Title: Epistemic interpretations of quantum mechanics have a measurement problem

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Series: Quantum Foundations

Date: April 09, 2019 - 3:30 PM

URL: http://pirsa.org/19040084

Abstract: Epistemic interpretations of quantum theory maintain that quantum states only represent incomplete information about the physical states of the world. A major motivation for this view is the promise to provide a reasonable account of state update under measurement by asserting that it is simply a natural feature of updating incomplete statistical information. Here we demonstrate that all known epistemic ontological models of quantum theory in dimension d â‰¥ 3, including those designed to evade the conclusion of the PBR theorem, cannot represent state update correctly. Conversely, interpretations for which the wavefunction is real evade such restrictions despite remaining subject to long-standing criticism regarding physical discontinuity, indeterminism and the ambiguity of the Heisenberg cut. This revives the possibility of a no-go theorem with no additional assumptions, and demonstrates that what is usually thought of as a strength of epistemic interpretations may in fact be a weakness. We also discuss hidden Markov models and their relationship to ontological models, demarcating the ways in which one might move â€˜outsideâ€™ the ontological models formalism.

Epistemic interpretations of quantum theory have a measurement problem

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PI Foundations group seminar, April 9, 2019

arxiv:1812.08218

Interpreting quantum theory

Interpreting quantum theory

ψ-ontic

- The quantum state is an element of reality

ψ-epistemic

- The quantum state describes *knowledge* of reality

ψ-doxastic

- The quantum state describes *beliefs* of agents

Motivating state update

The prevailing view, as articulated by Matt Leifer:

- "A straightforward resolution of the collapse of the wavefunction, the measurement problem, Schrödinger's cat and friends is one of the main advantages of ψ-epistemic interpretations."

Outline

I. Review/introduce the ontological models (OM) formalism

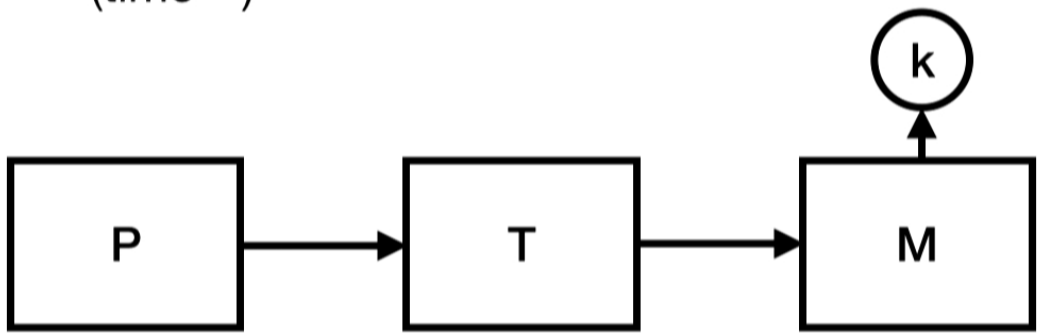
II. Restrictions on OMs from state update

III. Known ψ-epistemic OMs in $d \geq 3$ can't model state update

IV. OMs = HMMs (hidden Markov models)

Operational theories

(time→)

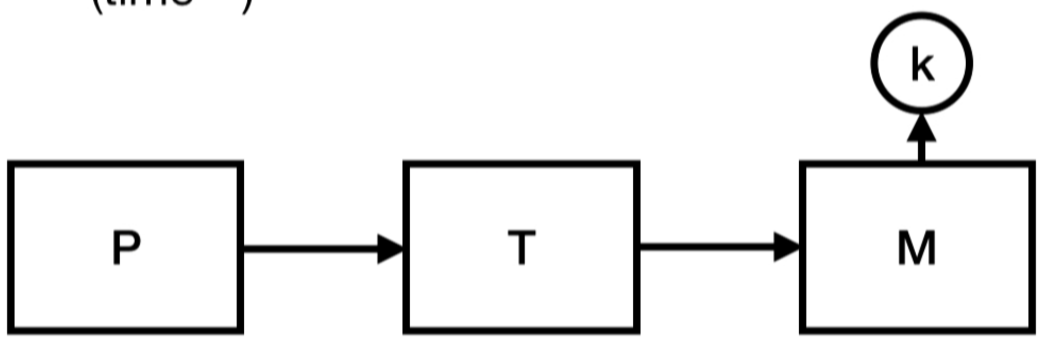


$$\Pr(k \mid M, T, P)$$

5

Operational theories

(time→)



$$\Pr(k \mid M, T, P)$$

$$P \in \mathscr{P}, \quad T \in \mathscr{T}, \quad M \in \mathscr{M}, \quad k \in \mathbb{Z}$$

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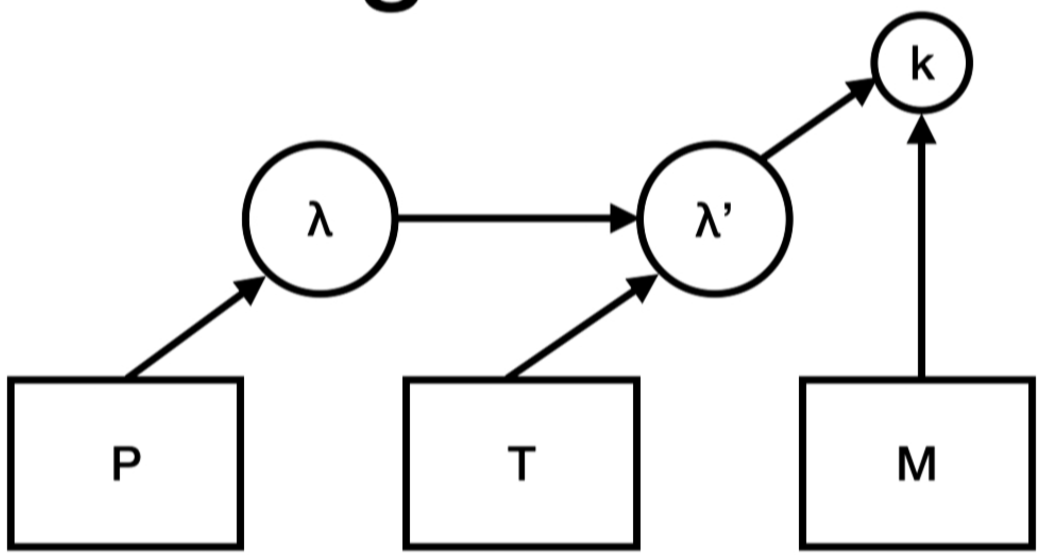
Ontological models



