Title: Foundations of Quantum Mechanics #5

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Abstract: Interferometry, measurement and interpretation. Beyond the quanta.

What do we lack in our understanding of quantum theory?

Classical Physics

- What is it about classical physics that makes it seem understandable?
- Classical physics provides us with a definite conception of physical reality, the universe as a machine.
- The mathematisation of this conception naturally gives rise to a mathematical framework — the classical modelling framework.
- Classical physical theories are all built within this framework.
- The details of each theory are drawn from experimental observations and general physical principles.

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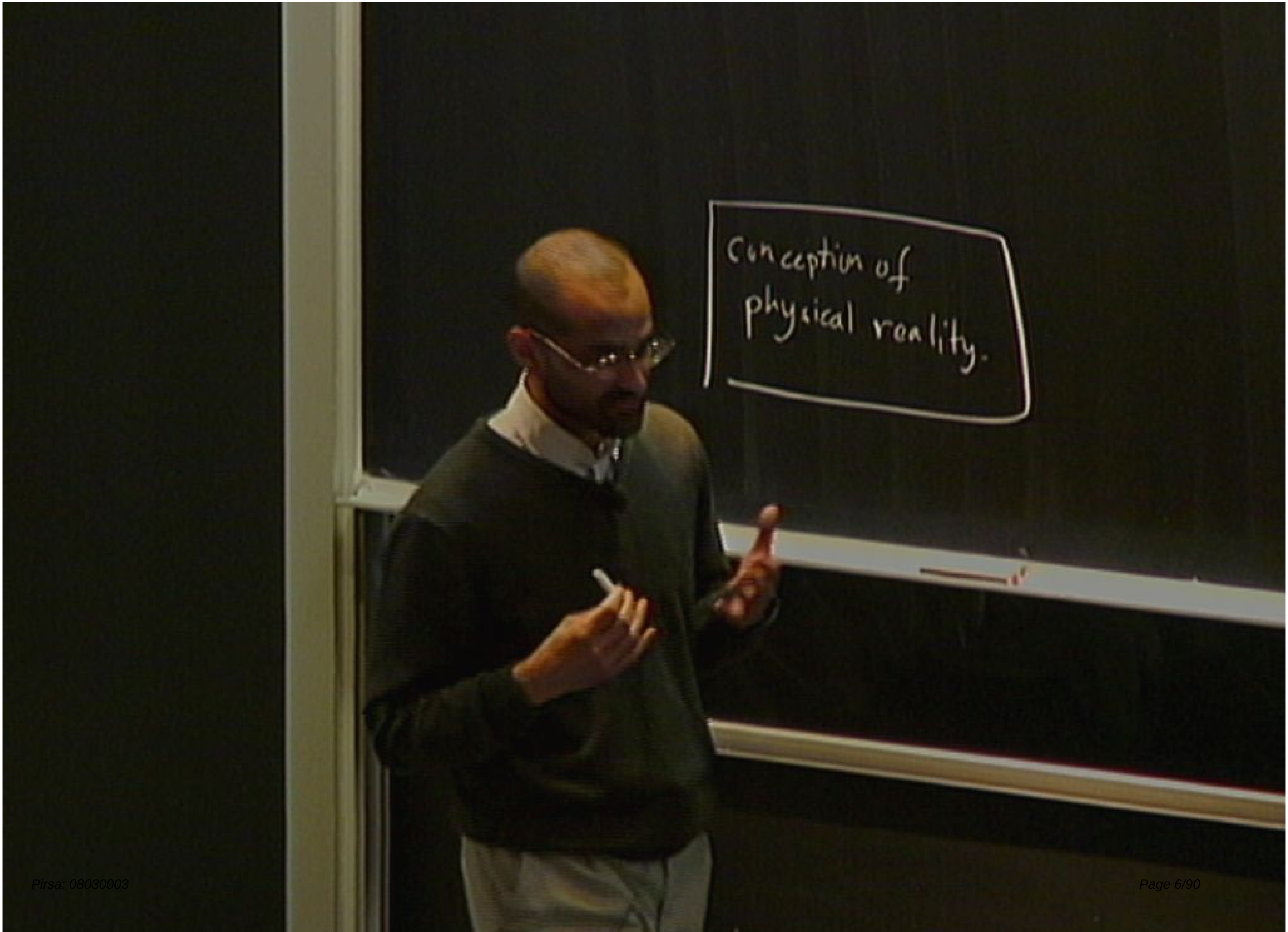
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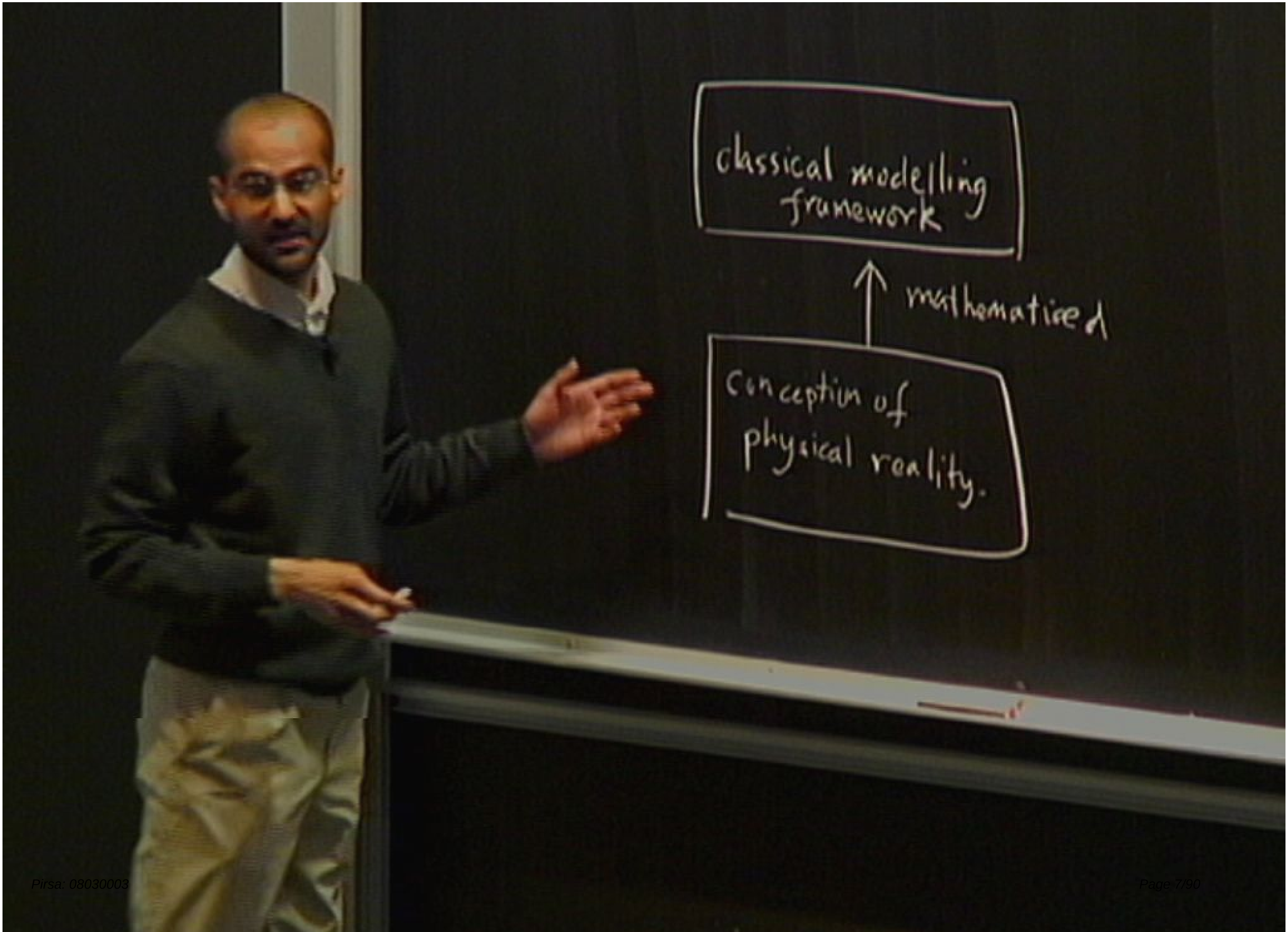
