OWEN MARONEY

No Fleas on Schrodinger

How insoluble is the measurement problem?

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UNIVERSITY OF CAMBRIDGE
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No Fleas on Schrodinger

- What is the Measurement Problem?
  - Why are so many convinced it is insoluble?
  - And what does that mean?
- Instability and classical states.
  - How the flea on Schrodinger's cat seems to avoid the comb of insolubility proofs.
- Or does it?
  - The cat scratches back at the flea.

The
(Traditional)
Measurement Problem

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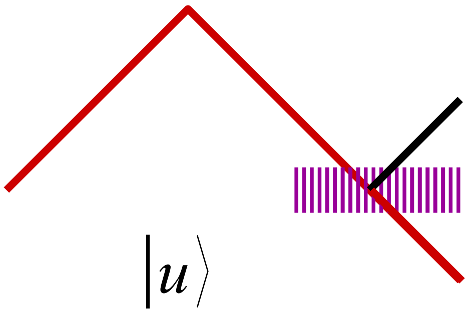
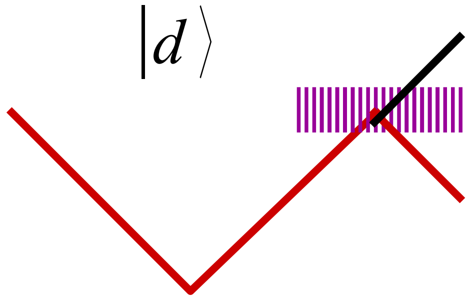
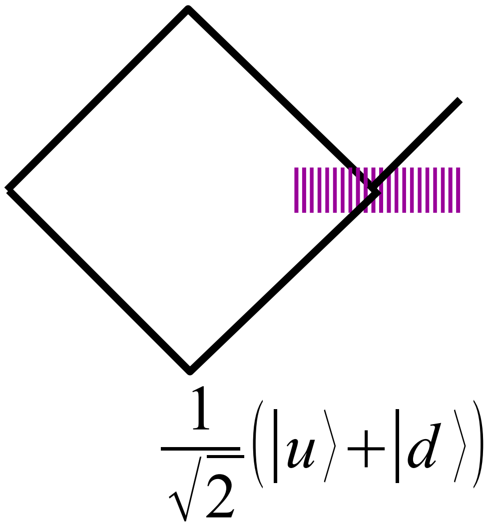
Quantum superposition is not statistical mixture...







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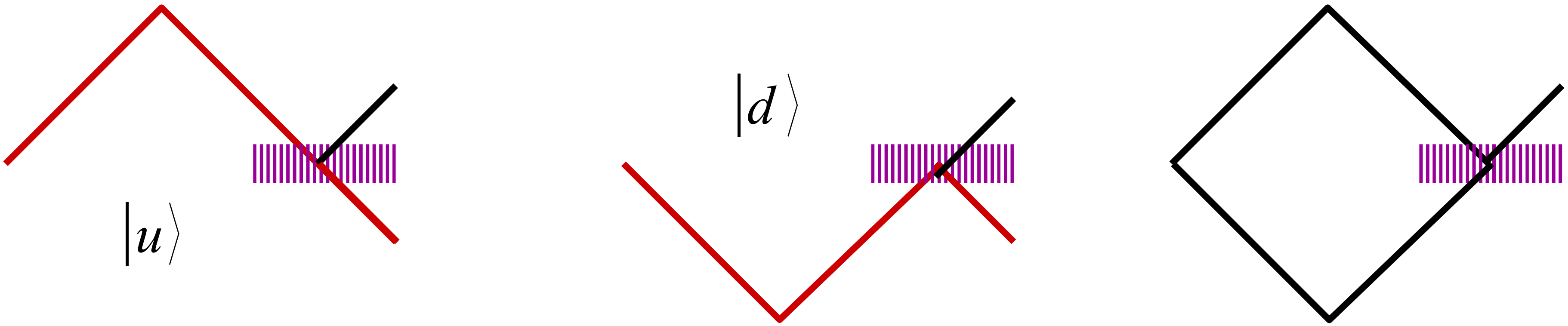