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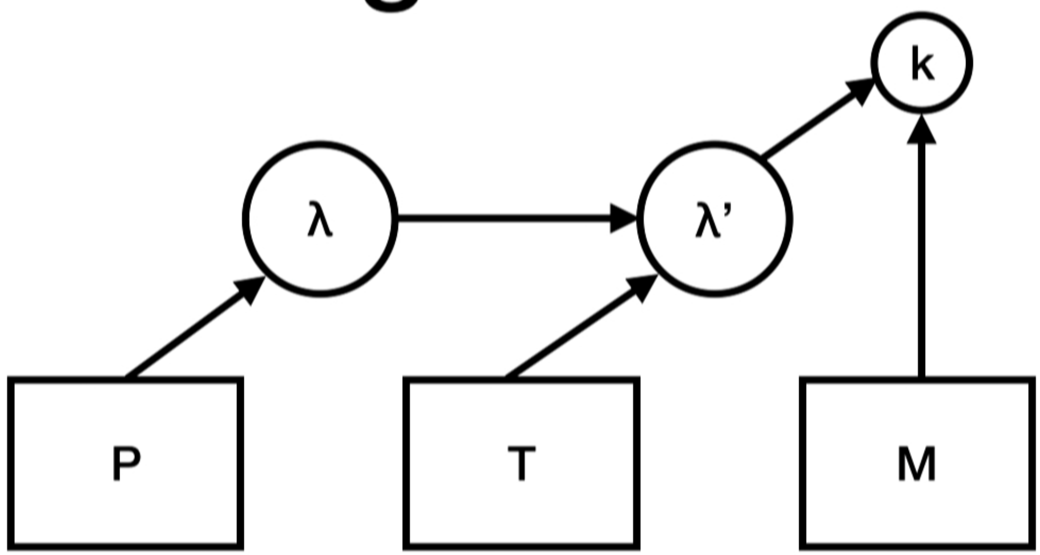
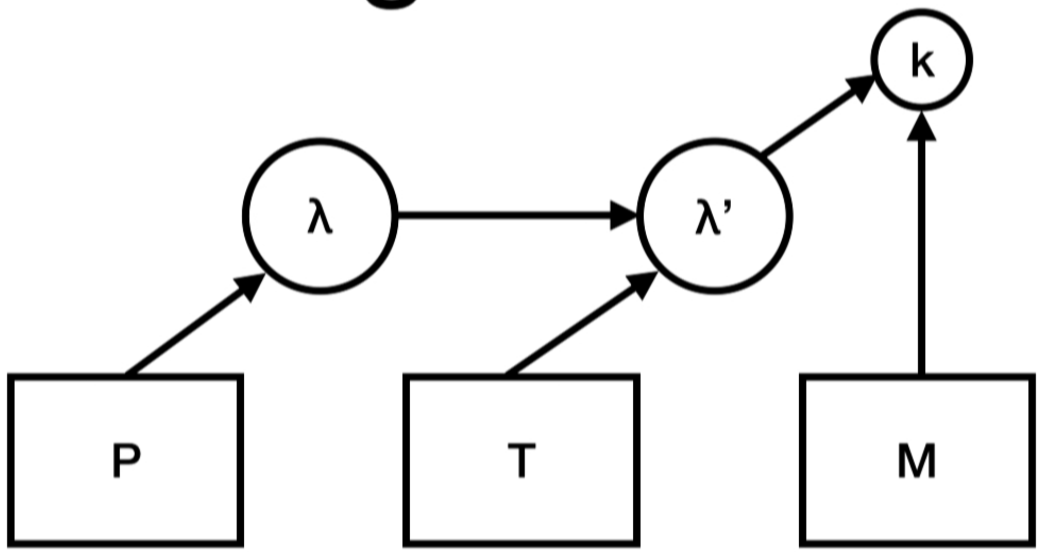
Ontological models



$$\lambda \in \Lambda, \quad \mu(\lambda\,|\,P), \quad \Gamma(\lambda'\,|\,\lambda, T), \quad \xi(k\,|\,\lambda', M)$$

Ontological models



$$\lambda \in \Lambda, \quad \mu(\lambda \,|\, P), \quad \Gamma(\lambda' \,|\, \lambda, T), \quad \xi(k \,|\, \lambda', M)$$

$$\int_\Lambda d\lambda \int_\Lambda d\lambda' \, \xi(k \,|\, \lambda', M)\Gamma(\lambda' \,|\, \lambda, T)\mu(\lambda \,|\, P) = \Pr(k \,|\, M, T, P)$$

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Supports

Definition 1: The *support of a preparation P* is

$$\mathbb{S}(\mu(\,\cdot\,|\,P)) = \{\lambda \in \Lambda\,|\,\mu(\lambda\,|\,P) > 0\}\,.$$

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$$\Delta_\psi = \bigcup_{P_\psi \in \mathscr{P}_\psi} \mathbb{S}(\mu(\,\cdot\,|\,P_\psi))\,.$$

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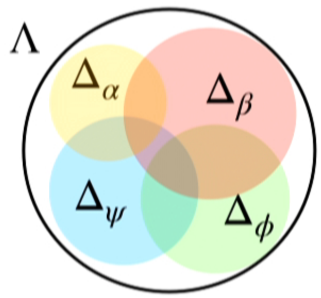
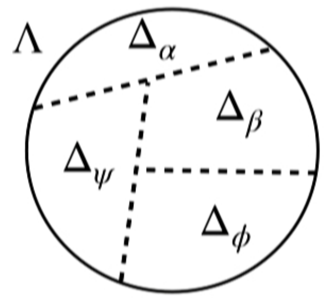
ψ-epistemic models