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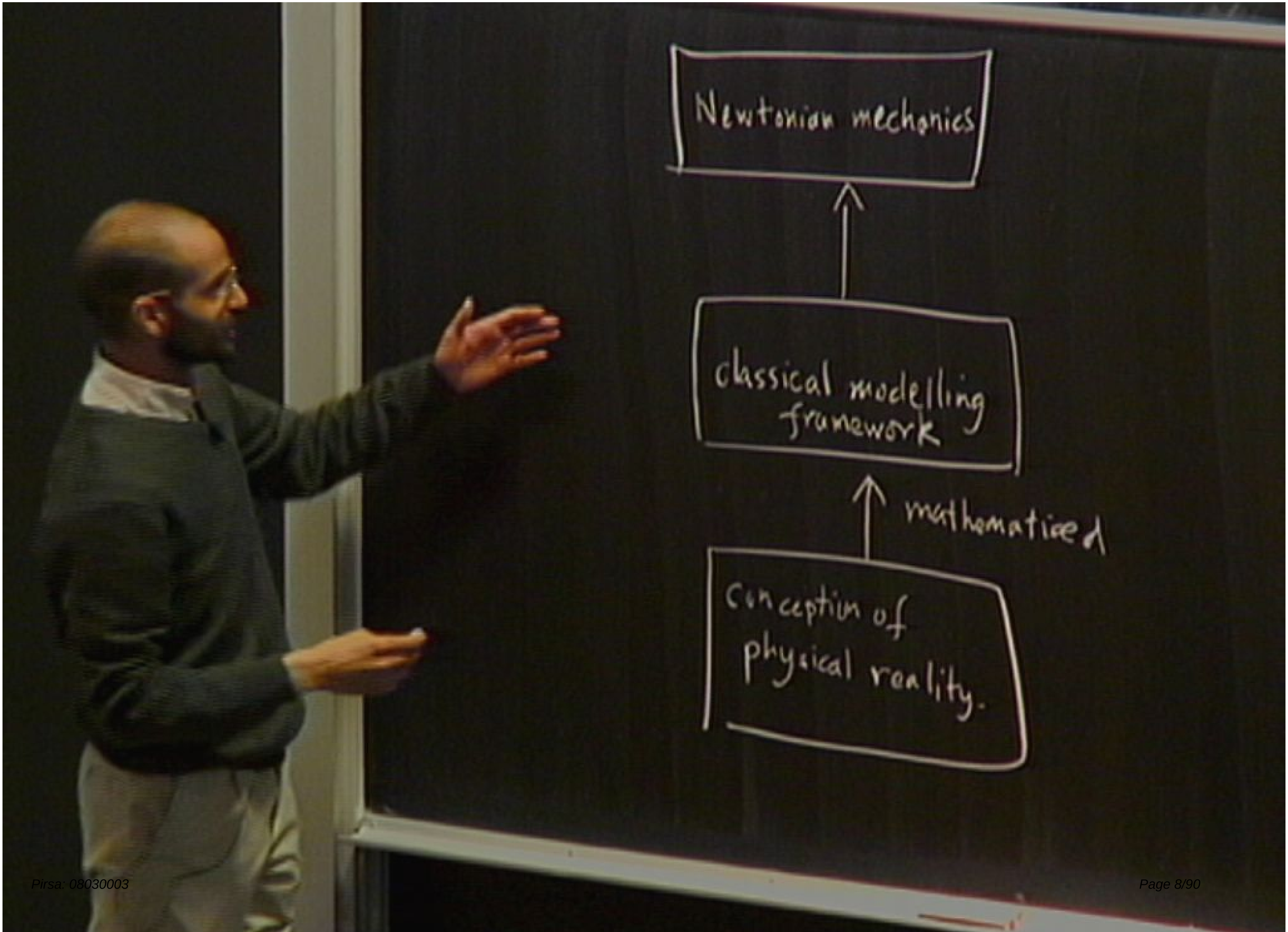
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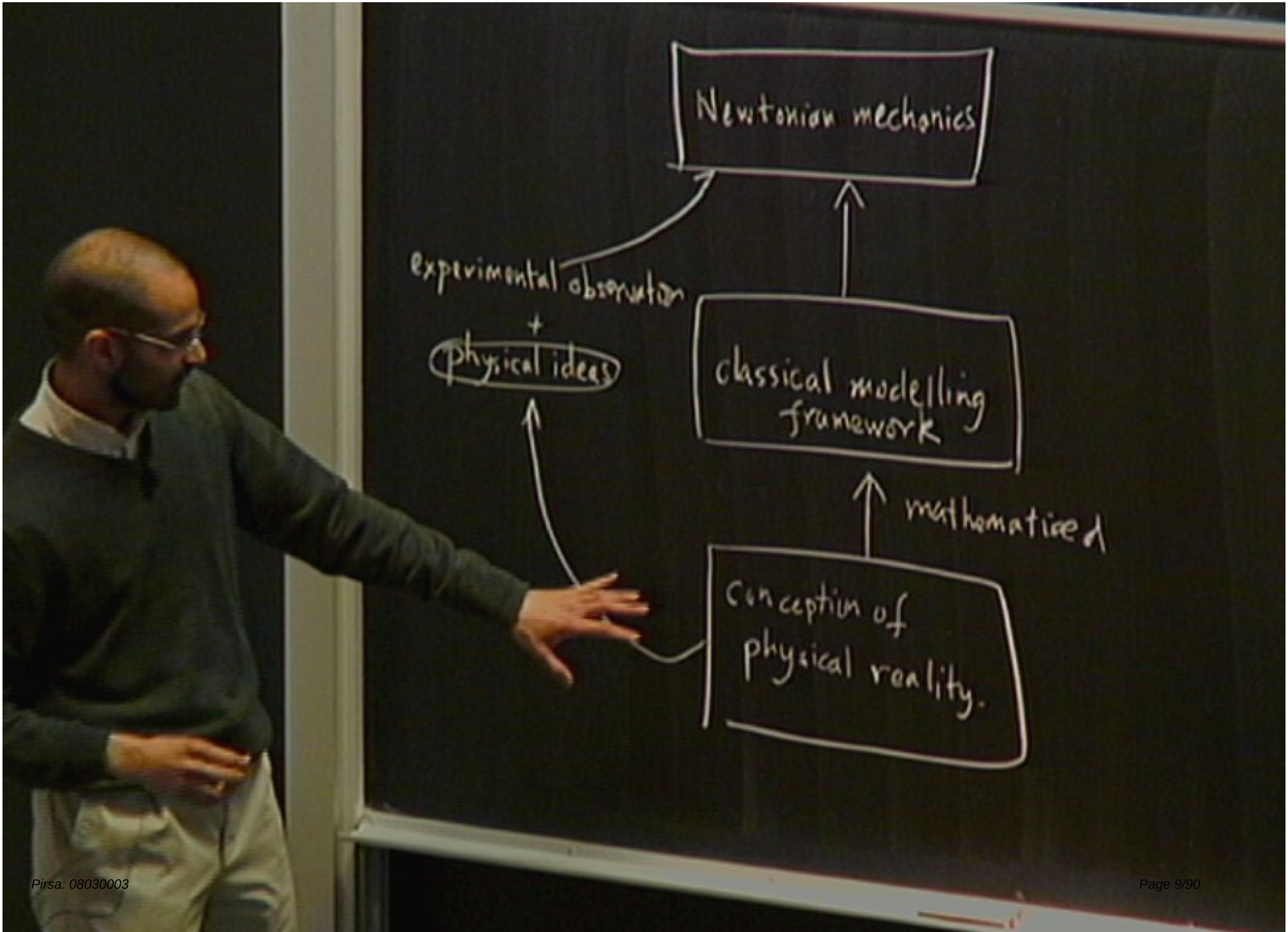
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The Mechanical Conception of Physical Reality.

