Title: Decoherence: Out with States, In with Causation

Speakers: Nicholas Ormrod

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Abstract:

I introduce a modern perspective on decoherence informed by quantum causal modelling, situate it in its historical context, and show how it resolves two long-standing problems in traditional approaches.

Decoherence is often told as a story about states, focused on the suppression of off-diagonal terms in a density matrix through correlation with an environment. Yet this sits uneasily with a key observation already in Zurek (1981): the unitary dynamics alone determine the preferred basis. Recent advances in quantum causal modelling enable a genuinely dynamics-first account: define decoherence directly in terms of causal influence, formalized as noncommutation relations that specify which generators can affect which observables. On this view, diagonal density matrices, correlations, and other state-level features are mere symptoms of decoherence, while decoherence itself is a property of the unitary dynamics.

A major payoff of this causal account is that, rather than designating one piece of the universe as the “system” and the rest as the “environment,” one can treat decoherence more democratically, allowing different systems to serve as environments for each other. In turn, this democratic perspective yields a unique consistent set of histories for any subset of unitarily interacting subsystems, and thus addressing the critique of consistent histories by Dowker and Kent (1994) by separating physically meaningful histories from uninformative ones.

Decoherence:
Out with States, in with Causation!

Nick Ormrod
Perimeter Institute
100 years of Quantum: Perspectives on its Past, Present, and Future

Preferred basis problem

$$\frac{1}{\sqrt{2}}\left|0\right\rangle_S + \frac{i}{\sqrt{2}}\left|1\right\rangle_S$$

$$\begin{aligned} H_{SA} &= I_S \otimes X_A - Z_S \otimes X_A \\ &= 2\left|1\right\rangle\left\langle 1\right|_S \otimes X_A \end{aligned}$$

$$\begin{aligned} &(\frac{1}{\sqrt{2}}\left|0\right\rangle_S + \frac{i}{\sqrt{2}}\left|1\right\rangle_S)\left|0\right\rangle_A \\ &\mapsto \ \left|\Psi\right\rangle_{SA} = \frac{1}{\sqrt{2}}\left|0\right\rangle_S\left|0\right\rangle_A + \frac{1}{\sqrt{2}}\left|1\right\rangle_S\left|1\right\rangle_A \\ &\qquad\qquad = \tfrac{1}{\sqrt{2}}\left|+\right\rangle_S\left|+\right\rangle_A + \tfrac{1}{\sqrt{2}}\left|-\right\rangle_S\left|-\right\rangle_A , \end{aligned}$$

Preferred basis solution

$$H_{AE} = I_A \otimes X_E - Z_A \otimes X_E$$

$$\frac{1}{\sqrt{2}}(|0\rangle_S |0\rangle_A + |1\rangle_S |1\rangle_A) |0\rangle_E$$
$$\mapsto |\Phi\rangle_{SAE} = \frac{1}{\sqrt{2}} |0\rangle_S |0\rangle_A |0\rangle_E - \frac{i}{\sqrt{2}} |1\rangle_S |1\rangle_A |1\rangle_E$$

$$\begin{aligned}\rho_{SA} &= \mathrm{Tr}_E |\Phi\rangle \langle\Phi|_{SAE} \\ &= \frac{1}{2} |0\rangle \langle 0|_S \otimes |0\rangle \langle 0|_A + \frac{1}{2} |1\rangle \langle 1|_S \otimes |1\rangle \langle 1|_A \\ &= \begin{bmatrix} \frac{1}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2} \end{bmatrix}\end{aligned}$$

Pointer basis of quantum apparatus: Into what mixture does the wave packet collapse?

W. H. Zurek

Center for Theoretical Physics, The University of Texas at Austin, Austin, Texas 78712
*and California Institute of Technology, Pasadena, California 91125**

(Received 3 April 1981)

The form of the interaction Hamiltonian between the apparatus and its environment is sufficient to determine which observable of the measured quantum system can be considered "recorded" by the apparatus. The basis that

Zurek's 1981 insight

$$H_{AE} = I_A \otimes X_E - \underbrace{Z_A \otimes X_E}_{H_{\text{int}}}$$

$$[M_A \otimes I_E,\ H_{\text{int}}] = 0 \quad \Longleftrightarrow \quad \exists a, b \in \mathbb{C}:\ M_A = a\,|0\rangle\,\langle 0|_A + b\,|1\rangle\,\langle 1|_A$$

$$\therefore\ \text{pointer basis} = \{|0\rangle_A\,, |1\rangle_A\}\ ✓$$

A question

Given that the unitary dynamics alone determine a preferred basis, why does Zurek conceptualize the preferred basis in terms of states?

What is decoherence?

"[D]iagonality alone is only a symptom–and not a cause–of the effective classicality of the preferred states. And, as all symptoms, it has to be used with caution in diagnosing its origin: Causes of diagonality may, on occasion, differ from those relevant for the dynamics of the process of decoherence..." (Zurek, 1993)

What is decoherence?