Definition 3: Two states ψ,ϕ are *ontologically indistinct* if

$$\Delta_\phi \cap \Delta_\psi \neq \varnothing \,.$$





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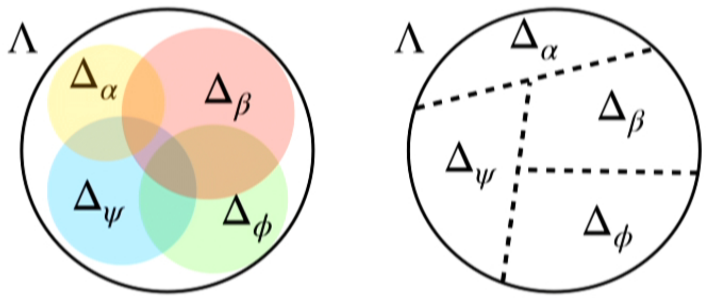

Definition 4: An OM is (minimally) *ψ-epistemic* if there exists a pair of nonidentical states that are ontologically indistinct.

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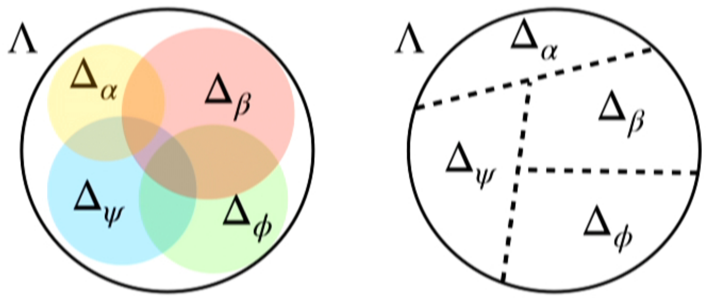

Definition 4: An OM is (minimally) *ψ-epistemic* if there exists a pair of nonidentical states that are ontologically indistinct.

Definition 5: An OM is *pairwise ψ-epistemic* if all pairs of nonorthogonal states are ontologically indistinct.

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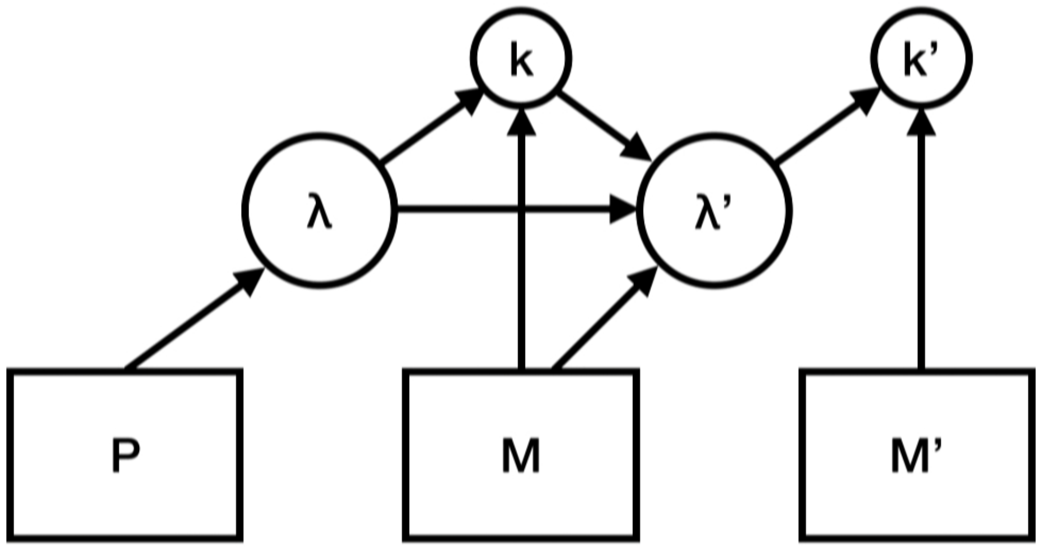
State update



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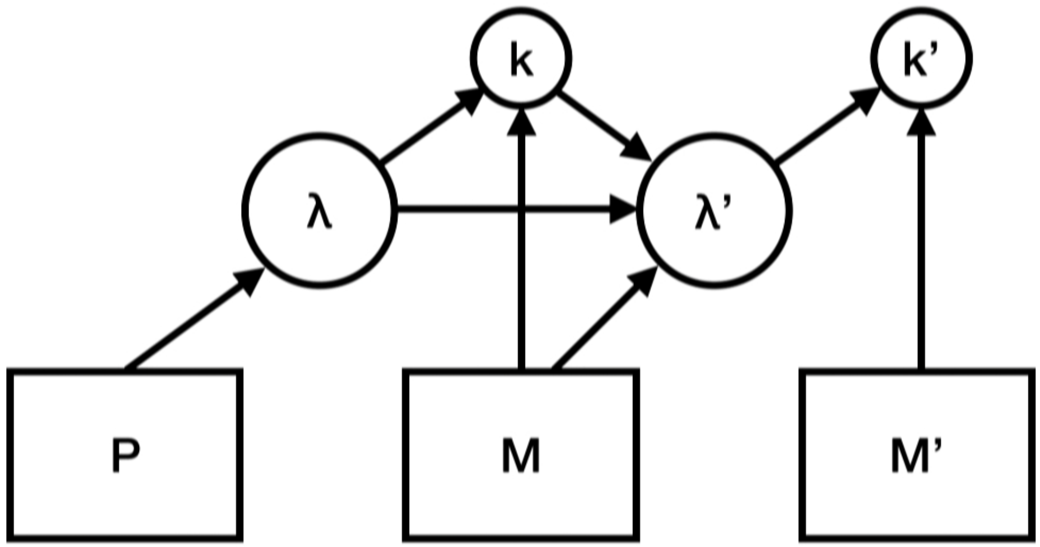
State update



