Title: Compatibility of implicit and explicit observers in quantum theory and beyond

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Abstract:

Compatibility of implicit and explicit observers in quantum theory and beyond

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Implicit observer

1) States $\psi \in \mathbb{C}^d$

2) Transformations $\psi \rightarrow U\psi, \quad U \in \mathrm{SU}(d)$

3) Measurements $(F_1, ..., F_n) \quad \sum_i F_i = \mathbb{I}$

4) Probabilities $p(F_i|\psi) = \langle\psi|F_i|\psi\rangle$

5) Composition $\psi_{AB} \in \mathbb{C}^{d_A} \otimes \mathbb{C}^{d_B}$

Explicit observer

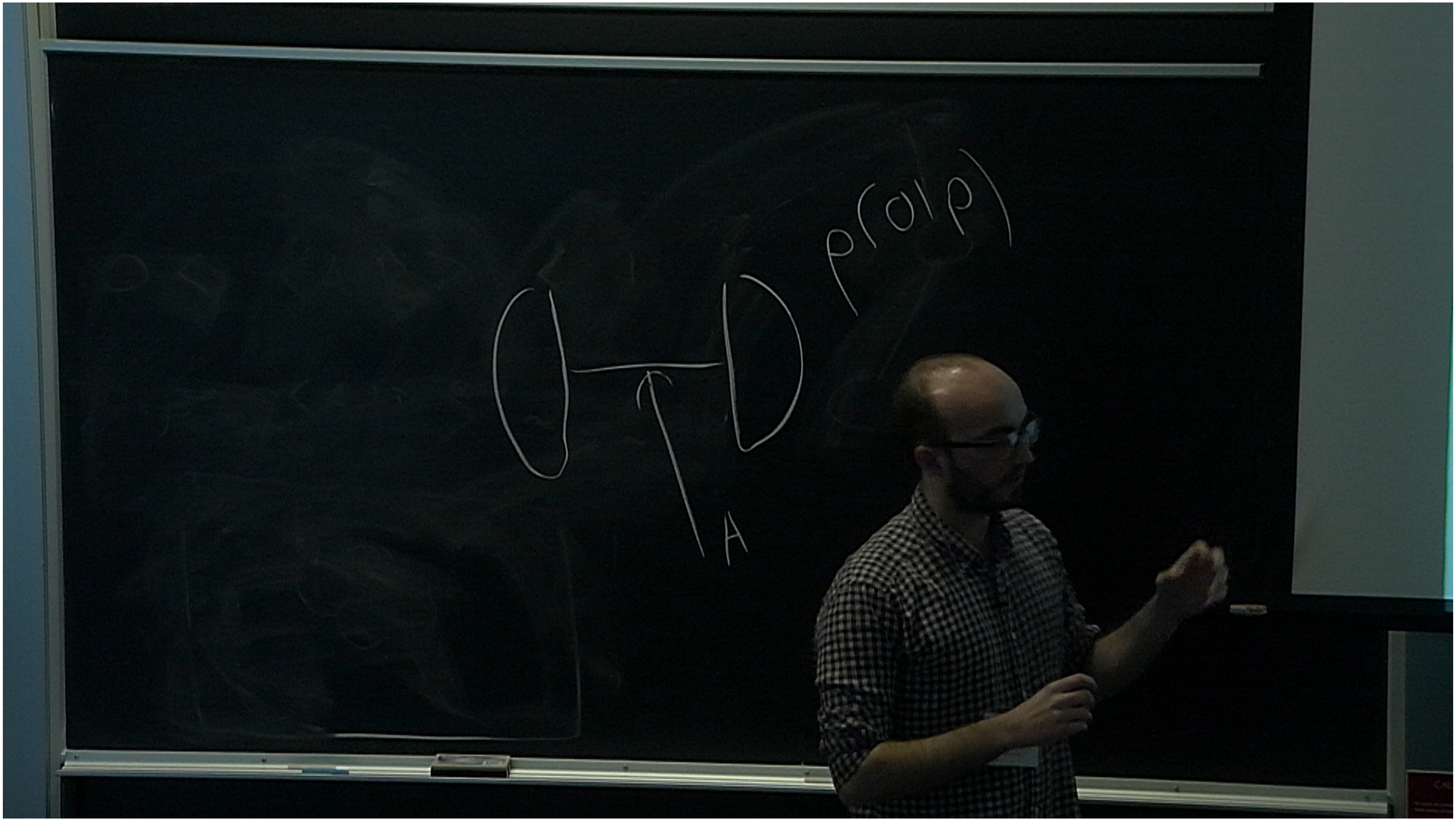
$$|0\rangle_C \otimes |0\rangle_F \otimes |0\rangle_W + |1\rangle_C \otimes |1\rangle_F \otimes |1\rangle_W$$

Wigner and Teller (from wigner.mta.hu)

Universal theories

All actions where the agent is implicitly present (measurement and preparation) can be modelled with the agent described explicitly as a non-classical system.

Compatibility between implicit and explicit observers. Reductionism. Realism. MWI


ρ(a|p)
A

Aims

- Discuss how the observer comes into play in quantum theory (explicit vs implicit).
- See which properties of quantum theory allow for universality.
- Does changing the measurement postulates affect the peaceful coexistence between explicit and implicit observer?
- Is universality a generic feature of the quantum dynamical structure or is it unique to the quantum measurement postulates?
- Theories with modified measurements are not universal.

Structure

- Example: implicit and explicit observers in the measurement process
- Explicit and implicit obverver in the preparation process: purification
- Theories with alternative measurement postulates violate purification
- Conclusion and points for discussion

Implicit and explicit observers in measurement procedures

Implicit/Explicit agents: measurement process

$$|\psi\rangle = \sum_i \alpha_i |i\rangle \rightarrow |i\rangle \qquad\qquad p(i|\psi) = |\alpha_i|^2$$

$$|\text{ready}\rangle|\psi\rangle \rightarrow \sum_i \alpha_i |\text{see } i\rangle|i\rangle$$

$$p(\text{see } i|\psi) = p(i|\psi)$$

The fact that outcomes are associated to eigenvectors (PVM) makes it easy to interpret the dynamical branches as corresponding to different outcomes and observer states.

Implicit/Explicit agents: measurement process

$$|\psi\rangle = \sum_i \alpha_i |i\rangle \to |i\rangle \qquad p(i|\psi) = f(\alpha_i)$$

$$|\text{ready}\rangle|\psi\rangle \to \sum_i \alpha_i |\text{see } i\rangle|i\rangle$$

$$p(\text{see } i|\psi) = p(i|\psi)$$

Outcomes are associated to eigenvectors (PVM) so maintains the dynamical branching interpretation.