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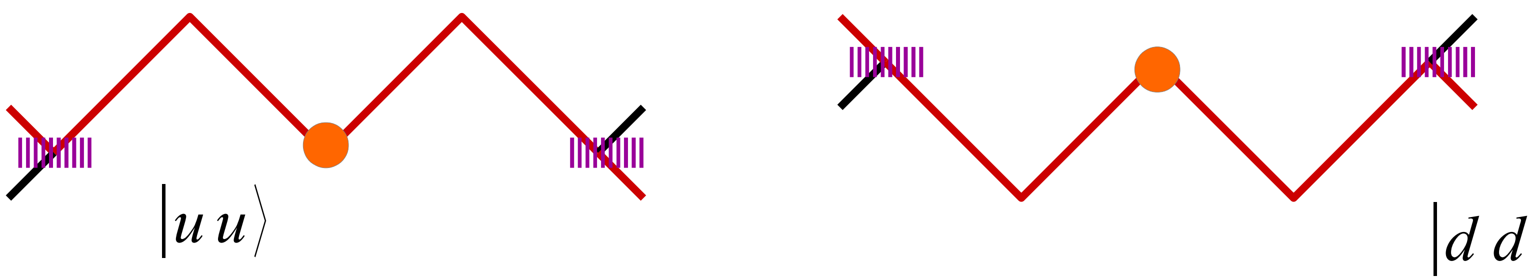
... even when it is an entangled superposition.



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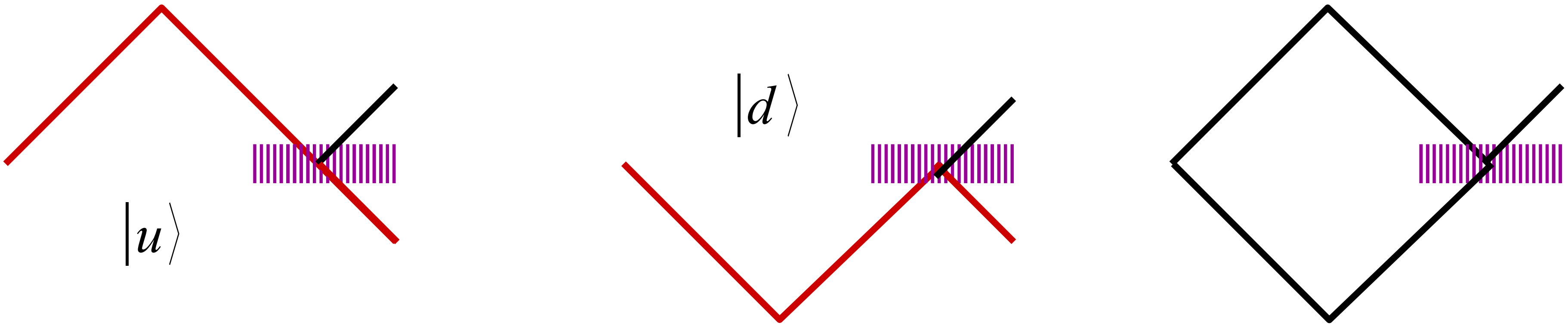

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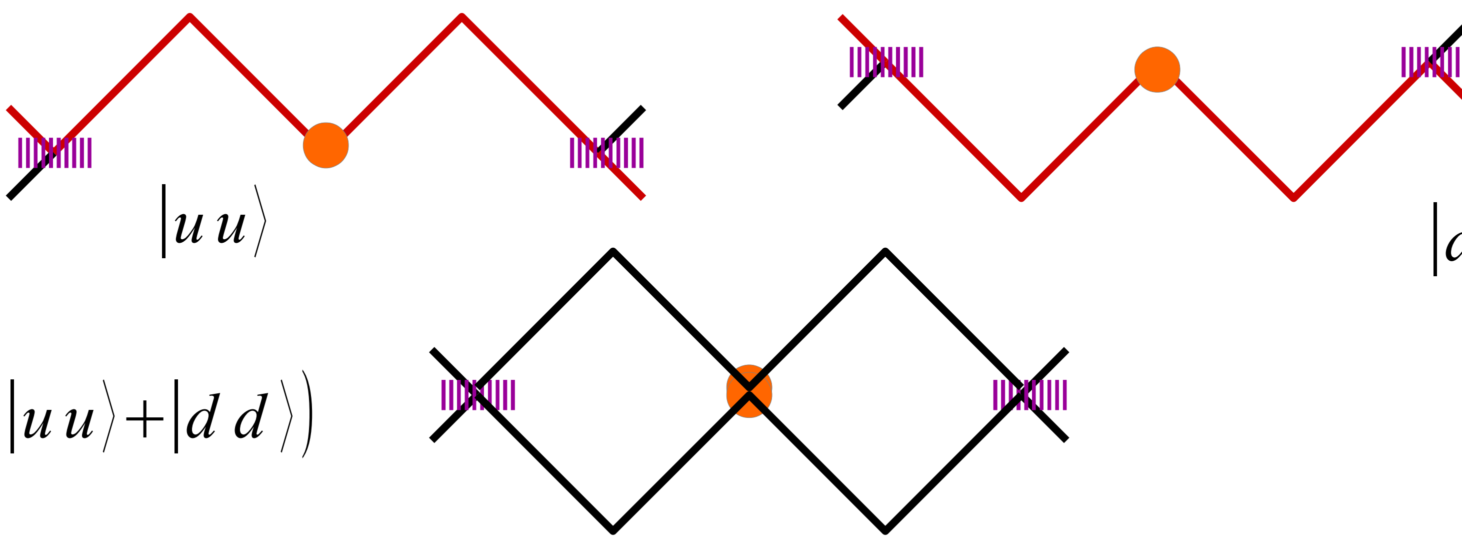

