Title: Towards a realist's interpretation of the path integral

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Abstract: <span>Having a fundamental spacetime view of physics, appears more justified in attempting to construct a quantum theory of gravity. In this talk, motivated by the latter,  a path integral approach is adopted and an attempt to construct a self-consistent realistic histories formulation of quantum theory is presented. After revising the histories viewpoint of classical physics, the quantum case is considered. However, the nature of the probabilities arising from the path integral, leads us to alter the classical picture. The new ontology is that of a coevent (or a coarse grained history), and we analyse the consequences of this (relatively) novel proposal.</span>

# Towards a realist's interpretation of the path integral

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- Motivation for path integral/histories
- The classical picture for histories
- Quantum histories & quantum measure
- The problem with QT: Zero Covers
- A proposed solution:

  The coevents formulation (Sorkin)
- Two examples
- Summary & Conclusions

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# Motivation for path integrals

- In Hamiltonian QT, space and time are NOT in equal footing
- This eventually leads to the problem of time in QG
- The path integral formulation of QT, can be casted in relativistic form, while the Hamiltonian cannot.
- Dirac in "The Lagrangian in Quantum Mechanics", 1933:

  "There is an alternative [..] provided by the Lagrangian"

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form, since it marks out a particular time variable as the canonical conjugate of the Hamiltonian function"

- Most realistic interpretations of quantum theory, lie heavily on the Hamiltonian formalism (dBB, many worlds, collapse models as usually presented)

Need for an interpretation that:

1. Is suited for the path integral formulation

2. Is suited for closed systems with no external observers

• Coevent formulation satisfies the above two conditions and is an attempt for a *realistic, histories* formulation of QT.

# Classical Physics and Histories

- Ontology: A full history of the system $h$.

e.g. non-relativistic particle: a trajectory, specifying the position at each moment of time.

- Space of conceivable realities: Histories space $\Omega$ consisting of all possible histories $h_i$'s.

i.e. each history is a point in $\Omega$.

- Physical properties/questions: Subsets $A \subseteq \Omega$ and are called events.

e.g. "$x \in \Delta$ at time $t_1$" $\Rightarrow$ $\{h \in \Omega | h(t) \in \Delta\}$

- The set of events, forms a Boolean algebra which we call event algebra $\mathcal{U}$.



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- One single history $h_i$ is actually realised

- The realised history $h_i$, possesses a property $A$ iff $h_i \in A$

- Given a realised history $h_i$, one can list all the properties that this reality possesses, that no measurement can change and in a context-independent way.

- Which history is realised:

(I) Deterministic physics:

Initial Conditions & Dynamics $\Rightarrow$
Determine uniquely the realised history

(II) Stochastic physics:

Initial Conditions & Dynamics $\Rightarrow$
Defines a measure (classical) $\mu$ on $\Omega$ (e.g. Wiener measure).

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$\mu(A)$ is the probability that the realised history belongs to the event $A$.

- How to obtain predictions:

(1) Definite predictions: Events of $\mu(A) = 0$ do NOT occur (preclusion)

Cannot cover the full space $\Omega$ with (finite number of) zero sets:

$\nexists \quad \{A_i\}$ such that $\cup_i A_i = \Omega$
and $\mu(A_i) = 0 \quad \forall \quad i$

(2) Probabilistic: The meaning of probabilities for a closed non-repeatable system has been an issue of debate since the founding of probability theory. We adopt here the **Weak Cournot Principle**:

- A. Kent: “Path Integrals and Reality”

- K. B. Wharton: “Lagrangian-only Quantum Theory”

Difficult to recover standard QT, from a histories formulation in an alternative way.

At every approach, one should attempt to formulate them in terms of histories!

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# The Coevent Formulation

- There are many schemes of the coevent formulation. The most developed is the one presented here, known as the multiplicative scheme.

New Ontology: Reality is an event $C_i$, i.e. a subset of histories $C_i \subseteq \Omega$, or in other worlds a coarse-grained history, that obeys certain conditions. It is called: coevent

- Conditions:

(1) It is not subset of ANY quantum measure zero set. i.e. $\nexists Z | C_i \subseteq Z$

(2) Is the finest description subject to condition (1). i.e. $\nexists j | C_j \subset C_i$

- Physical Properties: Given coevent $C_i$ it possesses all the properties $A$, such that $C_i \subseteq A$ (non-contextual)

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- Can define a truth valuation function reflecting the above: $\phi_{C_i}(A) =$ True iff $C_i \subseteq A$

- Deductive reasoning (Modus Ponens). If $A$ is True and $A \subseteq B$ then $B$ is also true (even in quantum micro-world)

- Analogue of stochastic physics (many possible coevents given dynamics & initial conditions).

QT is generalization of classical stochastic physics rather than classical deterministic physics.