Implicit/Explicit agents: measurement process

$$p(i|\psi) = f(\alpha_i)$$

Such modified Born rules are problematic, have been shown to lead to signalling (modulo some minor assumptions).

$$p(\text{outcome}|\psi) = f(\alpha_1, ...\alpha_n)$$

If we want consistent modified implicit observers we need to remove the identification of outcomes and eigenvectors. Need to modify more than just the Born rule.

Implicit/Explicit agents: measurement process

$$|\psi\rangle = \sum_i \alpha_i |i\rangle$$

$$p(\text{outcome}|\psi) = f(\alpha_1, ...\alpha_n)$$

$$|\text{ready}\rangle|\psi\rangle \rightarrow \sum_i \alpha_i |\text{see } i\rangle|i\rangle$$

If outcome probabilities are given by functions of multiple coefficients it seems harder to obtain this explicit branching interpretation.

Change in measurements makes explicit modelling of measurement process challenging.

Implicit and explicit observers in preparation procedures

Interactions in alternative theories

- GPT: Observer, systems and CPT
- System-system interaction: $\mathbb{C}^{d_A} \otimes \mathbb{C}^{d_B}$
- Observer-system interaction: $p(a_i|\psi),\ |\psi\rangle \rightarrow |a_i\rangle$
- (CPT-system interaction): $\sum_i p_i|\psi_i\rangle\langle\psi_i|$

- Observer enters implicity in CPT-system interaction

Implicit/explicit agents: preparation process

$$\sum_{i=0}^{1} \frac{1}{2} |i\rangle\langle i|$$

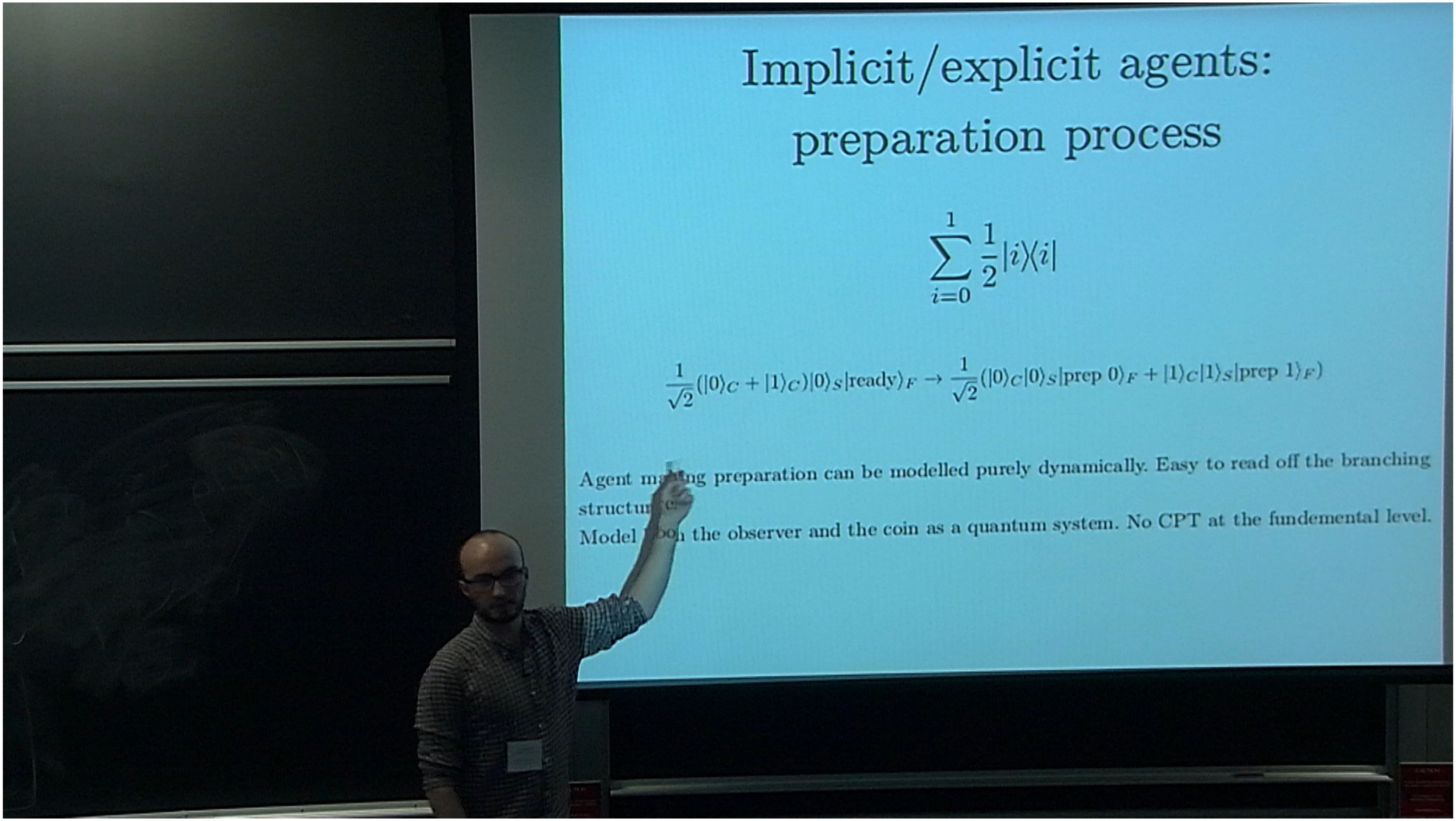
$$\frac{1}{\sqrt{2}}(|0\rangle_C + |1\rangle_C)|0\rangle_S|\text{ready}\rangle_F \rightarrow \frac{1}{\sqrt{2}}(|0\rangle_C|0\rangle_S|\text{prep } 0\rangle_F + |1\rangle_C|1\rangle_S|\text{prep } 1\rangle_F)$$

Agent making preparation can be modelled purely dynamically. Easy to read off the branching structure.
Model both the observer and the coin as a quantum system. No CPT at the fundemental level.

Analysis of the explicit quantum preparation procedure

It is universal (everything is a quantum system)
Mixed states are generated using entanglement
All mixed states can be generated in this manner

Purification: Every mixed state is the reduced state of a global pure state.