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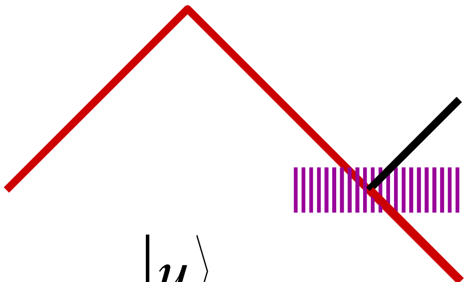

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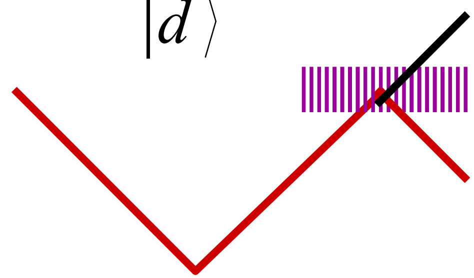

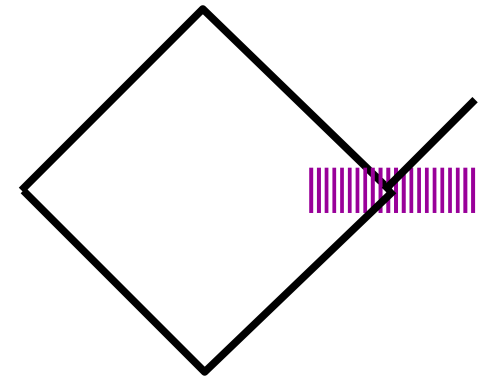

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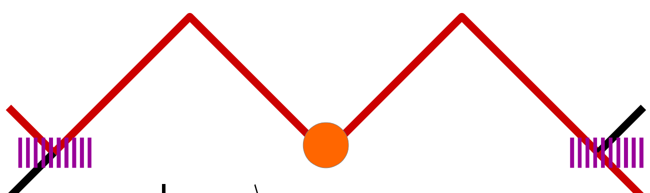

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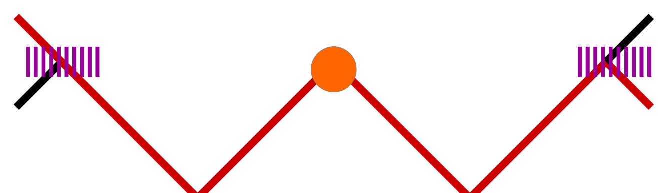

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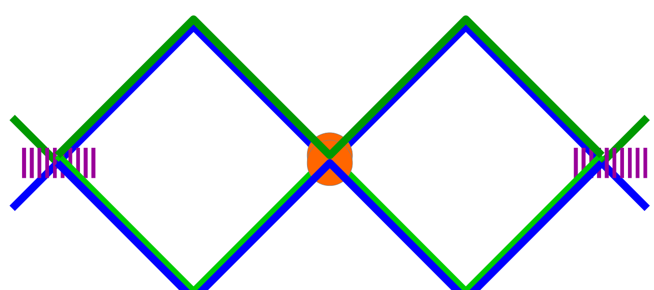

The (Traditional) Measurement Problem

1. Quantum mechanics is fundamental.
   Any measuring device is a quantum system

$$|M_0\rangle|u\rangle \to |M(u)\rangle|u\rangle$$

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3. Quantum mechanics is (still) fundamental.
   Dynamic evolution is Unitary

$$|M_0\rangle\left[\alpha_u|u\rangle + \alpha_d|d\rangle\right] \rightarrow \alpha_u|M(u)\rangle|u\rangle + \alpha_d|M(d)\rangle|d\rangle$$

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$$|M(u)\rangle \quad |\alpha_u|^2 \qquad \text{or} \qquad |M(d)\rangle \quad |\alpha_d|^2$$

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Superposition is not a mixture even when it is an entangled superposition.