"I feel that the term ***decoherence*** *is best reserved for the* ***process*** *which destroys quantum coherence when a system becomes correlated with other degrees of freedom." (Zurek, 1994)*

Another question

Why does Zurek define the process of decoherence in terms of its state-level symptoms, rather than directly in terms of the Hamiltonian responsible for them?

In with causation...

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Quantum Common Causes and Quantum Causal Models

John-Mark A. Allen,[1] Jonathan Barrett,[1] Dominic C. Horsman,[2] Ciarán M. Lee,[3] and Robert W. Spekkens[4]

Quantum Causal Models

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Cyclic quantum causal models

Jonathan Barrett [1], Robin Lorenz [1,2] ✉ & Ognyan Oreshkov[3]

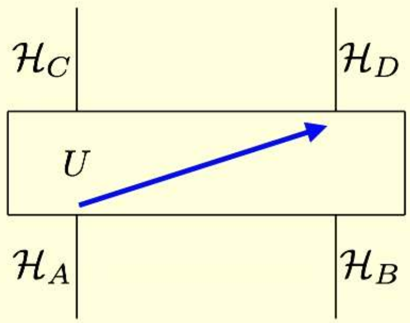
Causal structure in the presence of sectorial constraints, with application to the quantum switch

Nick Ormrod[1], Augustin Vanrietvelde[1,2,3], and Jonathan Barrett[1]

Quantum influences and event relativity

Nick Ormrod* and Jonathan Barrett†
Quantum Group, Department of Computer Science, University of Oxford

In with causation...



$$\mathcal{A} = \mathcal{L}(\mathcal{H}_A) \otimes I_B$$
$$\mathcal{D} = U^\dagger \big(I_C \otimes \mathcal{L}(\mathcal{H}_D)\big) U$$

$$M_A \in \mathcal{A} \text{ influences } \mathcal{D} \iff M_A \notin \mathcal{D}'$$
$$M_A \in \mathcal{A} \text{ accessible to } \mathcal{D} \iff \Big(\forall G_A \in \mathcal{A} : \quad [M_A, G_A] \neq 0 \implies G_A \notin \mathcal{D}'\Big)$$

1. The complete set of **non**influencing operators forms an algebra $\mathcal{A}_{\text{aut}}$.
2. The complete set of accessible operators form an algebra $\mathcal{A}_{\text{acc}}$.
3. Each algebra is the commutant of the other: $\mathcal{A}_{\text{acc}} = \mathcal{A} \cap \mathcal{A}'_{\text{aut}}$, $\mathcal{A}_{\text{aut}} = \mathcal{A} \cap \mathcal{A}'_{\text{acc}}$

In with causation...

$$\text{decoherence} \quad = \quad \text{noninfluence} \quad + \quad \text{accessibility}$$

$$\mathcal{A}_{\text{dec}} = \mathcal{A}_{\text{aut}} \cap \mathcal{A}_{\text{acc}}$$

commutative

$$\exists \text{ unique } \; \mathcal{H}_A = \bigoplus_i \mathcal{H}_A^i : \qquad M_A \in \mathcal{A}_{\text{dec}} \quad \Longleftrightarrow \quad M_A = \sum_i c_i \pi_A^{(i)}$$

Back to our example

$$e^{-iH_{SA}t} = |0\rangle\langle 0|_S \otimes I_A + |1\rangle\langle 1|_S \otimes e^{-i2X_A t}$$

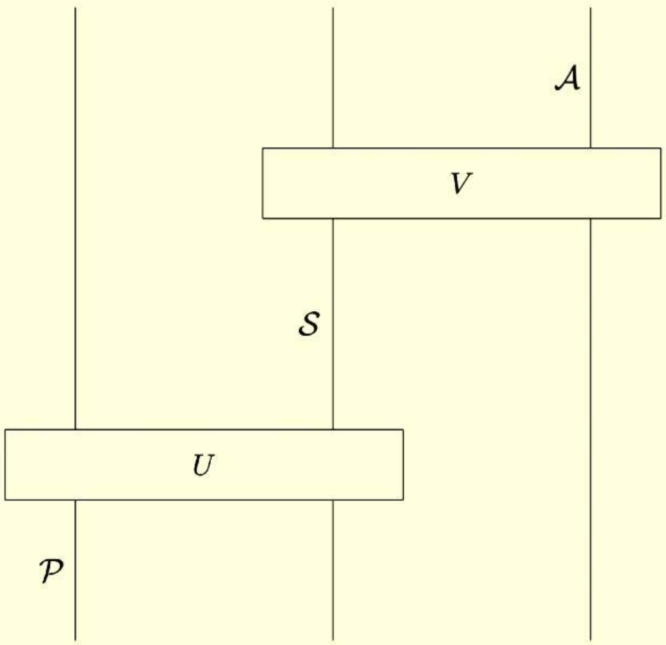
$$\mathcal{S}_{\text{aut}} = \{a\,|0\rangle\langle 0|_S \otimes I_A + b\,|1\rangle\langle 1|_S \otimes I_A\}$$