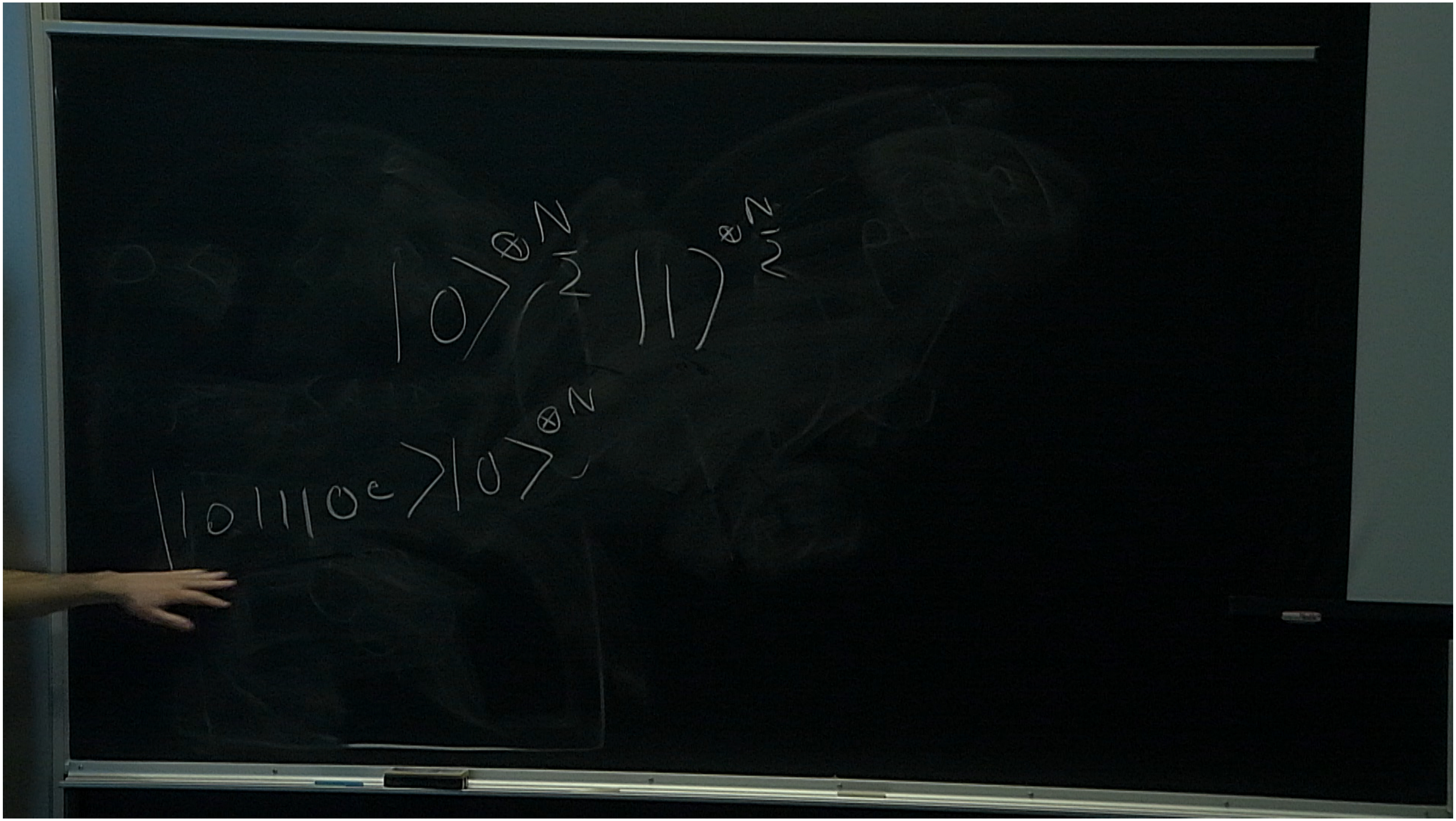

Implicit/explicit agents: preparation process
$\sum_{i=0}^{1} \frac{1}{2} |i\rangle\langle i|$
$\frac{1}{\sqrt{2}}(|0\rangle_C + |1\rangle_C)|0\rangle_S|\text{ready}\rangle_F \to \frac{1}{\sqrt{2}}(|0\rangle_C|0\rangle_S|\text{prep }0\rangle_F + |1\rangle_C|1\rangle_S|\text{prep }1\rangle_F)$
preparation can be modelled purely dynamically. Easy to read off the branching
the observer and the coin as a quantum system. No CPT at the fundemental level.

Universality and entanglement

Can prepare mixed states in a universal theory without entanglement.

Would need large amount of initial randomness (e.g. random bit string) encoded in NC systems.

See http://mateusaraujo.info/ for discussion.


$|0\rangle^{\otimes \frac{N}{2}} |1\rangle^{\otimes \frac{N}{2}}$
$|10111 0e\rangle |0\rangle^{\otimes N}$

Preparation procedure in alternative theories

Universality (for preparations) + entanglement based preparation of mixed states is equivalent to purification.

Do alternative theories obey purification?

Purification needed to explicitly model observers making preparations using entanglement.