$\eta(\lambda' \mid k, \lambda, M)$ for $\lambda \in \mathbb{S}(\xi(k \mid \cdot\,, M))$

Main results (2)

Theorem 1: If a projector Π maps two states to ontologically distinct states, then the response function for Π cannot have support on the overlap of these two states for any measurement context. Symbolically,

$$\Delta_{\Pi|\alpha\rangle} \cap \Delta_{\Pi|\beta\rangle} = \varnothing \implies \xi(\Pi \,|\, \lambda) = 0 \quad \forall \lambda \in \Delta_{\alpha} \cap \Delta_{\beta} \,.$$

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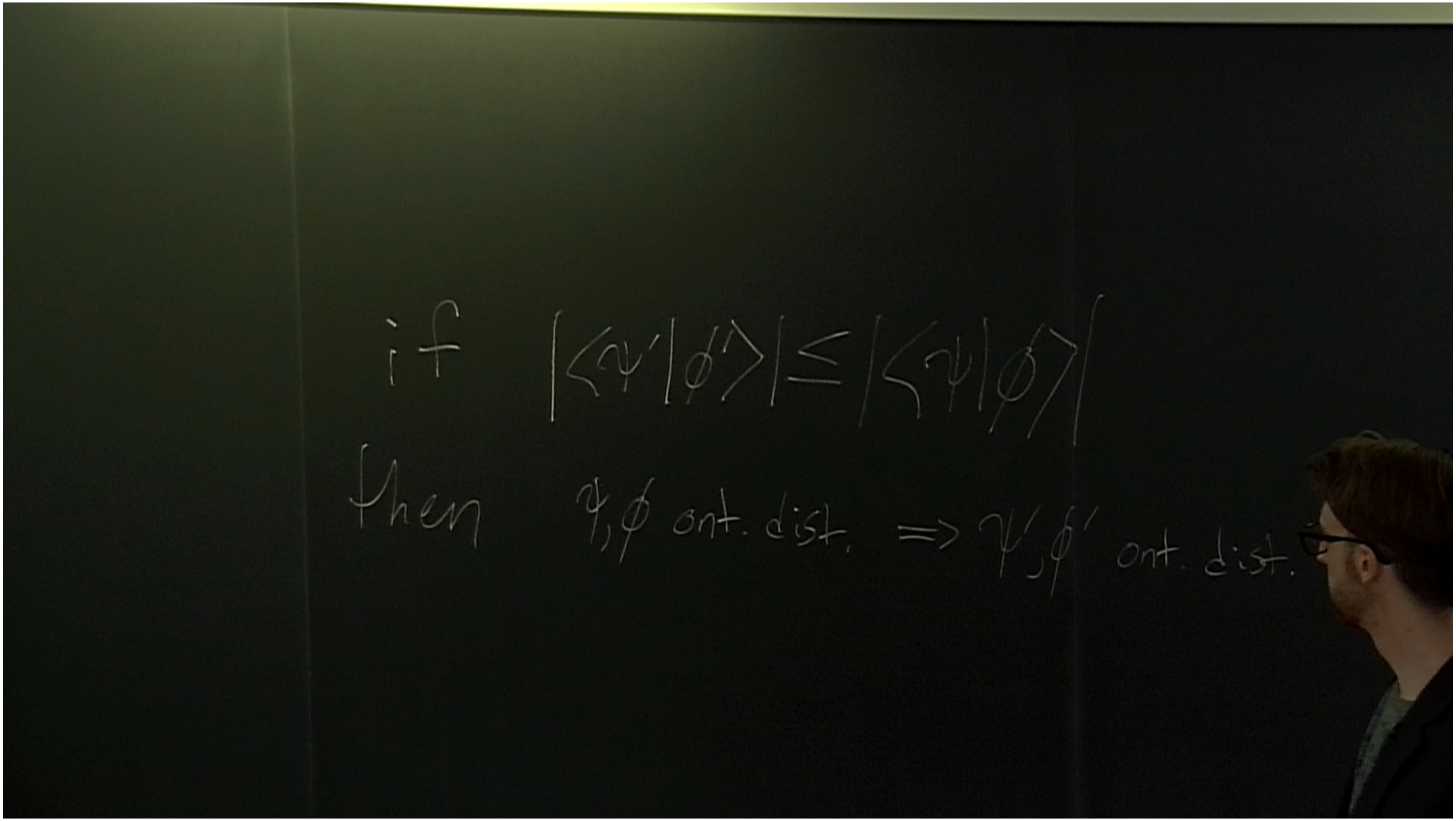
Compare to unitaries/transformations:

$$\Delta_{U|\alpha\rangle} \cap \Delta_{U|\beta\rangle} = \varnothing \implies \Delta_\alpha \cap \Delta_\beta = \varnothing \,.$$