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$$\alpha_u |M(u)\rangle |u\rangle + \alpha_d |M(d)\rangle |d\rangle$$

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  - Only one object exists (the wavefunction)
  - Only one evolution takes place (unitary)
  - Only one outcome occurs

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Most consistent attempts to interpret quantum theory follow (sometimes only implicitly) one or more of these strategies

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All consistent attempts to interpret quantum theory follow (sometimes only implicitly) one or more of these strategies?

The (Traditional) Measurement Problem

- Note!
  - Avoiding or embracing the trilemma is *not sufficient* to have an adequate quantum theory of measurement.
  - An adequate quantum theory of measurement must
    - Account for the appearance of a statistical mixture of outcomes
    - Account for their occurrence with Born rule frequencies

The (Traditional) Measurement Problem

But is all this even necessary?

Quantum mechanics is fundamental. Measuring device is a quantum system.

Not $|M_0\rangle$ but $\rho_M(0) = \sum_i w_i |M_{0,i}\rangle\langle M_{0,i}|$ $\qquad |\Psi(\alpha)\rangle = [\alpha_u|u\rangle + \alpha_d|d\rangle]$

$\rho_F(\alpha) = U\rho_M(0) \otimes |\Psi(\alpha)\rangle\langle\Psi(\alpha)| U^\dagger$ ***is*** a statistical mixture!

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Enter the insolubility proofs.

1. State equivalence: there are no $p(n),\, p(i|n)$ such that

$$\rho_F(\alpha)=\sum_{i,n} P(n)P(i|n)|M_{n,i}\rangle\langle M_{n,i}|\otimes|n\rangle\langle n|$$

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2. State evolution.

$$U\left(|M_{0,i}\rangle|\Psi(0)\rangle\right)$$

$$U\left(|M_{0,i}\rangle|\Psi(1)\rangle\right)$$

$U\left(|M_{0,i}\rangle|\Psi(\alpha)\rangle\right)$ eigenstates of $(\hat{M}\otimes Id)$

$$Tr\left[(\hat{M}\otimes Id)\rho_F(\alpha)\right]\neq Tr\left[(\hat{M}\otimes Id)\rho_F(0)\right]$$

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$$U(|M_{0,i}\rangle|\Psi(\alpha)\rangle)=\alpha_u U(|M_{0,i}\rangle|\Psi(0)\rangle)+\alpha_d U(|M_{0,i}\rangle|\Psi(1)\rangle)$$

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Enter the insolubility proofs. $\qquad \mathcal{H}_{\mathcal{W}}=\mathcal{H}_{\mathcal{E}}\otimes\mathcal{H}_S\otimes\mathcal{H}_O$

1. State equivalence.
2. State evolution.
3. "State separation"

$\mathcal{A}_u$: all states in which u outcome observed

$\mathcal{A}_d$: all states in which d outcome observed

x in $\mathcal{A}_u$ and y in $\mathcal{A}_d$ are distinguishable: $|\langle x|y\rangle|^2<\epsilon\ll 1/2$

$U(|M_{0,i}\rangle|\Psi(0)\rangle)\in A_u \qquad U(|M_{0,i}\rangle|\Psi(1)\rangle)\in A_d \qquad U(|M_{0,i}\rangle|\Psi(\alpha)\rangle)\notin A_u\cup A_d$

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Not $|M_0\rangle$ but $\rho_M(0) = \sum_i w_i |M_{0,i}\rangle\langle M_{0,i}|$ $\quad |\Psi(\alpha)\rangle = [\alpha_u |u\rangle + \alpha_d |d\rangle]$

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1. State equivalence.
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4. No-signalling

$$|\Psi(\alpha)\rangle = [\alpha_u |u_1 u_2\rangle + \alpha_d |d_1 d_2\rangle]$$

$$U = e^{i(H_{M,1} \otimes Id_2)}$$

$$\rho_M(0) = p_u \rho_U + p_d \rho_d$$

$$U \rho_U \otimes |\Psi(\alpha)\rangle\langle\Psi(\alpha)| U^\dagger = \rho_M(u) \otimes |u_1 u_2\rangle\langle u_1 u_2|$$

The (Traditional) Measurement Problem

Insolubility proofs

1. State equivalence. *(von Neumann, Wigner et al.)*
2. State evolution. *(Fine, Brown et al.)*
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Common themes

- Environment is a density matrix.
- Ignorance interpretation of the density matrix.
- Real state is a pure state (system and environment)
- Single Unitary, used counterfactually.
- (1) & (2) Exact eigenstate of pointer observable.