Theories with alternative measurement postulates

Postulates of QT

1) States $\psi \in \mathbb{C}^d$

2) Transformations $\psi \to U\psi, \quad U \in \mathrm{SU}(d)$

3) Measurements $(F_1, \ldots, F_n) \quad \sum_i F_i = \mathbb{I}$

4) Probabilities $p(F_i|\psi) = \langle\psi|F_i|\psi\rangle$

5) Composition $\psi_{AB} \in \mathbb{C}^{d_A} \otimes \mathbb{C}^{d_B}$

Postulates of QT

1) States $\psi \in \mathbb{C}^d$

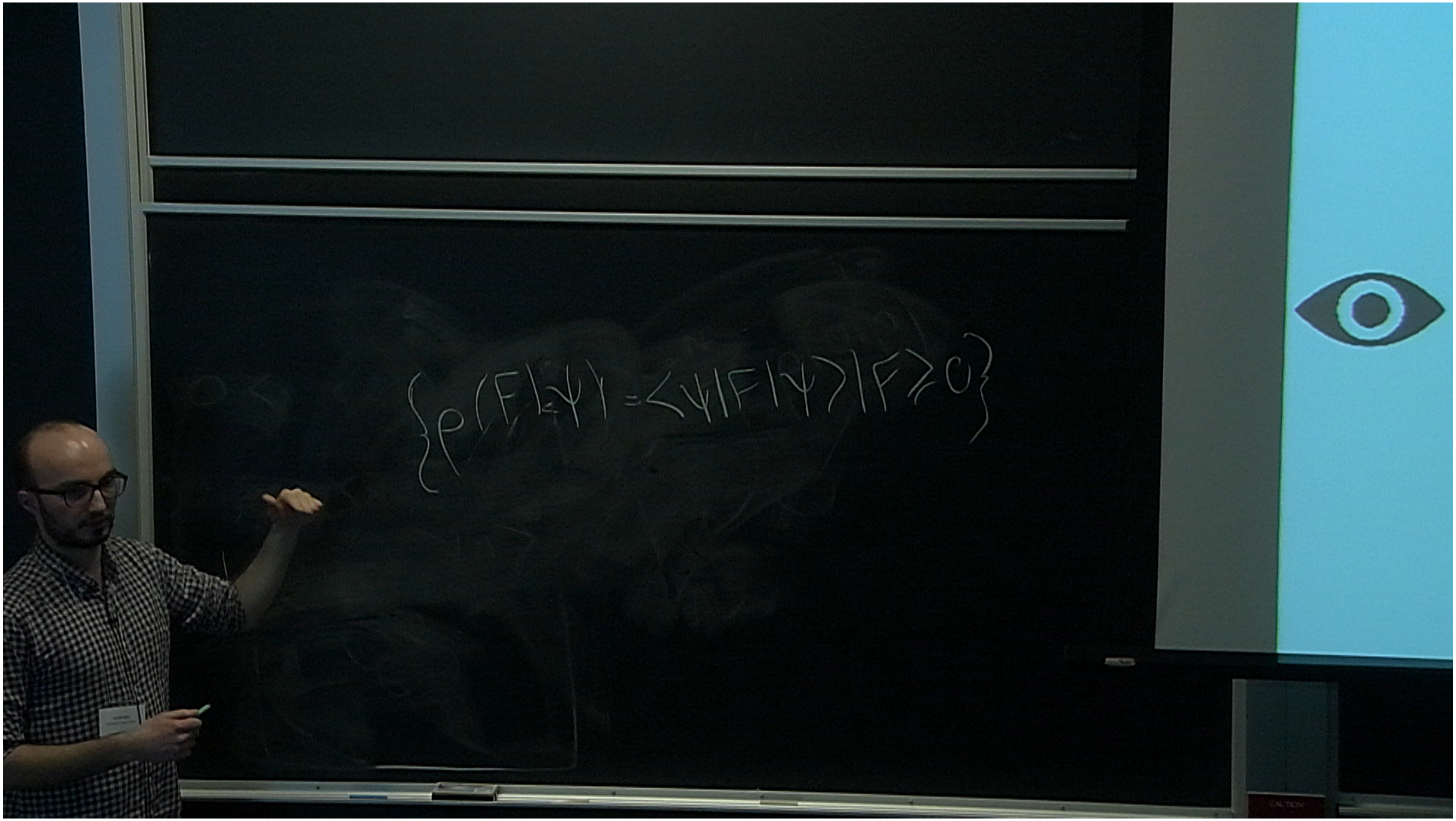
2) Transformations $\psi \to U\psi, \quad U \in \mathrm{SU}(d)$

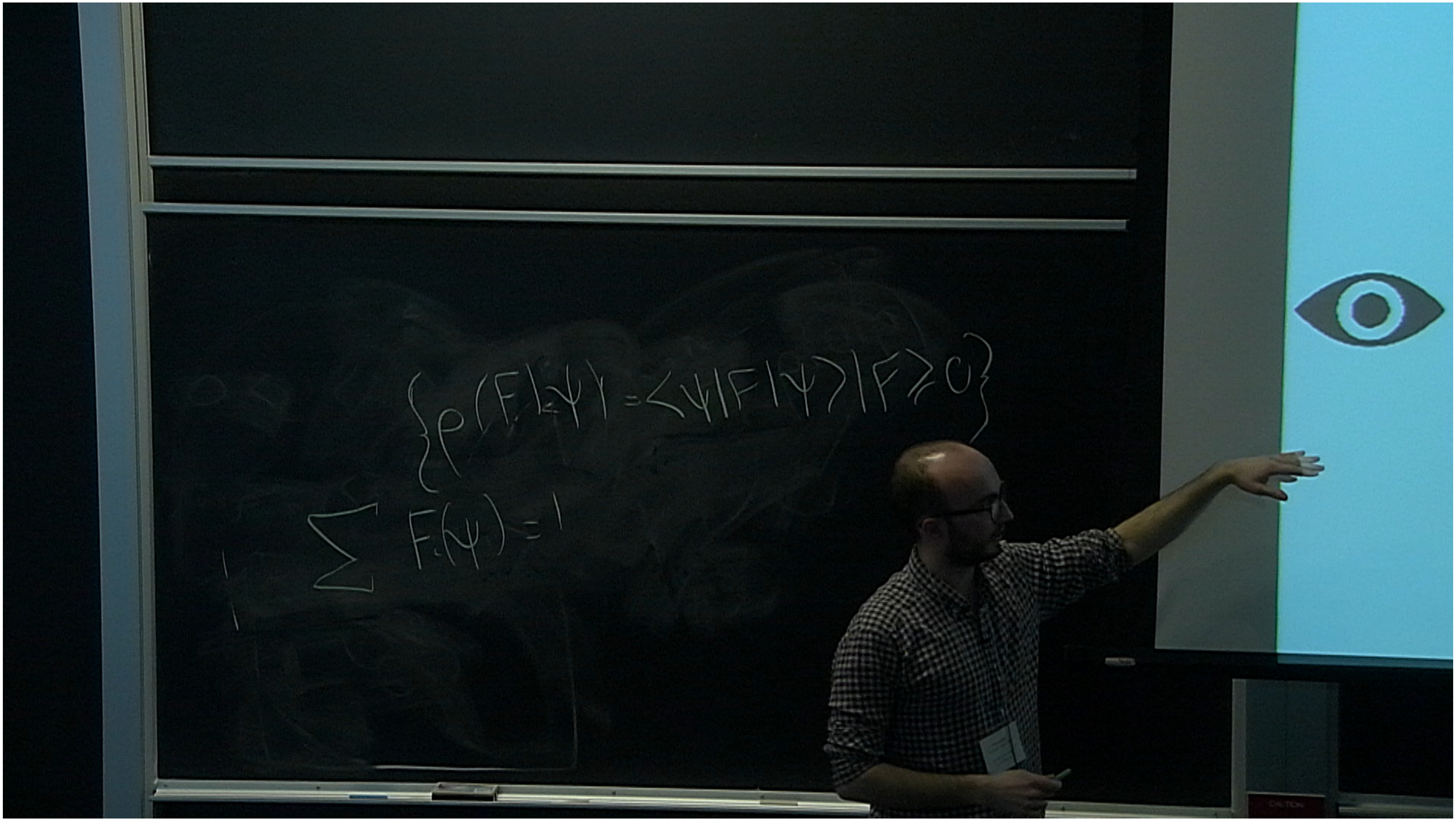
3)

$$\{p(F|\psi) = \langle\psi|F|\psi\rangle | \forall F \geq 0\}$$

4)

5) Composition $\psi_{AB} \in \mathbb{C}^{d_A} \otimes \mathbb{C}^{d_B}$


{ρ(F|ψ) = <ψ|F|ψ> | F ≥ 0}


{ρ(F_i|ψ) = ⟨ψ|F_i|ψ⟩ | F_i ≥ 0}
Σ F_i(ψ) = 1

Postulates of alternative theories

1) States $\psi \in \mathbb{C}^d$

2) Transformations $\psi \to U\psi, \quad U \in \mathrm{SU}(d)$

3)

$$\mathcal{F} = \{p(F|\psi) = F(\psi)\}$$

4)

