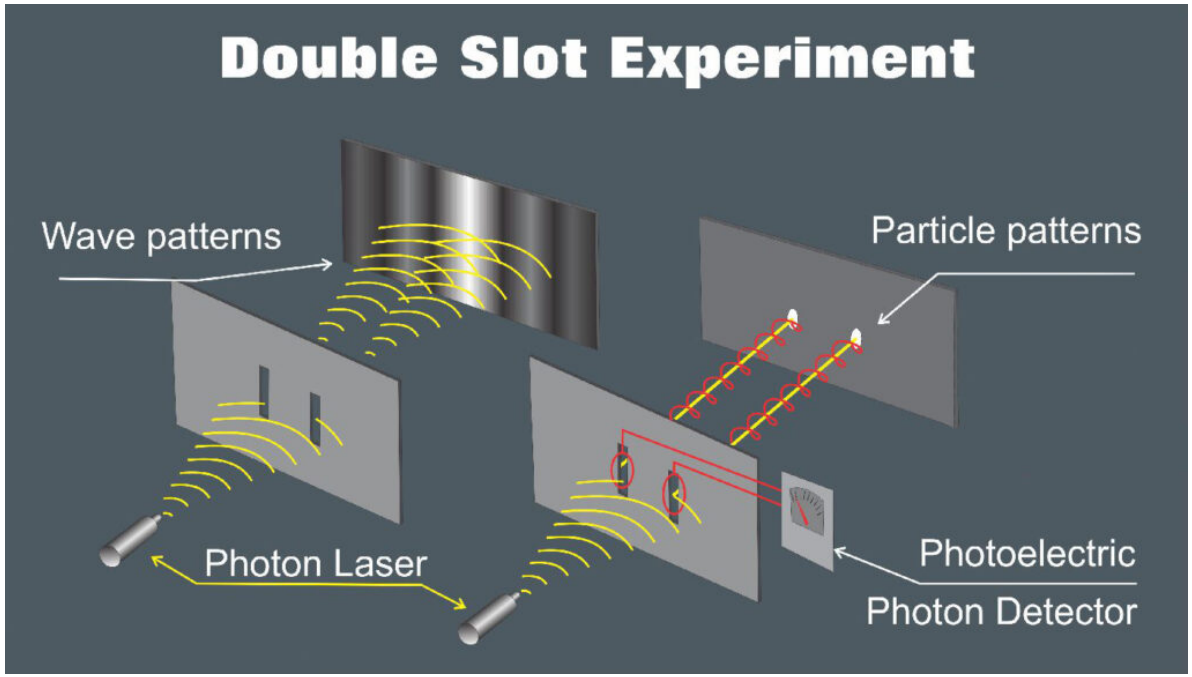
CASA Colloquium

Superposition and Measurement I

One of the fundamental aspects of quantum mechanics.

Superposed Quantum State

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$



Superposition and Measurement II

Measuring a quantum state 'collapses' the quantum state and localizes the particle depending on the choice of measurement basis.

Born Rule

The Born Rule is a postulate that states that the probability of finding a result for a variable (called an observable) is given by $\langle\psi|\,\hat{P}\,|\psi\rangle$ where $\hat{P}$ is the projection corresponding to the observable.

Entanglement

A bizarre consequence of superposition.

An Entangled State

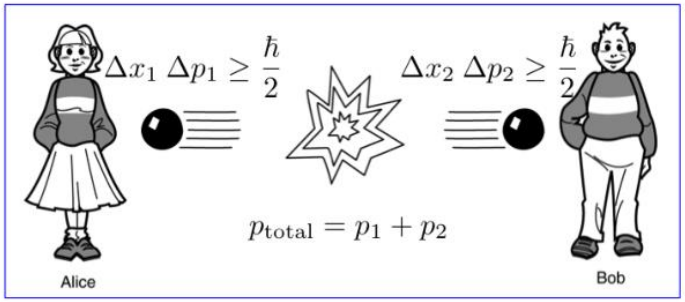
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B)$$

The EPR Paradox

Einstein, Podolsky, and Rosen questioned whether quantum mechanics is truly random. Maybe there are just hidden variables that we don't currently see in the theory.