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Insolubility proofs target an attempt to avoid the trilemma. Embracing the trilemma (by picking one of the known strategies) lies outside their scope.

Enter The Flea

Rethinking the problem: Instability and Classical States

Classical states and the flea

- Proposal:
  - Taking the classical limit $\hbar \rightarrow 0$
    - $|\Psi(q)\rangle$ ☛ $P(q)$
  - Quantum is still fundamental.

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    - $|\Psi(q)\rangle$ ☛ $P(q)$
  - Quantum is still fundamental.
  - Some pure quantum states have a classical limit which is a pure classical state.
    - $|\Psi(q)\rangle$ ☛ $\delta(q-x)$
  - Measurement outcomes should be quantum states in (approaching) a classical limit with a pure classical state

Classical states and the flea

- Problem:
  - Take the double well potential

$$|\Psi(u)\rangle \;☛\; \delta(a-x)$$

$$|\Psi(d)\rangle \;☛\; \delta(a+x)$$

$$|\Psi(1/2)\rangle \;☛\; \frac{1}{2}\delta(a-x)+\frac{1}{2}\delta(a+x)$$

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- Enter the Flea:
  - In the classical limit, small perturbations are amplified

$$V_u \qquad |\Psi(1/2)\rangle \;\text{☛}\; \delta(a-x)$$

$$V_d \qquad |\Psi(1/2)\rangle \;\text{☛}\; \delta(a+x)$$

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$$\frac{1}{\sqrt{2}}\left(|u\rangle + |d\rangle\right) ☛ \frac{1}{2}\delta(a-x) + \frac{1}{2}\delta(a+x)$$

$$\frac{1}{\sqrt{2}}\left(|u\rangle - |d\rangle\right) ☛ \frac{1}{2}\delta(a-x) + \frac{1}{2}\delta(a+x)$$

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$$\frac{1}{\sqrt{2}}\left(\left|u\right\rangle+\left|d\right\rangle\right) \;☛\; \frac{1}{2}\delta(a-x)+\frac{1}{2}\delta(a+x)$$

$$\frac{1}{\sqrt{2}}\left(\left|u\right\rangle-\left|d\right\rangle\right) \;☛\; \frac{1}{2}\delta(a-x)+\frac{1}{2}\delta(a+x)$$

    - In the classical limit, these states become indistinguisable by the classical observables
    - Fine grained quantum detail may remain?

An Itch to Scratch

An Itch Requiring Scratching

- Get the Born rule right?

$$V_u \quad |\Psi(1/2)\rangle \;☛\; \delta(a-x)$$

$$V_d \quad |\Psi(1/2)\rangle \;☛\; \delta(a+x)$$

Probabilities come from probabilities of *perturbation*, not the state

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Probabilities come from probabilities of *perturbation*, not the state

$$|\Psi(\alpha)\rangle \;☛\; |\alpha_u|^2\delta(a-x)+|\alpha_d|^2\delta(a+x)$$

Need:

$$V_u \quad |\Psi(\alpha)\rangle \;☛\; \delta(a-x) \qquad |\alpha_u|^2$$

with

$$V_d \quad |\Psi(\alpha)\rangle \;☛\; \delta(a+x) \qquad |\alpha_d|^2$$

Need a spectrum of fluctuations, affecting each state differently.

An Itch Requiring Scratching

- Get the Born rule right?

$V_u \quad |\Psi(1/2)\rangle$ ☛ $\delta(a-x)$

$V_d \quad |\Psi(1/2)\rangle$ ☛ $\delta(a+x)$

Probabilities come from probabilities of *perturbation*, not the state

$|\Psi(\alpha)\rangle$ ☛ $|\alpha_u|^2\delta(a-x)+|\alpha_d|^2\delta(a+x)$

Need:

$V_u \quad |\Psi(\alpha)\rangle$ ☛ $\delta(a-x)$ with $|\alpha_u|^2$

$V_d \quad |\Psi(\alpha)\rangle$ ☛ $\delta(a+x)$ with $|\alpha_d|^2$

Need a spectrum of fluctuations, affecting each state differently.