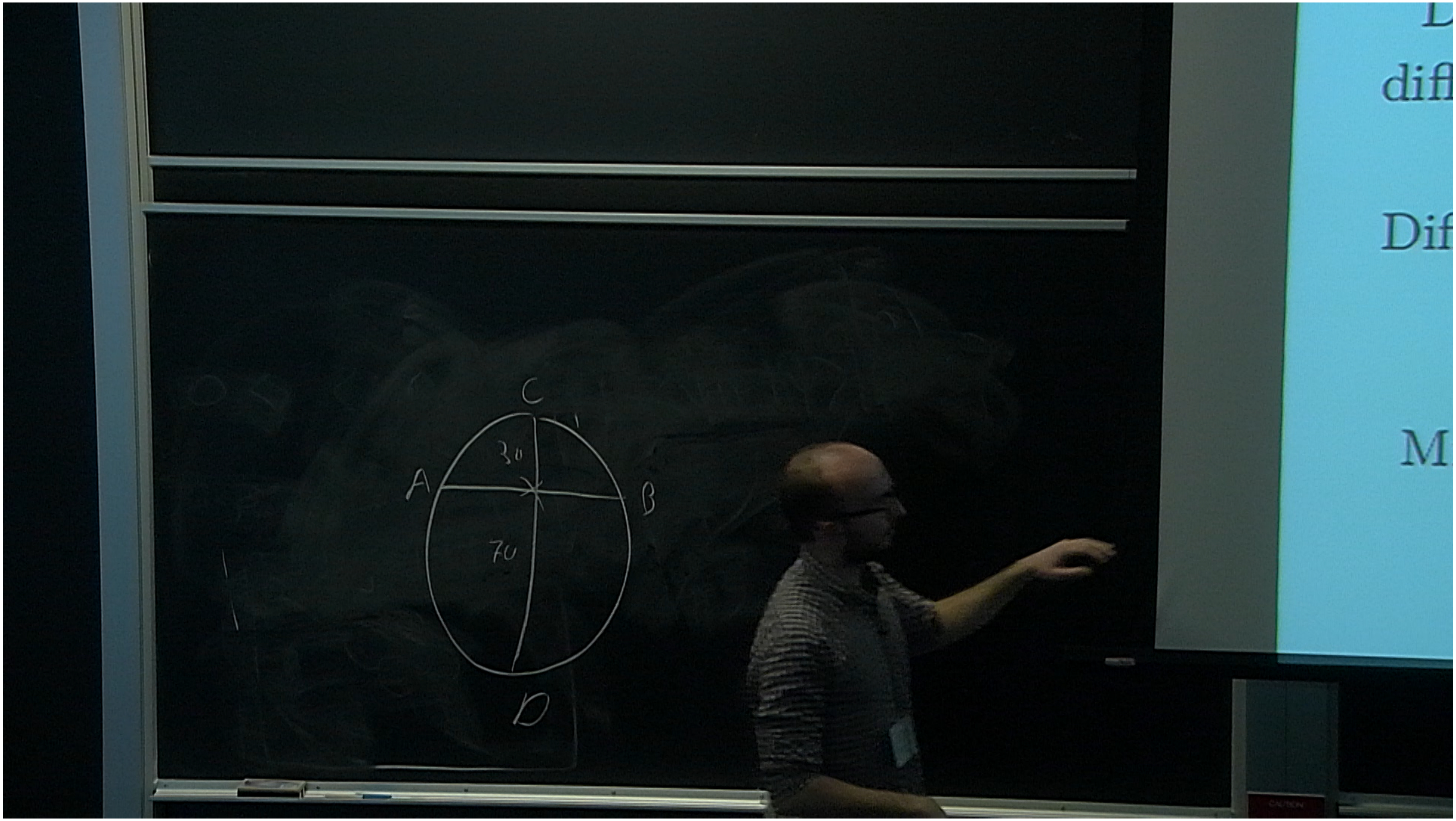
5) Composition $\psi_{AB} \in \mathbb{C}^{d_A} \otimes \mathbb{C}^{d_B}$

Consequences of modifying measurement postulates

Different measurement postulates imply that different sets of ensembles are indistinguishable.

Different classes of indistinguishable ensembles, implies different set of mixed states.

Mixed states no longer correspond to density matrices.


C
A
B
D
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Postulates of alternative theories

1) States $\psi \in \mathbb{C}^d$

2) Transformations $\psi \to U\psi, \quad U \in \mathrm{SU}(d)$

3)

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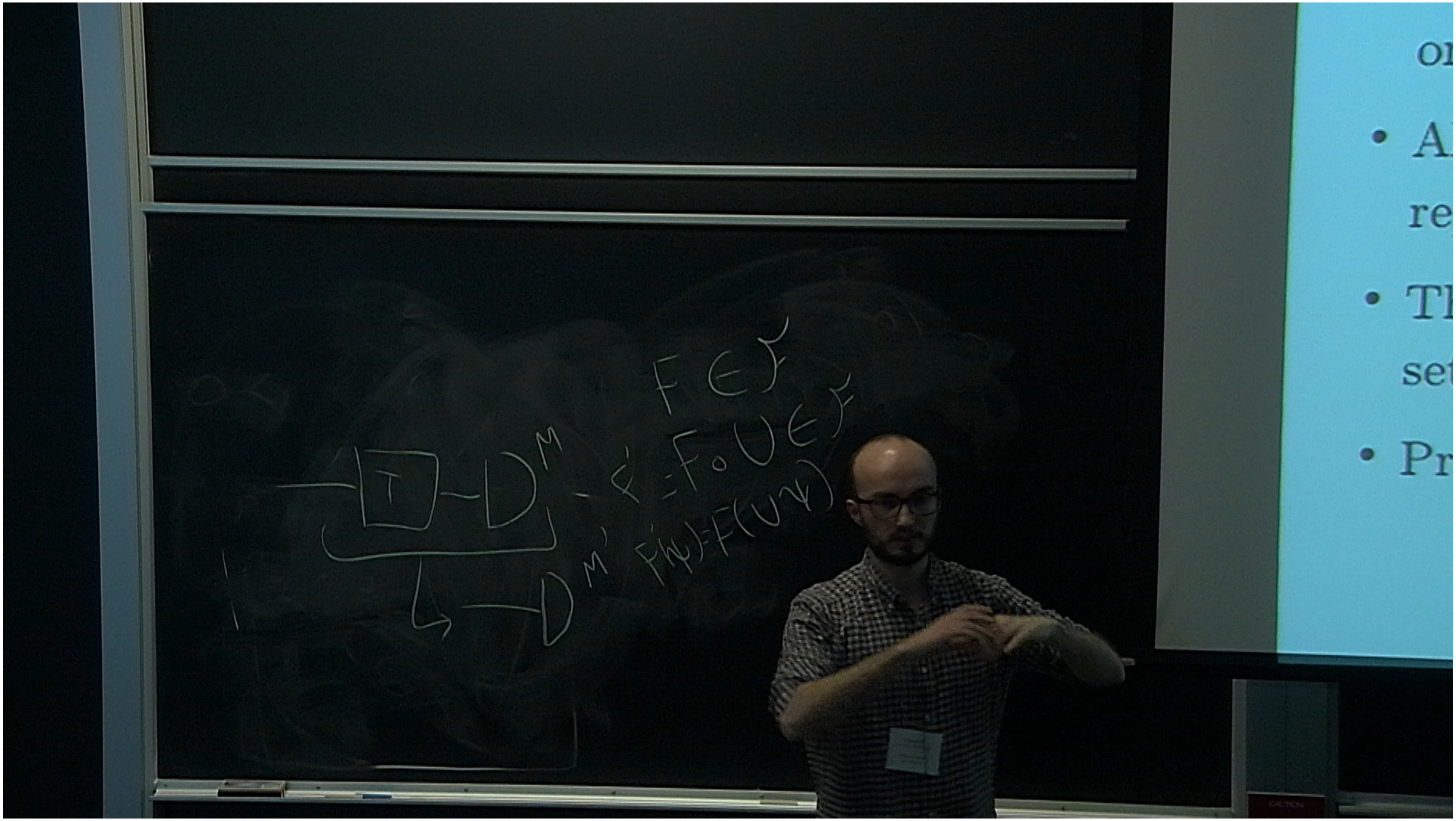
Consequences of modifying measurement postulates