- Role of Measurements: Same as in classical stochastic physics. Restrict the set of potential realities/coevents to those consistent with the outcome of the measurement (does NOT alter the coevents)

- If measure $\mu$ is classical $\Rightarrow$ single histories and classical physics

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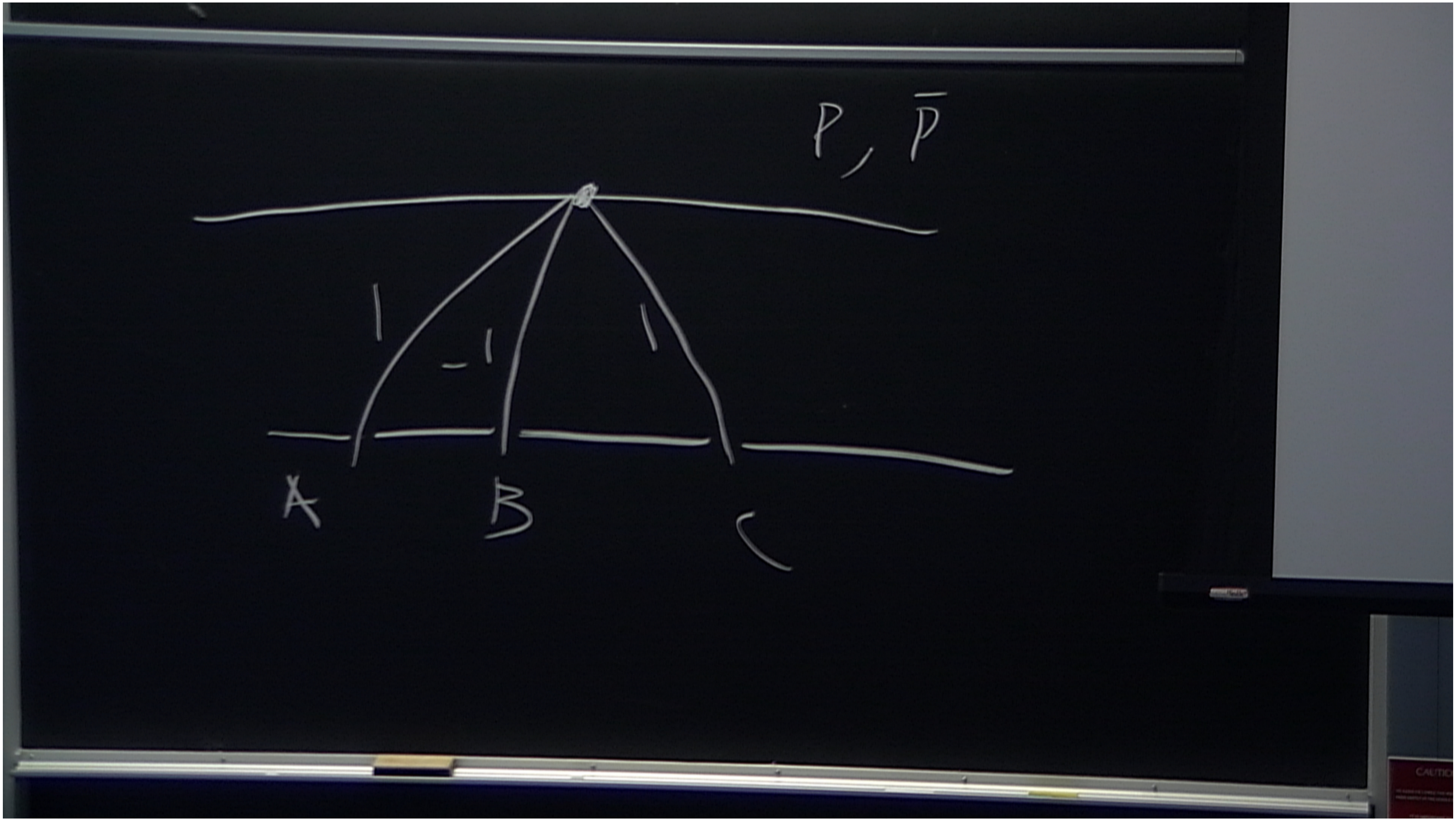
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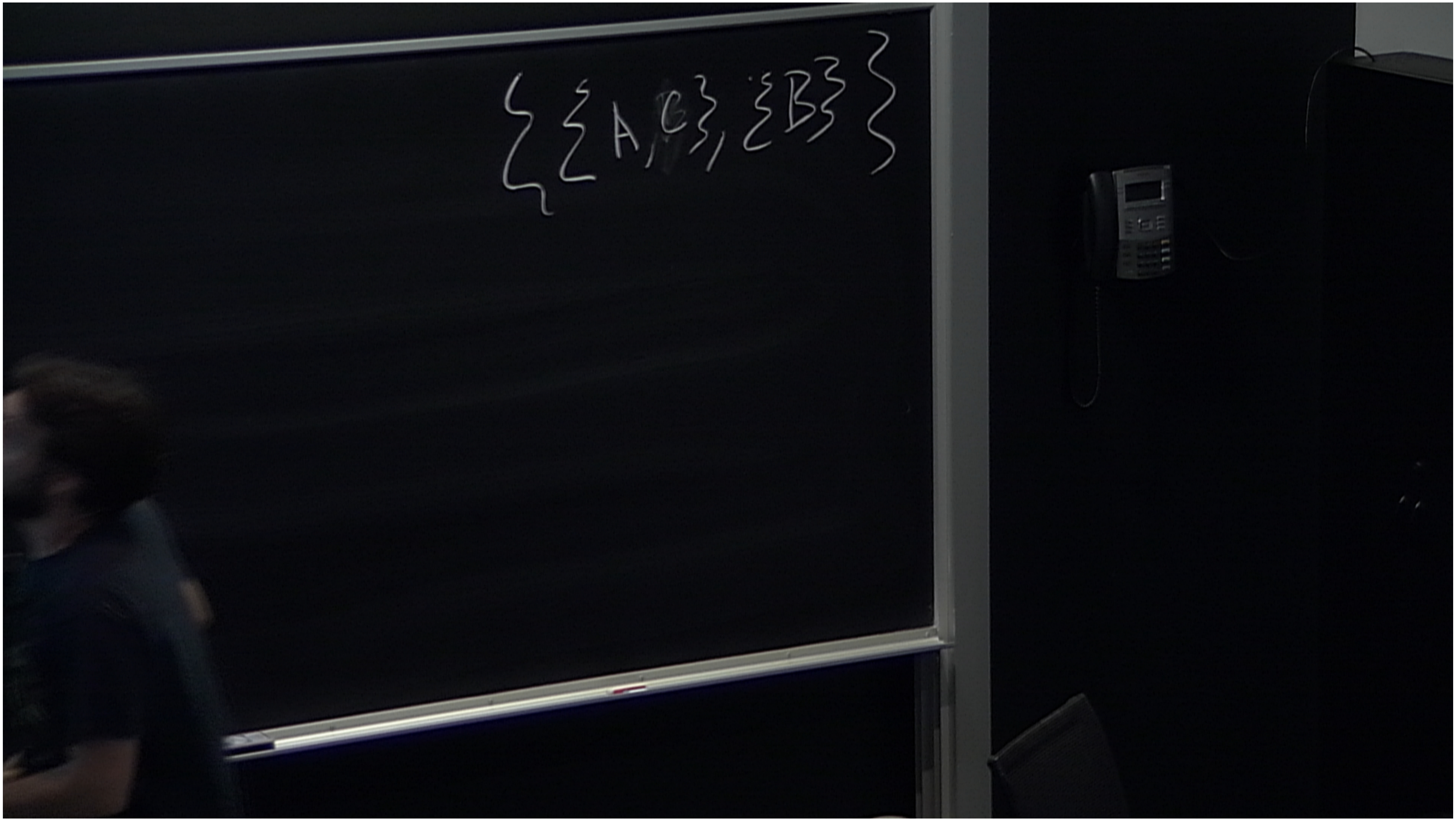
{{A, C}, {B}}