$$\mathcal{S}_{\text{acc}} = \{a\,|0\rangle\langle 0|_S \otimes I_A + b\,|1\rangle\langle 1|_S \otimes I_A\}$$

$$\mathcal{S}_{\text{dec}} = \{a\,|0\rangle\langle 0|_S \otimes I_A + b\,|1\rangle\langle 1|_S \otimes I_A\}$$

$$\implies \{|0\rangle_S\,, |1\rangle_S\} \text{ preferred}$$ ✓

Decoherence in unitary circuits



$$\mathcal{P}^{\downarrow}_{\text{aut}} = \mathcal{P} \cap \{\}' \quad \mapsto \quad \mathcal{H}_P = \bigoplus_{e_P^{\downarrow}} \mathcal{H}_P^{e_P^{\downarrow}}$$

$$\mathcal{P}^{\uparrow}_{\text{aut}} = \mathcal{P} \cap (\mathcal{S} \vee \mathcal{A})' \quad \mapsto \quad \mathcal{H}_P = \bigoplus_{e_P^{\uparrow}} \mathcal{H}_P^{e_P^{\uparrow}}$$

$$\mathcal{S}^{\downarrow}_{\text{aut}} = \mathcal{S} \cap \mathcal{P}' \quad \mapsto \quad \mathcal{H}_S = \bigoplus_{e_S^{\uparrow}} \mathcal{H}_S^{e_S^{\uparrow}}$$

$$\mathcal{S}^{\uparrow}_{\text{aut}} = \mathcal{S} \cap \mathcal{A}' \quad \mapsto \quad \mathcal{H}_S = \bigoplus_{e_S^{\downarrow}} \mathcal{H}_S^{e_S^{\downarrow}}$$

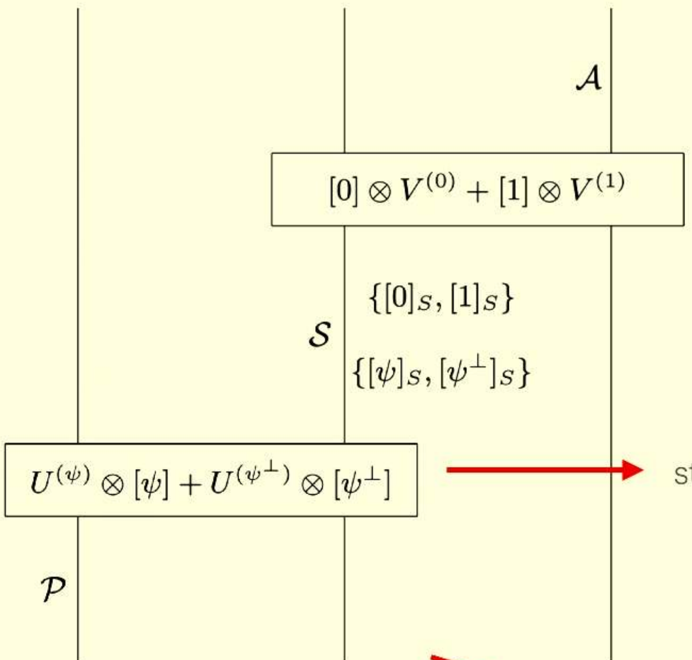
$$\mathcal{A}^{\downarrow}_{\text{aut}} = \mathcal{A} \cap (\mathcal{P} \vee \mathcal{S})' \quad \mapsto \quad \mathcal{H}_A = \bigoplus_{e_A^{\uparrow}} \mathcal{H}_A^{e_A^{\uparrow}}$$

$$\mathcal{A}^{\uparrow}_{\text{aut}} = \mathcal{A} \cap \{\}' \quad \mapsto \quad \mathcal{H}_A = \bigoplus_{e_A^{\downarrow}} \mathcal{H}_A^{e_A^{\downarrow}}$$

these preferred decompositions always define a consistent history set

$$p(e_P^{\downarrow}, e_P^{\uparrow}, e_S^{\downarrow}, e_S^{\uparrow}, e_A^{\downarrow}, e_A^{\uparrow}) = \frac{1}{d}\mathrm{Tr}(\pi_P^{\downarrow e_P^{\downarrow}} \pi_P^{\uparrow e_P^{\uparrow}} \pi_S^{\downarrow e_S^{\downarrow}} \pi_S^{\uparrow e_S^{\uparrow}} \pi_A^{\downarrow e_A^{\downarrow}} \pi_A^{\uparrow e_A^{\uparrow}})$$

Out with states!



state preparation

hence no need for input state

$$p(e_S^{\uparrow} = k | e_S^{\downarrow} = \psi) \quad = \quad |\langle k|\psi\rangle|^2$$

all quantum predictions reproduced in this formalism, so we get a complete dynamics-first interpretation of quantum theory!

Quantum influences and event relativity

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