Number of parameters needed to specify mixed state changes.

Different state space, but with same manifold of pure states.

Possible sets $\mathcal{F}$

- Various operational principles impose constraints on the allowed sets of OPFs.
- All allowed sets can be fully classified using representation theory.
- These are just the representations acting on the sets of mixed states.
- Provides us an infinite family of systems



Hierarchy of theories

- Quantum state space is the most compressed
- All alternatives to the measurement postulates give state spaces which are more classical
- All state spaces live somewhere between quantum and (infinite dimensional) classical state space

Properties of bi-partite systems

- Violation of local tomography.
- Violation of purification.
- Local tomography: Full state tomography of bi-partite system possible with joint local measurements alone.

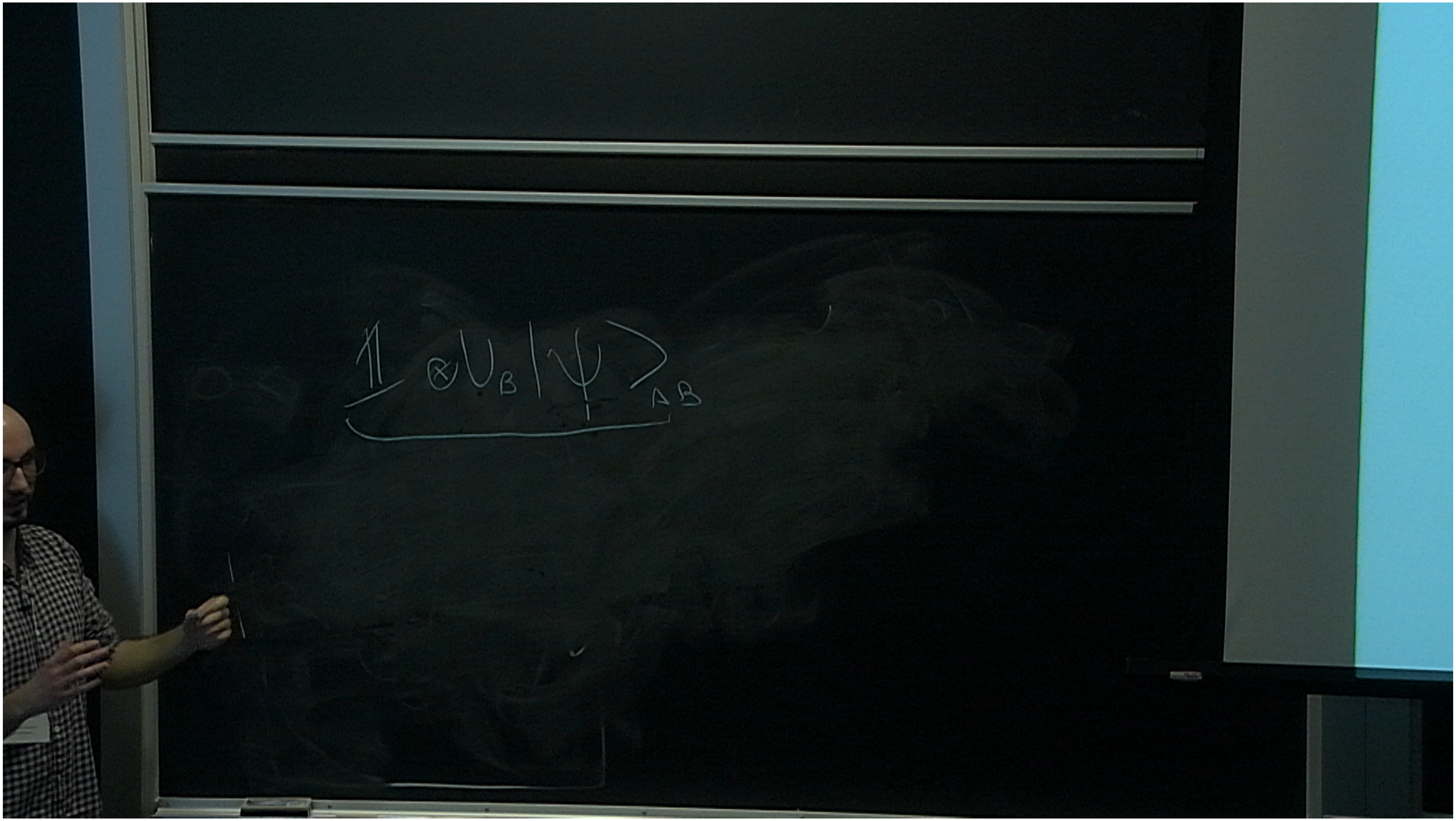
No purification proof

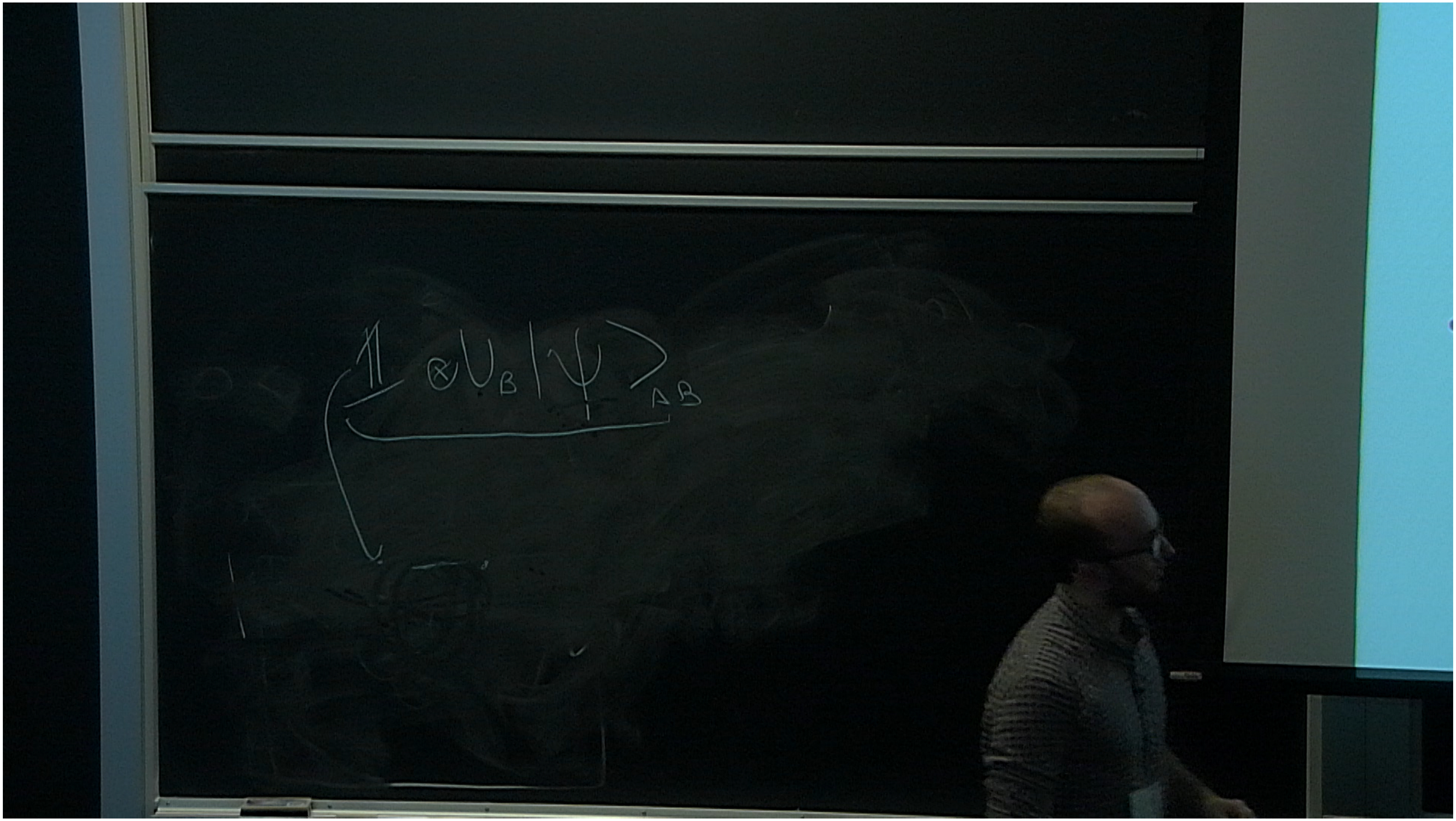