The EPR Paradox

Two particles produced with known total momentum P_{total}, and fly far away.
Alice can not measure at the same time position (x_1) and momentum (p_1) of particle 1.
Bob can not measure at the same time position (x_2) and momentum (p_2) of particle 2.



But:
If *Alice* measures p_1, then automatically p_2 is *known*, since $p_1+p_2= p_{total}$
If *Alice* measures x_1, then p_1 is unknown and therefore also p_2 is *unknown*.

How can a decision of Alice to measure x_1 or p_1 affect the quantum state of Bob's particle (x_2 or p_2) at the same time over a long distance?
Communication with speed faster than the speed of light? Contradiction with causality?
Is there "local realism" or "spooky action at a distance"?

Bell Inequalities

John Bell provided some insight into the EPR paradox in his famous paper.[1] His theorem, aptly named **Bell's Theorem**, assumed that hidden variables were present behind quantum theory. The **Bell Inequalities** derived from the theorem are consistent with *local* hidden variable theories but are inconsistent with quantum mechanics. This has been demonstrated experimentally.[2]

1. Bell, "On the Einstein Podolsky Rosen paradox."
2. Clauser et al., "Proposed Experiment to Test Local Hidden-Variable Theories."

So What?

The violation of Bell's Inequalities demonstrates that there are no local hidden variables at play behind quantum theory. In other words, a measurement does not uncover something that is already there, but fundamentally changes the quantum system.

Wigner's Friend

In the late 1900s, Eugene Wigner sought to investigate the 'collapse' of the quantum system after measurement.[3]

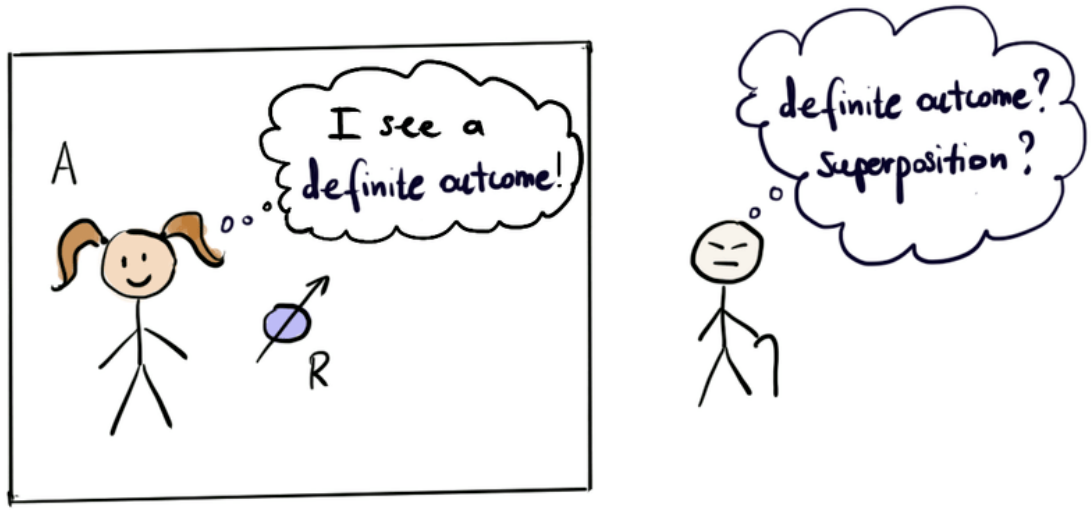


Figure: Credit to Fraser, Nurgalieva, and Rio[4]

3. Wigner, "Remarks on the Mind-Body Question."
4. Fraser, Nurgalieva, and Rio, "Quantum Epistemology and Constructivism."

Extended Wigner's Friend Scenarios

These take up the mantle of Wigner's ideas by probing the metaphysical assumptions behind quantum theory, i.e. derive a set of Bell Inequalities and violate them.