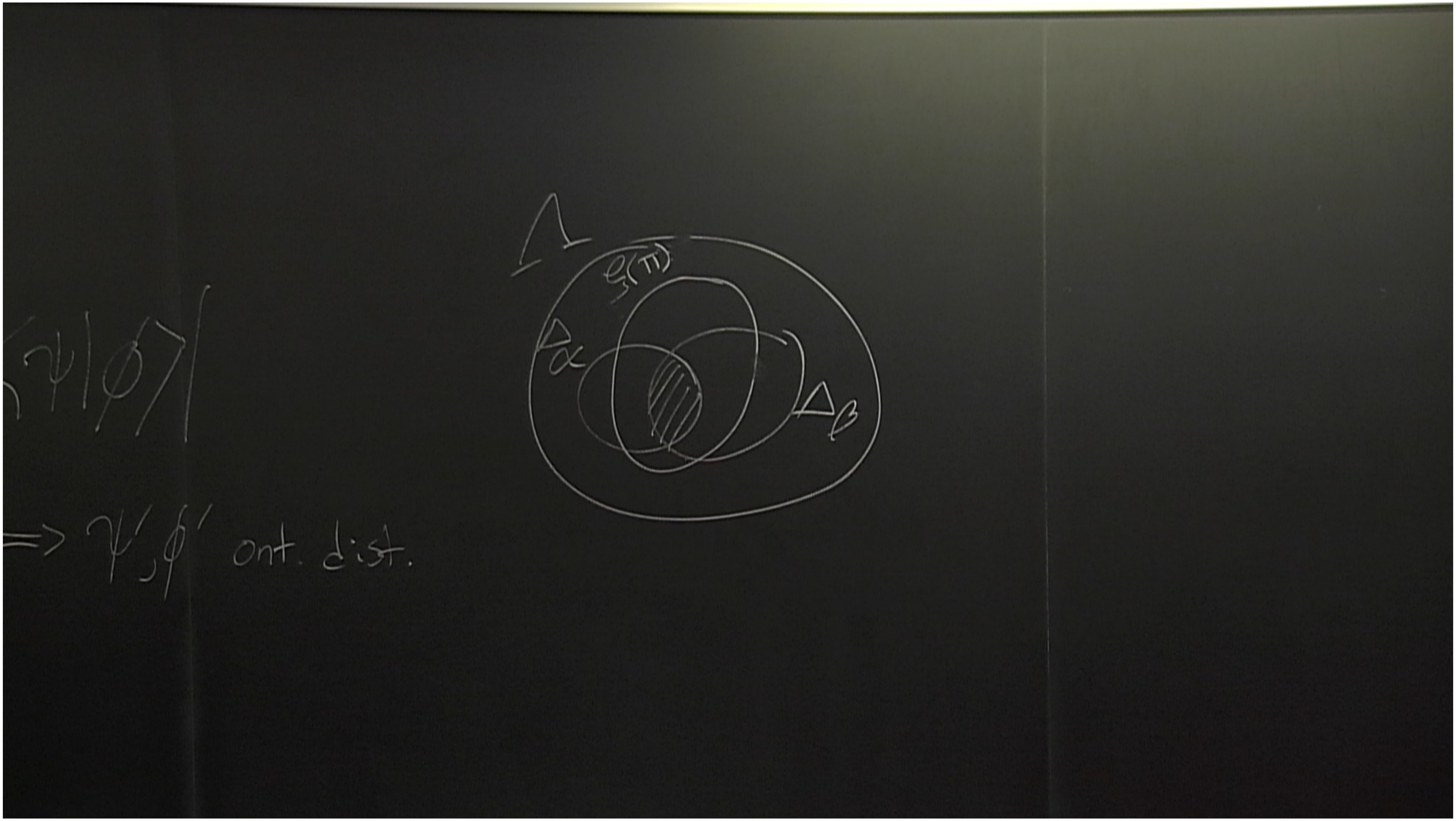

if $|\langle\psi'|\phi'\rangle| \leq |\langle\psi|\phi\rangle|$
then ψ,ϕ ont. dist. $\Rightarrow$ ψ',ϕ' ont. dist.

Known ψ-epistemic OMs can't reproduce state-update

All three known examples of ψ-epistemic models in $d \geq 3$ break:

- LJBR (not pairwise, full theory)
- ABCL (pairwise, full theory)
- Kitchen sink (pairwise, arbitrary finite subtheories)

Pick arbitrary pair of (ont. indistinct) states α,β → Construct projector Π that maps to ont. distinct states, so by Thm 1 $\xi=0$ on overlap → From model def., show $\xi=1$ on overlap → Contradiction, QED


⟨ψ|φ⟩|
⟹ ψ', φ' ont. dist.
Λ
Δα
Δβ

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The stabilizer subtheory still supports ψ-epistemic models:

- *n*-quo*p*it via Wigner function
- *n*-qubit via Lillystone & Emerson (forthcoming)

A note on transformations

Including transformations also restricts epistemic theories further than prepare-measure-once:

- LJBR cannot represent transformations
- ABCL unknown (but a sub-model definitely can't)
- Kitchen sink *can* represent transformations, assuming a closed subtheory as in stabilizer subtheory

Additionally, a condition on inner products derivable from CPTP transformations can be derived from just projective measurement update

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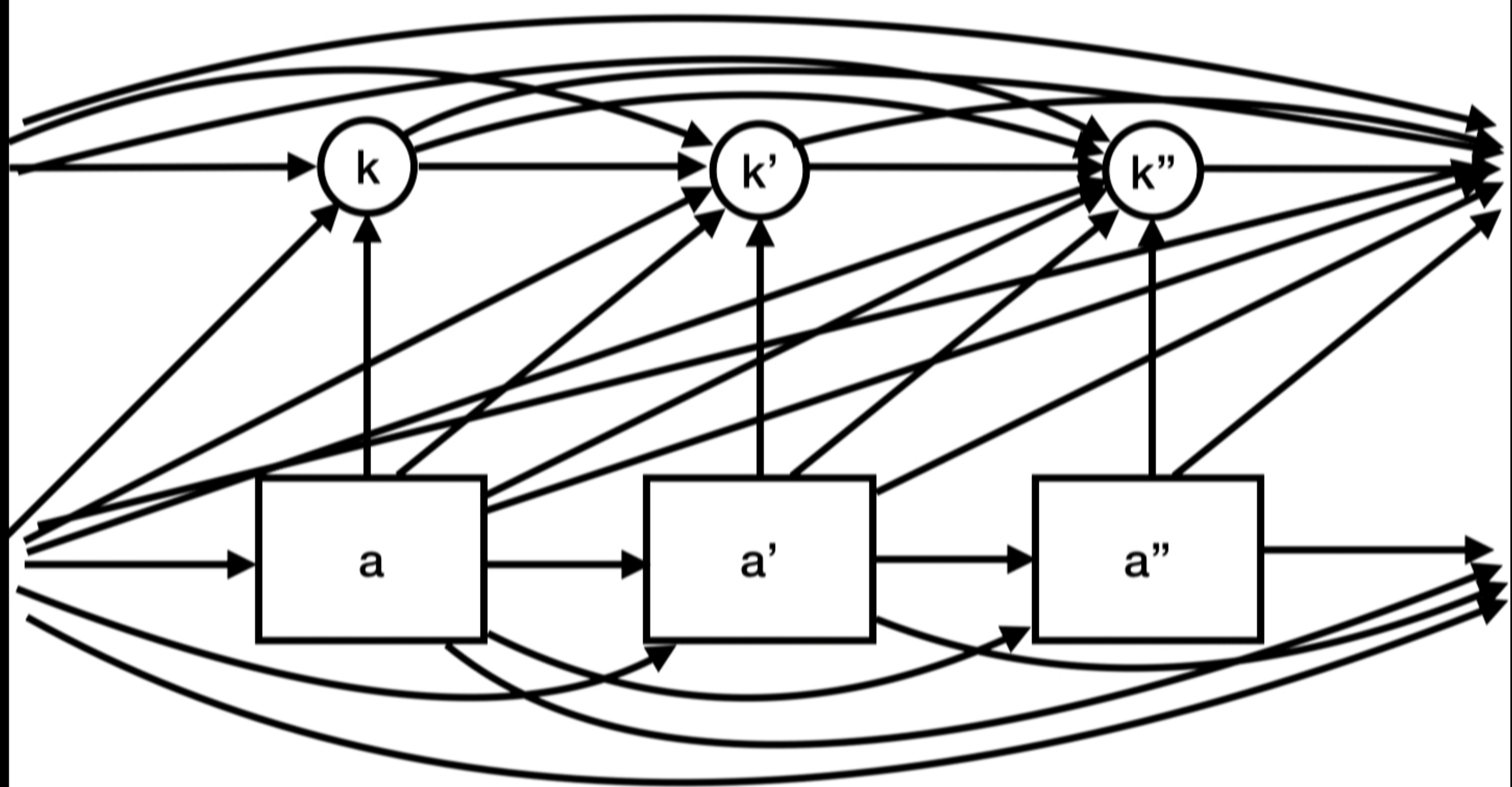
Stochastic channel