Essential intuition: The physical universe is a vast machine.

By virtue of this conception, the physical universe has some fundamental properties:

- It is rationally understandable.
  - **Law-like:** It follows quantitative rules (laws) that we can formulate and comprehend.
  - **Uniformity of Nature:** These rules apply everywhere and at all times.
  - **Decomposability:** It is possible to discover these rules by studying parts of the universe in isolation from the rest.

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- In particular:
  - **Universal Time:** Everything changes in step with a 'universal time'.
  - **Describability:** Physical universe completely described at any time by its state and some intrinsic real parameters.
  - **Law of Motion:** A universal law of motion determines the state at any other time and is reversible.
  - **Measurements:** Outcomes of measurements are determined by the state.
  - **Reproducibility:** Measurements can be performed in a manner which is reproducible.
  - **Transparency:** There exists a measurement whose outcomes which uniquely pin down the state of the system, whatever the state happens to be.

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The Mechanical Conception

Classical Modelling Framework

- **Time** is represented by $t \in \mathbb{R}$.
- **Physical state** is represented by $\mathbf{S} \in \mathcal{S}$, where $\mathcal{S} \subseteq \mathbb{R}^n$.
- **Dynamics** are represented by one-to-one map, $\mathcal{M}$, over $\mathcal{S}$.
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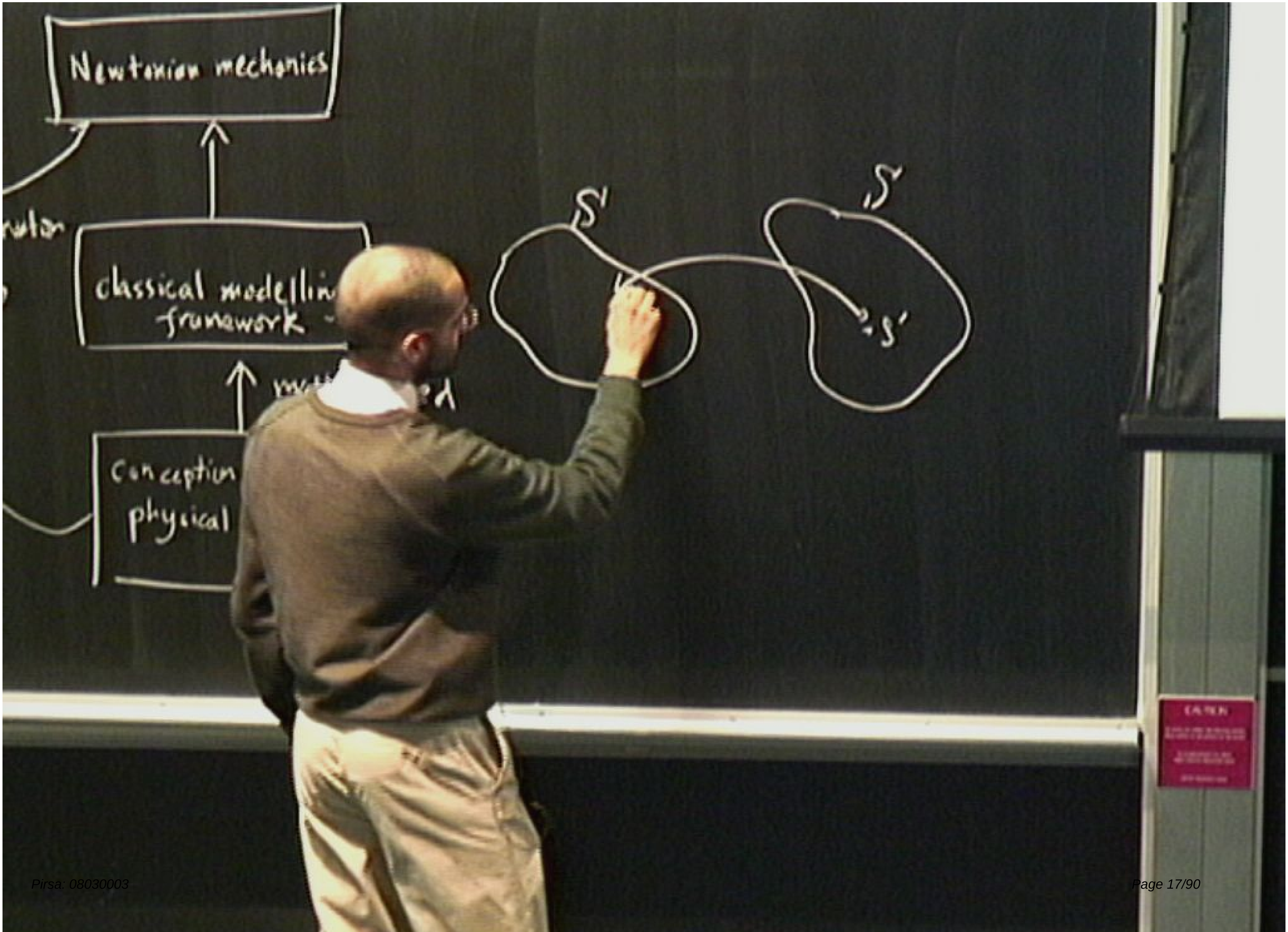
Newtonian mechanics
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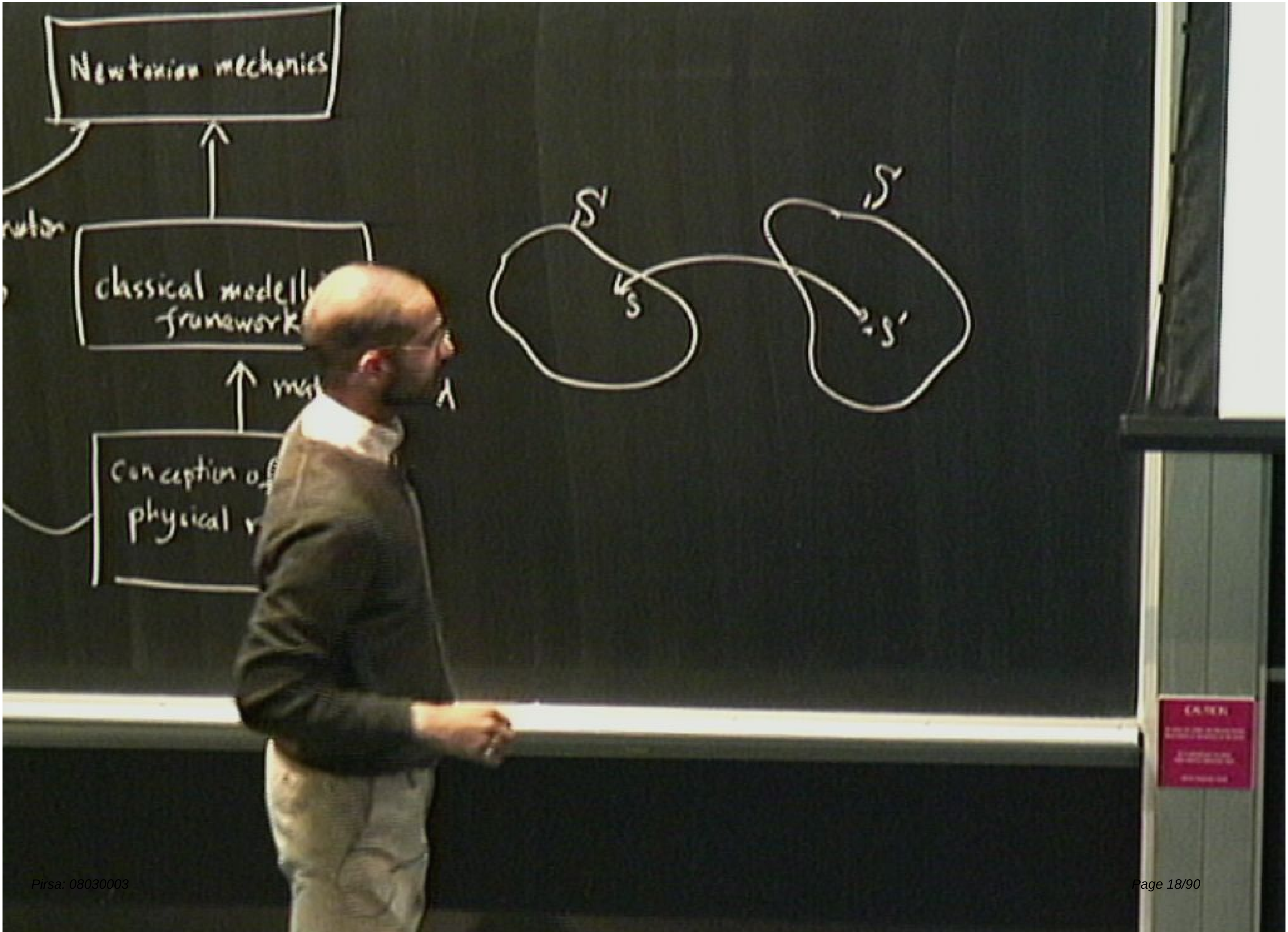
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Newtonian Mechanics