Frauchiger and Renner

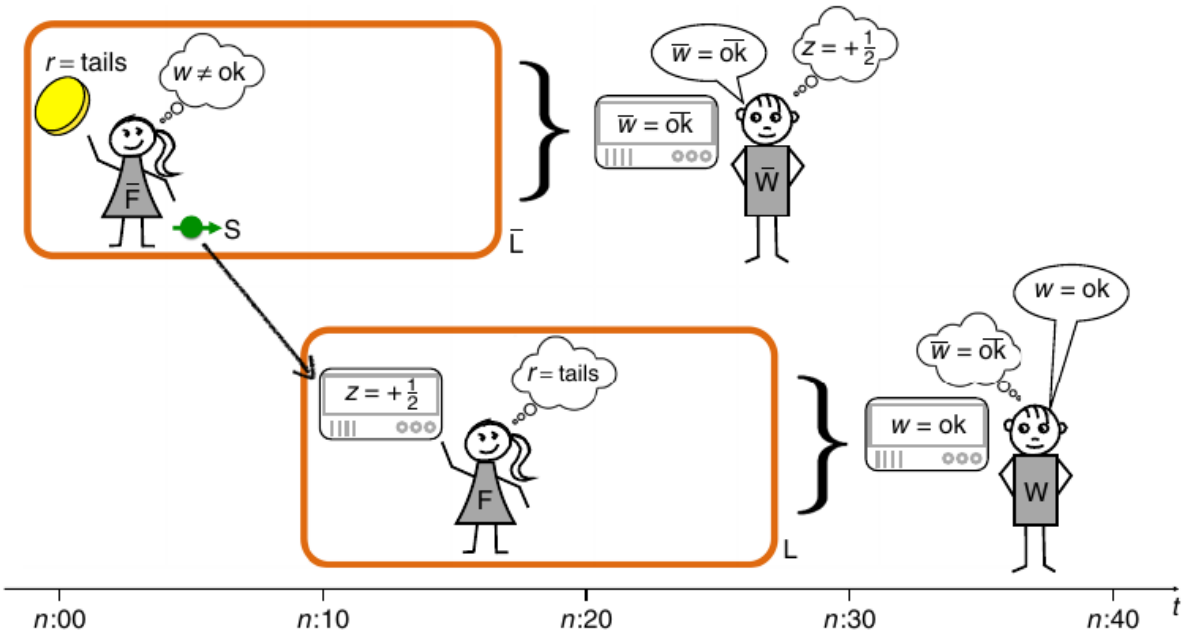


Fig. 2 Illustration of the Gedankenexperiment. In each round $n = 0, 1, 2, \ldots$ of the experiment, agent $\overline{\mathsf{F}}$ tosses a coin and, depending on the outcome r, polarises a spin particle S in a particular direction. Agent F then measures the vertical polarisation z of S. Later, agents $\overline{\mathsf{W}}$ and W measure the entire labs $\overline{\mathsf{L}}$ and L (where the latter includes S) to obtain outcomes $\overline{w}$ and w, respectively. For the analysis of the experiment, we assume that all agents are aware of the entire procedure as specified in Box 1, but they are located at different places and therefore make different observations. Agent F, for instance, observes z but has no direct access to r. She may however use quantum theory to draw conclusions about r

Figure: Credit to Frauchiger and Renner[5]

5. Frauchiger and Renner, "Quantum theory cannot consistently describe the use of itself."

Metaphysical Assumptions of Frauchiger and Renner

Assumption Q: If Agent A knows that $\langle\psi|\,\hat{\pi_{x=1}}\,|\psi\rangle = 1$, then Agent A can conclude that $x = 1$.
Assumption C: Suppose Agent A knows that Agent B knows that, with the same theory, $x = 2$. Then Agent A is certain that $x = 2$.
Assumption S: Suppose Agent A is certain that $x = 2$ at time t. Then Agent A must deny the claim that they are certain $x = 1$ at that same time.

Thoughtful Local Friendliness I

Another EWFS, this time with different metaphysical assumptions.[6] Here they are:

1. Local Agency: Any intervention, made in a manner appropriate for randomized experimental trials of a given phenomenon, is uncorrelated with any set of physical events that are relevant to that phenomenon and outside the future light-cone of that intervention.
2. Physical Supervenience: Any thought supervenes upon some physical event(s) in the brain (or other information-processing unit as appropriate) which can thus be located within a bounded region in space-time.
3. Ego Absolutism: My communicable thoughts are absolutely real.