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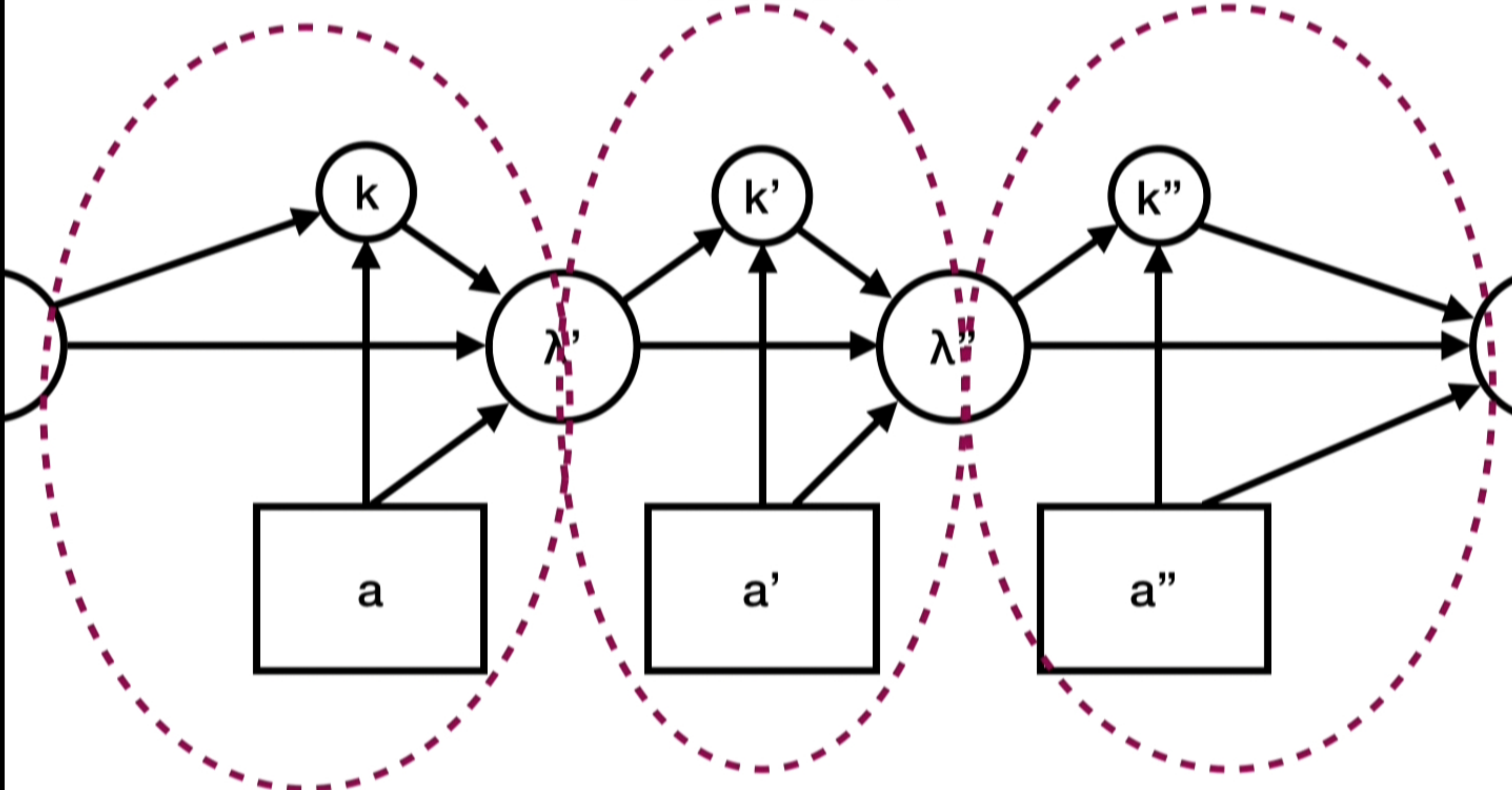
HMM