$$\mathbb{I}_A \otimes U_B |\psi\rangle_{AB} \sim |\psi\rangle_{AB}$$

All states in this equivalence class mapped to same reduced state.
Multiple equivalence classes can be mapped to same state

Can parametrise this space of equivalence classes of global states. N_E is number of parameters of this space, N_L is number of parameters of local state space.

$$\text{Purification} \implies N_E \leq N_L$$


$\mathbb{1} \otimes U_B |\psi\rangle_{AB}$


𝟙 ⊗ U_B |ψ⟩_AB

Consequences

- There are some mixed states which cannot be prepared with entanglement.
- There are some actions of the implicit agent which cannot be modelled explicitly as non-classical systems entangling.
- Caveat: Can explicitly model preparations if agent has large amount of randomness (encoded in non-classical systems).

Multipartite systems in alternative theories

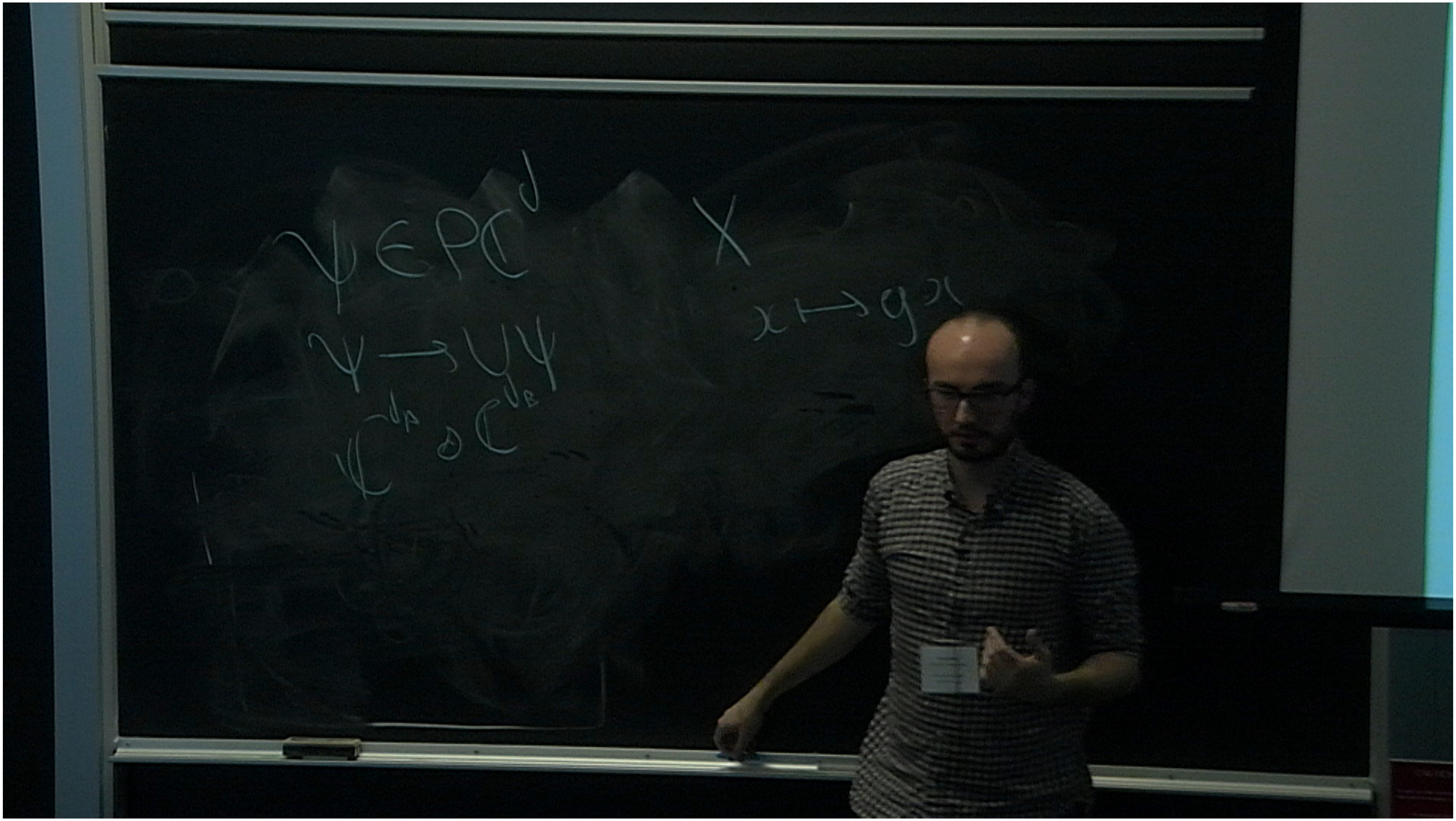
- Wigner's friend scenario requires multi-partite systems.
- Theories in this talk work for bi-partite systems.
- Current hypothesis: non-associative.