Thoughtful Local Friendliness II

4. Friendliness: If a system displays independent cognitive ability at least on par with my own, then they are a party with cognition at least on par with my own, and any thought they communicate is as real as any communicable thought of my own.

and two technological assumptions:

1. Human-Level Artificial Intelligence
2. Universal Quantum Computing

Thoughtful Local Friendliness III

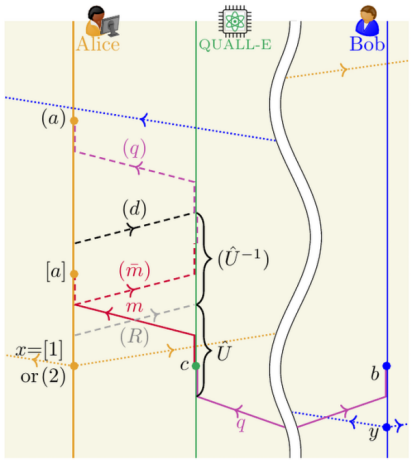


Figure 3: Space-time diagram of the proposed experiment to test LF^{ϑ}. The protocol and spatio-temporal relations between events is identical to that of Fig. 2, with QUALL-E replacing Charlie, and with more details specific to the implementation in a quantum computer. QUALL-E and Bob each observe one of an entangled pair of qubits that has been distributed to them (lavender lines). Actions or events or process that may or may not occur depending on Alice's choice x are indicated by dashed lines and/or brackets. Square brackets pertain when Alice chooses $x = 1$: she reads QUALL-E's message m and thereby obtains her result $[a]$. Round brackets pertain when Alice chooses $x = 2$: she sends instructions (R) to the processor on which QUALL-E is running, to logically reverse the unitary evolution $\hat{U}$ that ran in the preceding time interval of duration $T/2$; she does not read m but rather sends it back to QUALL-E, in reverse order $(\bar{m})$, so that it arrives in time to play its necessary role in effecting the inverse unitary $(\hat{U}^{-1})$; she sends a message (d) to QUALL-E to arrive at the end of this reversal, "Do not measure the qubit; pass it directly to me."; she receives the qubit (q) and measures it in a basis different from its logical basis, yielding result (a).

Figure: Credit to Wiseman, Cavalcanti, and Rieffel[7]

6. Wiseman, Cavalcanti, and Rieffel, "A "thoughtful" Local Friendliness no-go theorem: a prospective experiment with new assumptions to suit."

7. Wiseman, Cavalcanti, and Rieffel.

Implementing a 'Thoughtful' Agent I

My current research is focusing on theoretically and experimentally implementing a 'thoughtful' agent using a framework from cognitive science, specifically active inference running on a free-energy principle.
There are two issues with 'observers' within current quantum models:

- The lack of cognitive architectures and agency within the observers.
- The lack of a quantum-classical transition

The Free-Energy Principle I

The classical free-energy principle provides a postulate on which to build an agent,[8] which has found great success. It is based on physical ideas, such as the least-action principle.[9]

Free Energy Principle

Cognitive agents seek to reduce uncertainty by minimizing their free energy based on internal models and sensory feedback.

The FEP is akin to Bayesian inference.
Mathematically,

$$F(s,\mu) = D_{\mathrm{KL}}[q(\psi|\mu)||p(\psi|m)] - E_q[\log p(s|\psi,m)] \qquad (1)$$

8. Oostrum, Langer, and Ay, "A concise mathematical description of active inference in discrete time."

9. Friston, *A free energy principle for a particular physics*.

The Holographic Principle I

We begin with something called the General Holographic Principle.

Generalized Holographic Principle

If $U = AB$ is a finite closed system, then if $|AB\rangle$ is separable, the classical information exchange between A and B is limited to N bits, where N is the dimension of the interaction Hamiltonian H_{AB}.