$$\Pr(k, \lambda' \,|\, a, \lambda)$$

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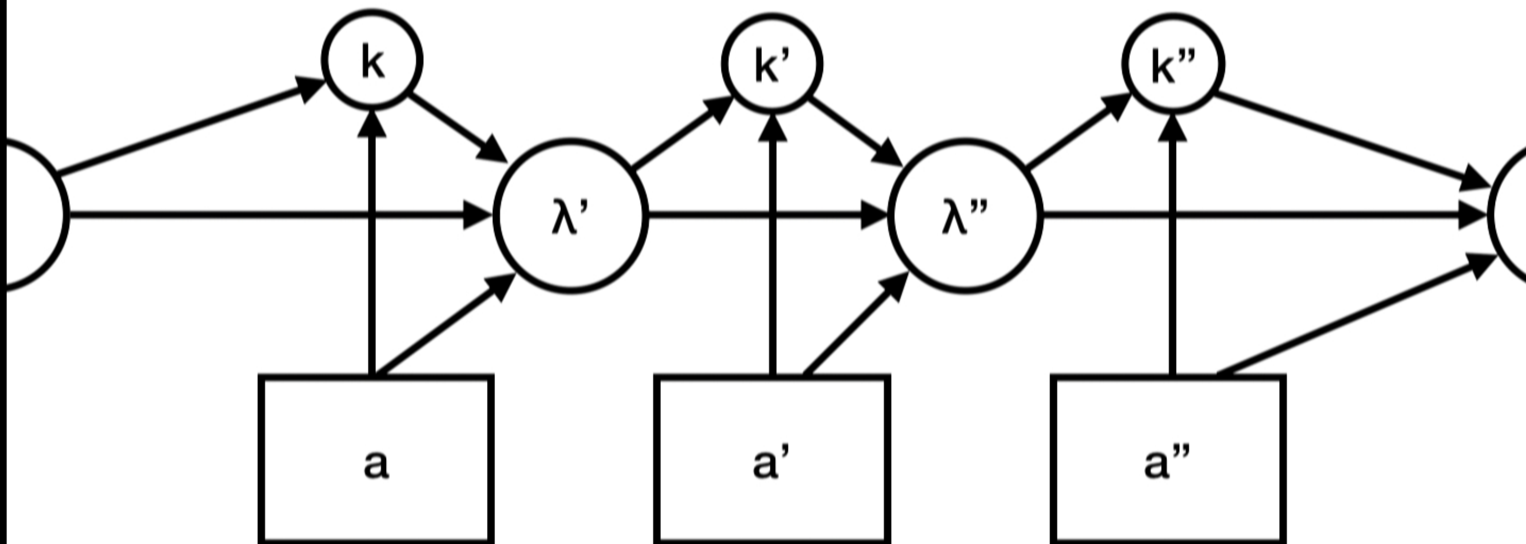
OMs = HMMs (1)



OMs = HMMs (2)

Start by factoring HMM specification, with $a \in \mathscr{P} \cup \mathscr{T} \cup \mathscr{M}$:

$$\Pr(k, \lambda' \,|\, \lambda, a) = \Pr(\lambda' \,|\, k, \lambda, a) \Pr(k \,|\, \lambda, a)$$

$$= \begin{cases} \mu(\lambda' \,|\, P)\delta_{k,0} & a = P \in \mathscr{P} \\ \Gamma(\lambda' \,|\, \lambda, T)\delta_{k,0} & a = T \in \mathscr{T} \\ \eta(\lambda' \,|\, k, \lambda, M)\xi(k \,|\, \lambda, M) & a = M \in \mathscr{M} \end{cases}$$

So what?

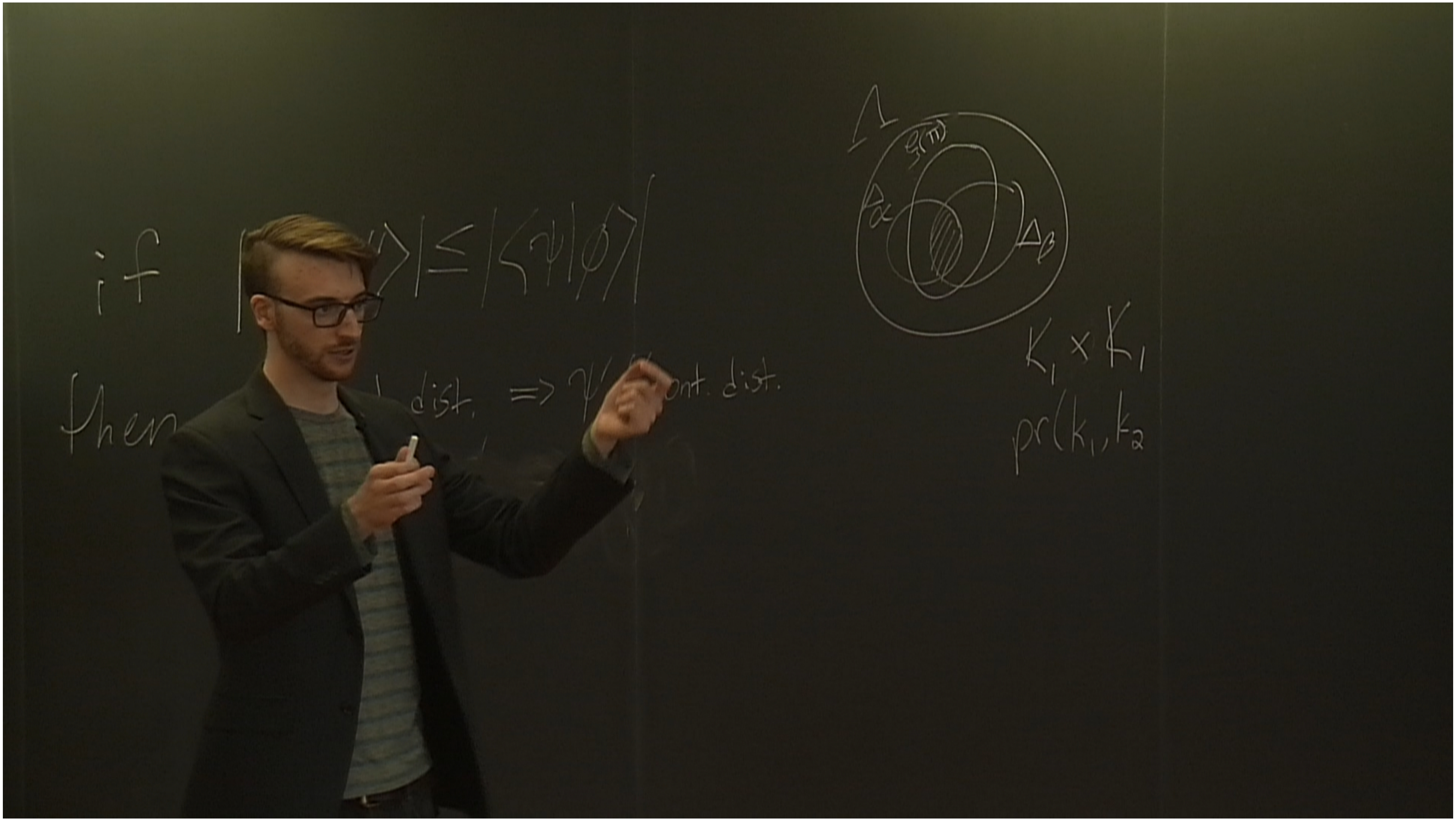
Allows us to write down a set of assumptions for OMs:

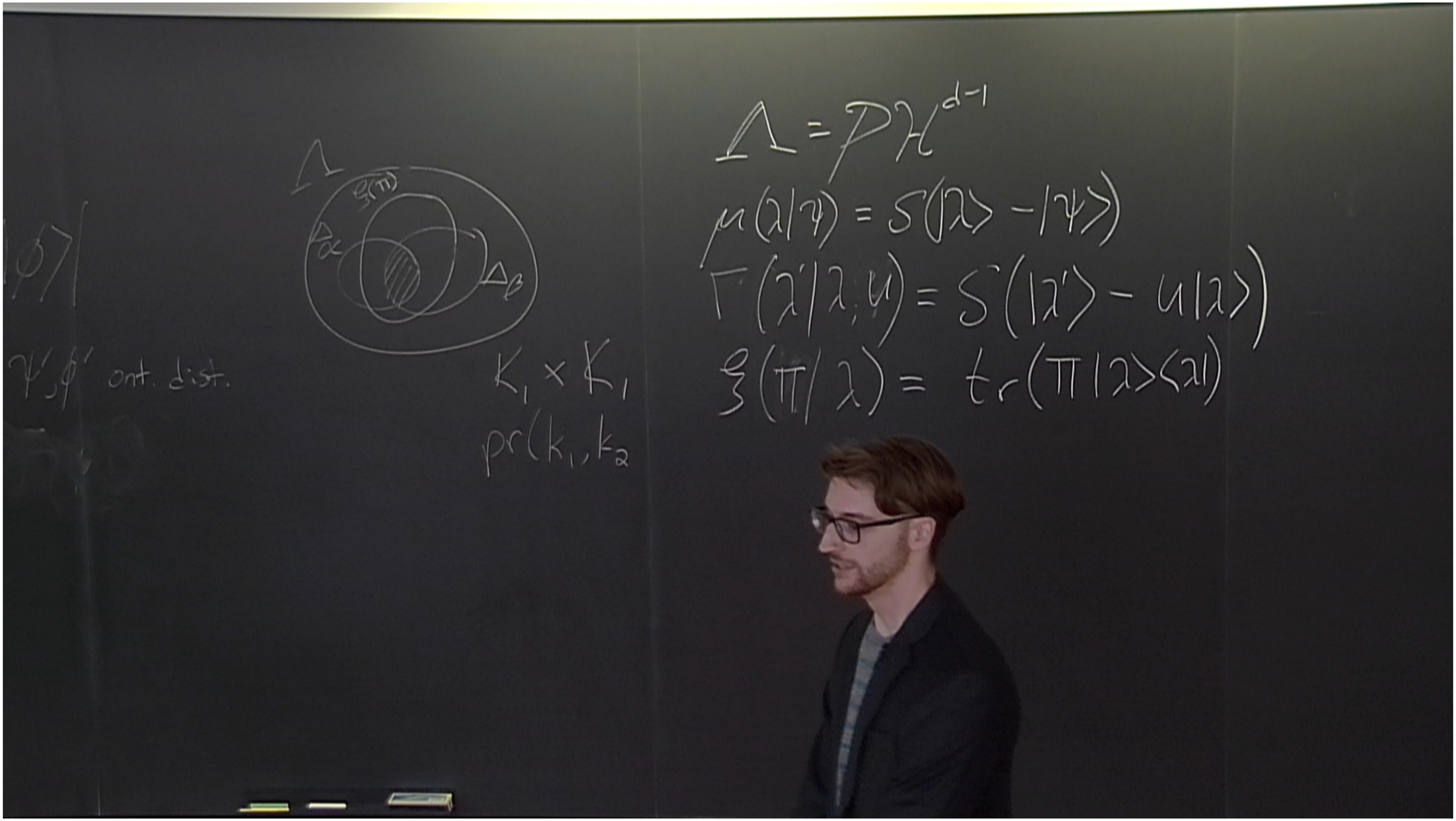
1. We can represent nature via stochastic channels

2. This process is *causal* (time-ordered)

3. This process is *stationary* (time-translation invariant)

4. The (real?) states of the system render the past and future conditionally independent


if
then
dist. ⇒ ψ′ ont. dist.
K₁ × K₁
pr(k₁, k₂


$\Lambda = P\mathcal{H}^{d-1}$
$\mu(\lambda|\psi) = \delta(|\lambda\rangle - |\psi\rangle)$
$\Gamma(\lambda'|\lambda, U) = \delta(|\lambda'\rangle - U|\lambda\rangle)$
$\xi(\Pi|\lambda) = tr(\Pi|\lambda\rangle\langle\lambda|)$
$K_1 \times K_1$
$pr(k_1, k_2$
ψ', ϕ' ont. dist.