Consequences for GPTs

- If purification required for universality generally then recent Lee/Selby result makes search for universal post-quantum theory problematic.
- Purification and local tomography are not generic features of non-classical theories.
- In the pure state/representation theoretic approach associativity is not a given.
- Cannot be content with analysis of bi-partite systems only.

Discussion

- How natural is the requirement of entanglement based preparation for universal theories?
- Purification is (more or less) equivalent to preparation universality? Can we find an equivalent principle for measurement universality?
- What features of the quantum dynamical structure lead to the branching structure of pure states?
- Are there other dynamical structures with these features?

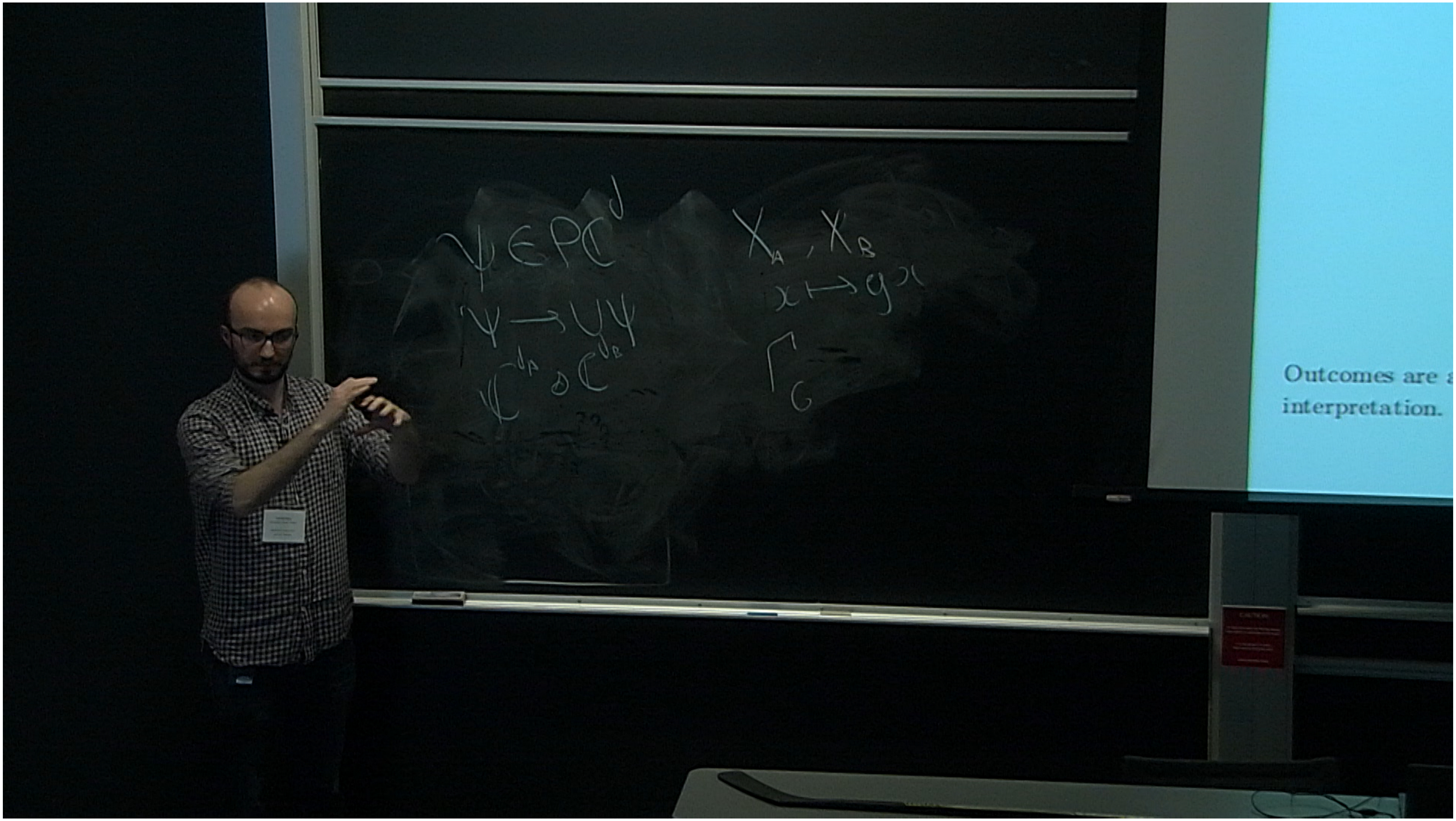

ψ ∈ PC^d
ψ → Uψ
ψ ∈ C^dA ⊗ C^dB
X
x ↦ gx

Conclusion

- Modifying the implicit observer leads to incompatibility with the explicit observer.
- Specifically preparation process cannot be modelled explicitly in alternative theories.
- The quantum measurement postulates are the only ones which allow for a universal theory.

Conclusion

- Joint work with Lluis Masanes
- Thank you for your attention


Outcomes are
interpretation.