But still need to keep:

$|\Psi(u)\rangle$ ☛ $\delta(a-x)$ $\qquad$ $|\Psi(d)\rangle$ ☛ $\delta(a+x)$

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For each $\quad |\Psi(\alpha)\rangle$ ☛ $|\alpha_u|^2 \delta(a-x) + |\alpha_d|^2 \delta(a+x)$

$$\{V_i\} = \{V_i(u \ |\alpha)\} \cup \{V_i(d \ |\alpha)\}$$

Need

$V_i(u \ |\alpha) \qquad |\Psi(\alpha)\rangle$ ☛ $\delta(a-x) \quad |\alpha_u \ |^2 = \sum_i p_i(u \ |\alpha)$

$V_i(d \ |\alpha) \qquad |\Psi(\alpha)\rangle$ ☛ $\delta(a+x) \quad |\alpha_d \ |^2 = \sum_i p_i(d \ |\alpha)$

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Need a spectrum of fluctuations, affecting each state differently.

$$V_i \qquad p_i$$

For each $\left|\Psi(\alpha)\right\rangle$ ☛ $|\alpha_u|^2\delta(a-x)+|\alpha_d|^2\delta(a+x)$

$$\{V_i\}=\{V_i(u\ |\alpha)\}\cup\{V_i(d\ |\alpha)\}$$

Need

$V_i(u\ |\alpha)$ $\quad \left|\Psi(\alpha)\right\rangle$ ☛ $\delta(a-x)$ $\quad |\alpha_u\ |^2=\sum_i p_i(u\ |\alpha)$

$V_i(d\ |\alpha)$ $\quad \left|\Psi(\alpha)\right\rangle$ ☛ $\delta(a+x)$ $\quad |\alpha_d\ |^2=\sum_i p_i(d\ |\alpha)$

If such a spectrum exists, *define*:

$$\rho_E=\sum_i p_i|\Phi_i\rangle\langle\Phi_i| \qquad H_E=H_0\otimes Id_E+\sum_i V_i\otimes|\Phi_i\rangle\langle\Phi_i| \qquad U_T=e^{iH_E t}$$

$U_T\rho_E\otimes|\Psi(\alpha)\rangle\langle\Psi(\alpha)|U_T^\dagger$ ☛ $\delta(a-x)$ $\quad |\alpha_u\ |^2=\sum_i p_i(u\ |\alpha)$

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Clearly now back in the realm of the earlier insolubility proofs.

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$$U_T \rho_E \otimes |\Psi(\alpha)\rangle\langle\Psi(\alpha)| U_T^\dagger \to \delta(a-x) \qquad |\alpha_u \ |^2 = \sum_i p_i (u \ |\alpha)$$

Clearly now back in the realm of the earlier insolubility proofs.

How do they fare?

1. State equivalence.
2. State evolution.
3. "State separation"
4. No-signalling

(1) & (2): Unclear. Both use exact eigenstates of the pointer observable, that may be avoidable by the classical limit.

(4) : Could be avoided by requiring the perturbation to have interesting non-local correlations.

An Itch Requiring Scratching

$$\rho_E = \sum_i p_i |\Phi_i\rangle\langle\Phi_i| \qquad H_E = H_0 \otimes Id_E + \sum_i V_i \otimes |\Phi_i\rangle\langle\Phi_i| \qquad U_T = e^{iH_E t}$$

$$U_T \rho_E \otimes |\Psi(\alpha)\rangle\langle\Psi(\alpha)| U_T^\dagger \text{☛} \delta(a-x) \qquad |\alpha_u\;|^2 = \sum_i p_i(u\;\,|\alpha)$$

"State Separation" Proof $\quad \mathcal{H}_{\mathcal{W}} = \mathcal{H}_{\mathcal{E}} \otimes \mathcal{H}_S \otimes \mathcal{H}_O$

$\mathcal{A}_u$: all states in which ***u*** outcome observed

$\mathcal{A}_d$: all states in which ***d*** outcome observed

x in $\mathcal{A}_u$ and ***y*** in $\mathcal{A}_d$ are distinguishable: $|\langle x|y\rangle|^2 < \epsilon \ll 1/2$

An Itch Requiring Scratching

$$\rho_E = \sum_i p_i |\Phi_i\rangle\langle\Phi_i| \qquad H_E = H_0 \otimes Id_E + \sum_i V_i \otimes |\Phi_i\rangle\langle\Phi_i| \qquad U_T = e^{iH_E t}$$

$$U_T \rho_E \otimes |\Psi(\alpha)\rangle\langle\Psi(\alpha)| U_T^\dagger \text{☛} \delta(a-x) \qquad |\alpha_u|^2 = \sum_i p_i (u \;|\alpha)$$