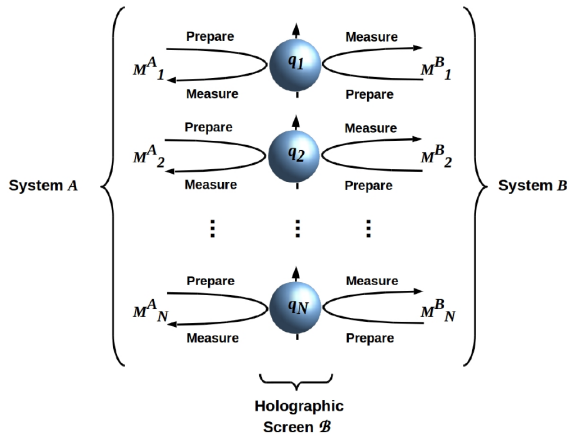


Figure 1: A holographic screen $\mathscr{B}$ separating systems A and B with an interaction H_{AB} given by Eq. (6) can be realized by an ancillary array of noninteracting qubits that are alternately prepared by A (B) and then measured by B (A). Qubits are depicted as Bloch spheres [27]. There is no requirement that A and B share preparation and measurement bases, i.e. QRFs. Adapted from [38] Fig. 1, CC-BY license.

Quantum Reference Frames I

We can break down the reference frames for each qubit into three sections.

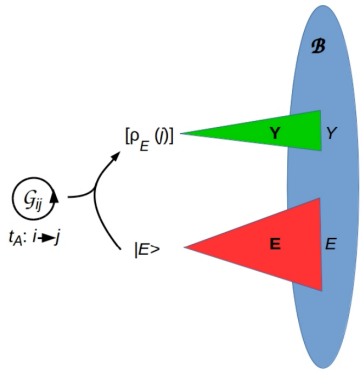


Figure 3: Cartoon illustration of QRFs required to write a readable memory of an observed environmental state $|E\rangle$. The QRFs **E** and **Y** read the state from E and write it to Y respectively. The clock $\mathcal{G}_{ij}$ is a time QRF that defines the time coordinate t_A.

Quantum Reference Frames II

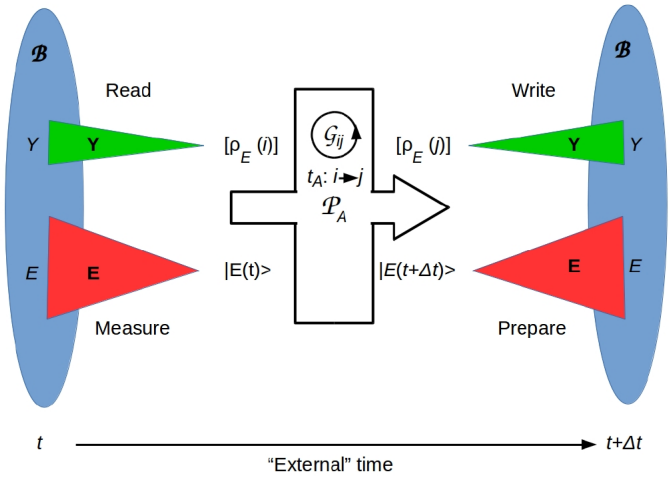


Figure 4: Cartoon illustration of one memory read-compare-write cycle defining one tick $i \to j$ of the internal clock $\mathcal{G}_{ij}$ and requiring an interval Δt of "external" time t. All QRFs and the comparison function are implemented by the quantum dynamics $\mathcal{P}_A$ (block arrow).

We can extend this to the entire measure and prepare cycle.

A Quantum-Theoretic Renovation

We can thus rewrite the free energy equation to

Quantum FEP

$$Er_X(k) = d(\mathcal{M}_X^A(k), \mathcal{M}_X(k))$$

where k represents the internal clock for the agent A, and $\mathcal{M}$ correspond to the observables that A could obtain. This represents the total reducible uncertainty about B at $t_A = k$, and as such, an upper bound on surprisal.

Reframing Reality

What does this all mean?
By using an observer developed from cognitive scientific principles, we can derive another set of Bell Inequalities and determine if they are violated with this type of observer.
If these inequalities are violated, it would point toward a type of reality that is fundamentally relational.