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# Two examples

Example 1: The 3-slit.

- Zero cover (see earlier): $\{A, B\}$ and $\{B, C\}$

- Single allowed coevent: $\{A, C\}$

- Finest classical partition: $\{\{A, C\}, \{B\}\}$

Homomorphism

- Consistent Histories:

Consistent set 1: $\{\{A\}, \{B, C\}\} \Rightarrow A$ occurs with probability $1$, $B \sqcup C$ never occurs (prob $0$). Implies that according to this consistent set, the system NEVER crosses from slit $C$

Consistent set 2: $\{\{C\}, \{A, B\}\} \Rightarrow C$ occurs with probability $1$, $A \sqcup B$ never occurs (prob

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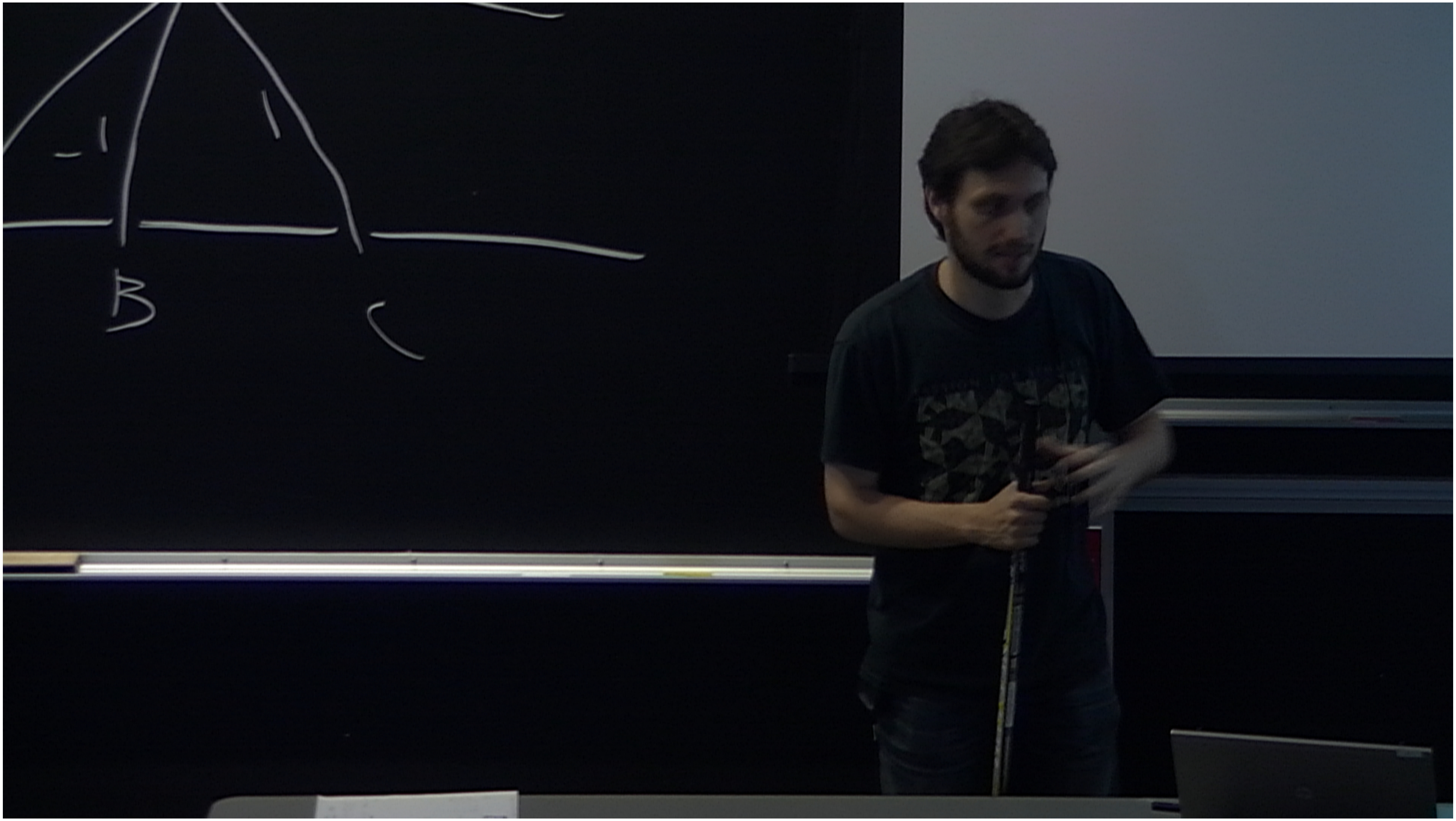
# Summary and Conclusions

- Taking the spacetime formulation of Quantum Theory rather than the Hilbert space, might be more natural choice in attempting to reconcile relativity with quantum theory and eventually construct a quantum theory of gravity.

- Among different formulations and interpretations of quantum theory, one must look for the one that will help us deepening our understanding and possibly open up possibilities solving other outstanding problems. Quantum gravity is such an example.

- If one adopts the histories formulations, is confronted with the existence of zero covers, which stops us from carrying over the classical histories view of reality.

- One looks for the smaller change in the ontology, that can be compatible with the quantum measure. Alternatively, one can attempt to alter the quantum measure (Kent, Wharton).


B
C

$\{h_1, h_2\}, \{h_1, h_3\}, \{h_1, h_4\}, \{h_5, h_6\}, \{h_6, h_7\}, \{h_6, h_8\}$

- Allowed coevents:

$\{h_2, h_3\}, \{h_2, h_4\}, \{h_3, h_4\},$
$\{h_5, h_7\}, \{h_5, h_8\}, \{h_7, h_8\}$

- Finest classical partition:

$\{\{h_1\}, \{h_2, h_3, h_4\}, \{h_6\}, \{h_5, h_7, h_8\}\}$

Homomorphism

- Consistent Histories (many (25) consistent sets!)

e.g. CS 1: $\{\{h_1, h_2\}, \{h_3, h_4, h_5, h_6, h_7, h_8\}\}$

$p(h_1, h_2) = 0$ and the complement is 1

CS 2: $\{\{h_1, h_2, h_5, h_6\}, \{h_3, h_4, h_7, h_8\}\}$

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