"State Separation" Proof $\mathcal{H}_W = \mathcal{H}_E \otimes \mathcal{H}_S \otimes \mathcal{H}_O$

$\mathcal{A}_u$: all states in which ***u*** outcome observed

$\mathcal{A}_d$: all states in which ***d*** outcome observed

x in $\mathcal{A}_u$ and ***y*** in $\mathcal{A}_d$ are distinguishable: $|\langle x|y\rangle|^2 < \epsilon \ll 1/2$

$$U(|i\rangle|\Psi(0)\rangle) \in A_u \qquad |\langle i, \Psi(0)| U_T^\dagger U_T |i, \Psi(\alpha)\rangle|^2 = |\alpha_u|^2 > \epsilon$$

$$U_T(|i\rangle|\Psi(1)\rangle) \in A_d \qquad |\langle i, \Psi(1)| U_T^\dagger U_T |i, \Psi(\alpha)\rangle|^2 = |\alpha_d|^2 > \epsilon$$

$$U_T(|i\rangle|\Psi(\alpha)\rangle) \notin A_u \cup A_d$$

An Itch Requiring Scratching

Recap: if there exists $V_i \quad p_i \qquad \{V_i\} = \{V_i(u \;|\alpha)\} \cup \{V_i(d \;|\alpha)\}$

$$|\Psi(\alpha)\rangle \;☛\; \delta(a-x) \qquad |\alpha_u \;|^2 = \sum_i p_i(u \;|\alpha)$$

Then there exists $\rho_E \quad U_T$

$$U_T \rho_E \otimes |\Psi(\alpha)\rangle\langle\Psi(\alpha)| U_T^{\dagger} ☛ \delta(a-x) \qquad |\alpha_u \;|^2 = \sum_i p_i(u \;|\alpha)$$

An Itch Requiring Scratching

Recap: if there exists V_i p_i $\{V_i\}=\{V_i(u|\alpha)\}\cup\{V_i(d|\alpha)\}$

$|\Psi(\alpha)\rangle$ ☛ $\delta(a-x)$ $|\alpha_u|^2=\sum_i p_i(u|\alpha)$

Then there exists ρ_E U_T

$U_T\rho_E\otimes|\Psi(\alpha)\rangle\langle\Psi(\alpha)|U_T^\dagger$ ☛ $\delta(a-x)$ $|\alpha_u|^2=\sum_i p_i(u|\alpha)$

But, state separation proof says

$|\langle i,\Psi(0)|U_T^\dagger U_T|i,\Psi(\alpha)\rangle|^2=|\alpha_u|^2>\epsilon$ not in $\mathcal{A}_d$

$|\langle i,\Psi(1)|U_T^\dagger U_T|i,\Psi(\alpha)\rangle|^2=|\alpha_d|^2>\epsilon$ not in $\mathcal{A}_u$

An Itch Requiring Scratching

Recap: if there exists V_i p_i $\{V_i\} = \{V_i(u\ |\alpha)\} \cup \{V_i(d\ |\alpha)\}$

$|\Psi(\alpha)\rangle$ ☛ $\delta(a-x)$ $|\alpha_u\ |^2 = \sum_i p_i(u\ |\alpha)$

Then there exists ρ_E U_T

$U_T \rho_E \otimes |\Psi(\alpha)\rangle\langle\Psi(\alpha)| U_T^\dagger$ ☛ $\delta(a-x)$ $|\alpha_u\ |^2 = \sum_i p_i(u\ |\alpha)$

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Taking the classical limit can increase (partial) indistinguisability
but it cannot increase (partial) distinguisability

An Itch Requiring Scratching

Recap: if there exists V_i p_i $\{V_i\} = \{V_i(u \ |\alpha)\} \cup \{V_i(d \ |\alpha)\}$

$|\Psi(\alpha)\rangle$ ☛ $\delta(a-x)$ $|\alpha_u \ |^2 = \sum_i p_i(u \ |\alpha)$

Then there exists ρ_E U_T

$U_T \rho_E \otimes |\Psi(\alpha)\rangle\langle\Psi(\alpha)| U_T^\dagger$ ☛ $\delta(a-x)$ $|\alpha_u \ |^2 = \sum_i p_i(u \ |\alpha)$

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Taking the classical limit can increase (partial) indistinguisability
but it cannot increase (partial) distinguisability

So ρ_E U_T cannot exist, so V_i p_i does not exist

An Itch Requiring Scratching

- Options
  - Generate the V_i by chancy random process?
    - No joy, it is just the existence of the p_i that matters

An Itch Requiring Scratching

- Options
  - Generate the V_i by chancy random process? No joy.
  - Make p_i state dependent?
    - Obvious choice $p_i(u|\alpha) = \left|\langle \Psi(0) | \Psi(\alpha) \rangle\right|^2$

An Itch Requiring Scratching

- Options
  - Generate the V_i by chancy random process? No joy.
  - Make p_i state dependent? eg. $p_i(u|\alpha) = \left|\langle \Psi(0) | \Psi(\alpha) \rangle\right|^2$
    - Correlating a noise field to the state

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = -\frac{\mathrm{i}}{\hbar}[H, \rho(t)] + \gamma \mathbf{A}\rho(t) \cdot \mathbf{A}^\dagger - \frac{\gamma}{2}\{\mathbf{A}^\dagger \cdot \mathbf{A}, \rho(t)\} \ . \qquad (7.51)$$

An Itch Requiring Scratching

- Options
  - Generate the V_i by chancy random process? No joy.
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$$\frac{\mathrm{d}}{\mathrm{d}t}|\phi(t)\rangle = \left[-\frac{\mathrm{i}}{\hbar}H + (\mathbf{A} - \mathbf{R}) \cdot \mathbf{V}(t) - \gamma(\mathbf{A} - \mathbf{R})^2 + \gamma(\mathbf{Q}^2 - \mathbf{R}^2)\right]|\phi(t)\rangle \ ,$$

$$\mathbf{R} = \langle \phi | \mathbf{A} | \phi \rangle \quad \mathbf{Q}^2 = \langle \phi | \mathbf{A}^2 | \phi \rangle \ . \qquad (7.43)$$

An Itch Requiring Scratching

- Options
  - Generate the V_i by chancy random process? No joy.
  - Make p_i state dependent? eg. $p_i(u|\alpha) = |\langle \Psi(0)|\Psi(\alpha)\rangle|^2$
    - Correlating a noise field to the state

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = -\frac{\mathrm{i}}{\hbar}[H, \rho(t)] + \gamma \mathbf{A}\rho(t)\cdot\mathbf{A}^\dagger - \frac{\gamma}{2}\{\mathbf{A}^\dagger\cdot\mathbf{A}, \rho(t)\} \; . \qquad (7.51)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}|\phi(t)\rangle = \left[-\frac{\mathrm{i}}{\hbar}H + (\mathbf{A}-\mathbf{R})\cdot\mathbf{V}(t) - \gamma(\mathbf{A}-\mathbf{R})^2 + \gamma(\mathbf{Q}^2 - \mathbf{R}^2)\right]|\phi(t)\rangle \; ,$$

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$$\mathbf{R} = \langle\phi|\mathbf{A}|\phi\rangle \qquad (7.43)$$

Dynamical reduction models

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An Itch Requiring Scratching

- Options
  - Generate the V_i by chancy random process? No joy.
  - Make p_i state dependent? $p_i(u|\alpha) = \left|\langle \Psi(0) | \Psi(\alpha) \rangle\right|^2$
    - Correlating a noise field to the state
      - eg. the GRW/CSL objective collapse strategy.
  - Correlate the environment to the state.

An Itch Requiring Scratching

- Options
  - Generate the V_i by chancy random process? No joy.
  - Make p_i state dependent? $p_i(u|\alpha) = |\langle\Psi(0)|\Psi(\alpha)\rangle|^2$
    - Correlating a noise field to the state
      - eg. the GRW/CSL objective collapse strategy.
  - Correlate the environment to the state.
    - Prepare $|\Psi(\alpha)\rangle$? Get $\rho_E(\alpha)$!
    - Actually avoids all the original insolubility proofs
    - Superdeterministic/retrocausal/conspiratorial

Conclusions

Conclusions

- Insolubility proofs target attempts to avoid the trilemma
  - They say nothing about embracing one of the strategies.
  - They target necessary, rather than sufficient, conditions
  - (Add a fourth strategy: superdetermination/retrocausal)
- State independant perturbations may avoid some insolubility proofs
  - (by being non-local and using the classical limit).
  - But they do not seem to avoid (implications of) the 'state separation' proof.
- State dependent perturbations might work.
  - But would do so by effectively embracing the objective collapse strategy.

Conclusions

Schrodinger's cat lives!

Conclusions

Schrodinger's cat lives!

Or doesn't ....

Conclusions

Schrodinger's cat lives!

Or doesn't ....

.... we don't really know ...

... that's sort of the point.