Using experimental observations (Galileo's laws of motion; Kepler's laws) together with intuitive physical notions (force, inertia), a particular theory is obtained.

- $S(t) = (\vec{r}_1, \ldots, \vec{r}_n; \dot{\vec{r}}_1, \ldots, \dot{\vec{r}}_n)$ for n particles labelled $1, \ldots, n$.
- $\mathcal{M}_t(dt) : S(t) \to S(t + dt)$,

  where $S(t+dt) = (\vec{r}_1 + \dot{\vec{r}}_1\, dt, \ldots, \vec{r}_n + \dot{\vec{r}}_n\, dt; \dot{\vec{r}}_1 + \vec{F}_1\, dt/m_1, \ldots, \dot{\vec{r}}_n + \vec{F}_n\, dt/m_n)$,

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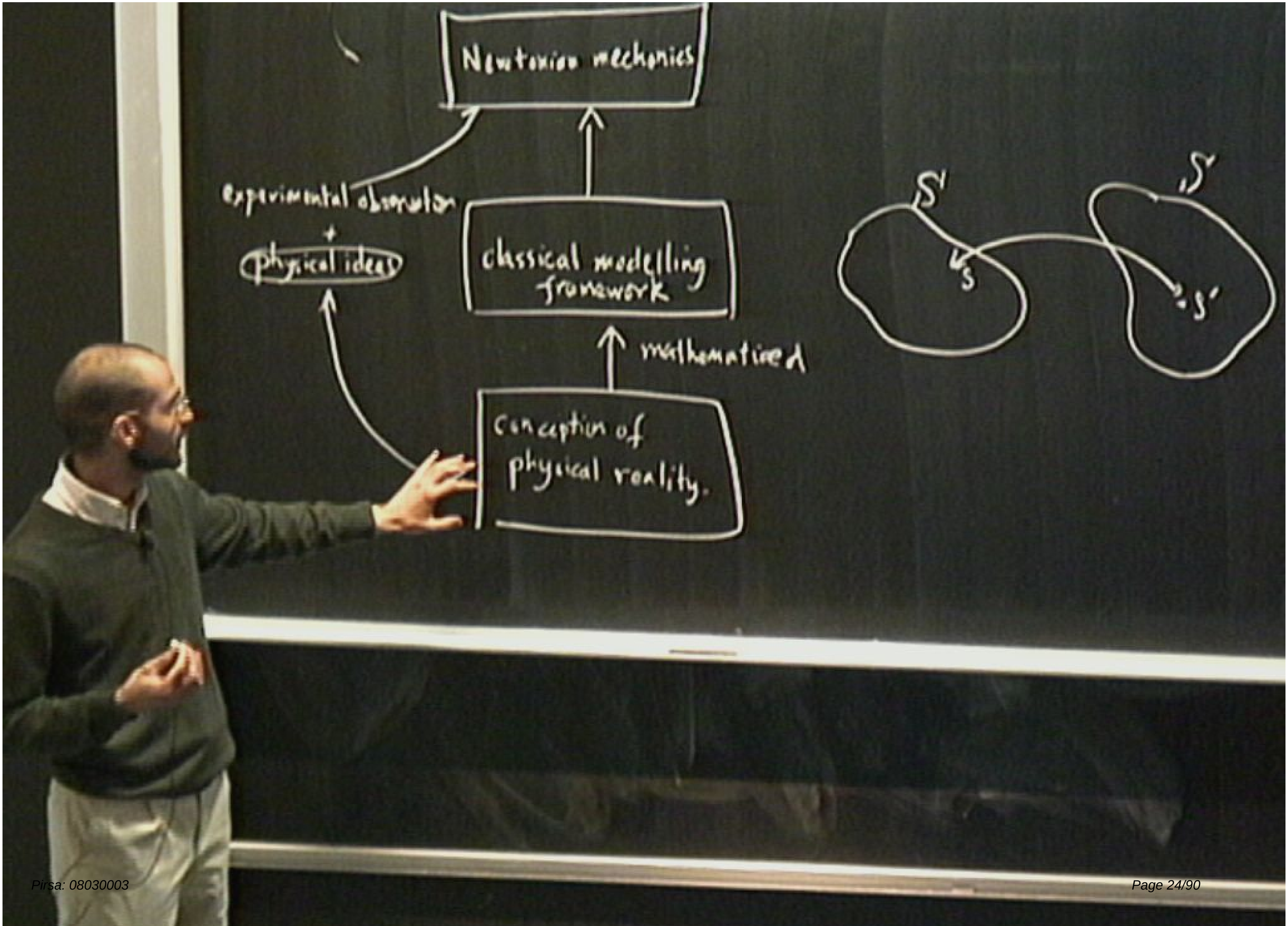
Historical Development of Quantum Theory: 1. A New Mechanics

New mechanics of Schroedinger and Heisenberg: a modification of classical physics guided by new physical ideas and mathematical guesswork.

- Many non-classical features: statistics, complementarity.
- Many mathematical features (e.g. complex numbers) had no obvious physical basis or meaning.
- Some key interpretation of the mathematics was given post hoc, e.g. $|\psi(x,t)|^2$ as probability density and not a physical wave.
- Pre-supposes the existence of the classical, everyday world of definiteness.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- Dirac and von Neumann developed a Quantum Modelling Framework through a mathematically-guided abstraction from the mechanics of Schroedinger and Heisenberg.
- It inherits from the mechanics of Schroedinger and Heisenberg:
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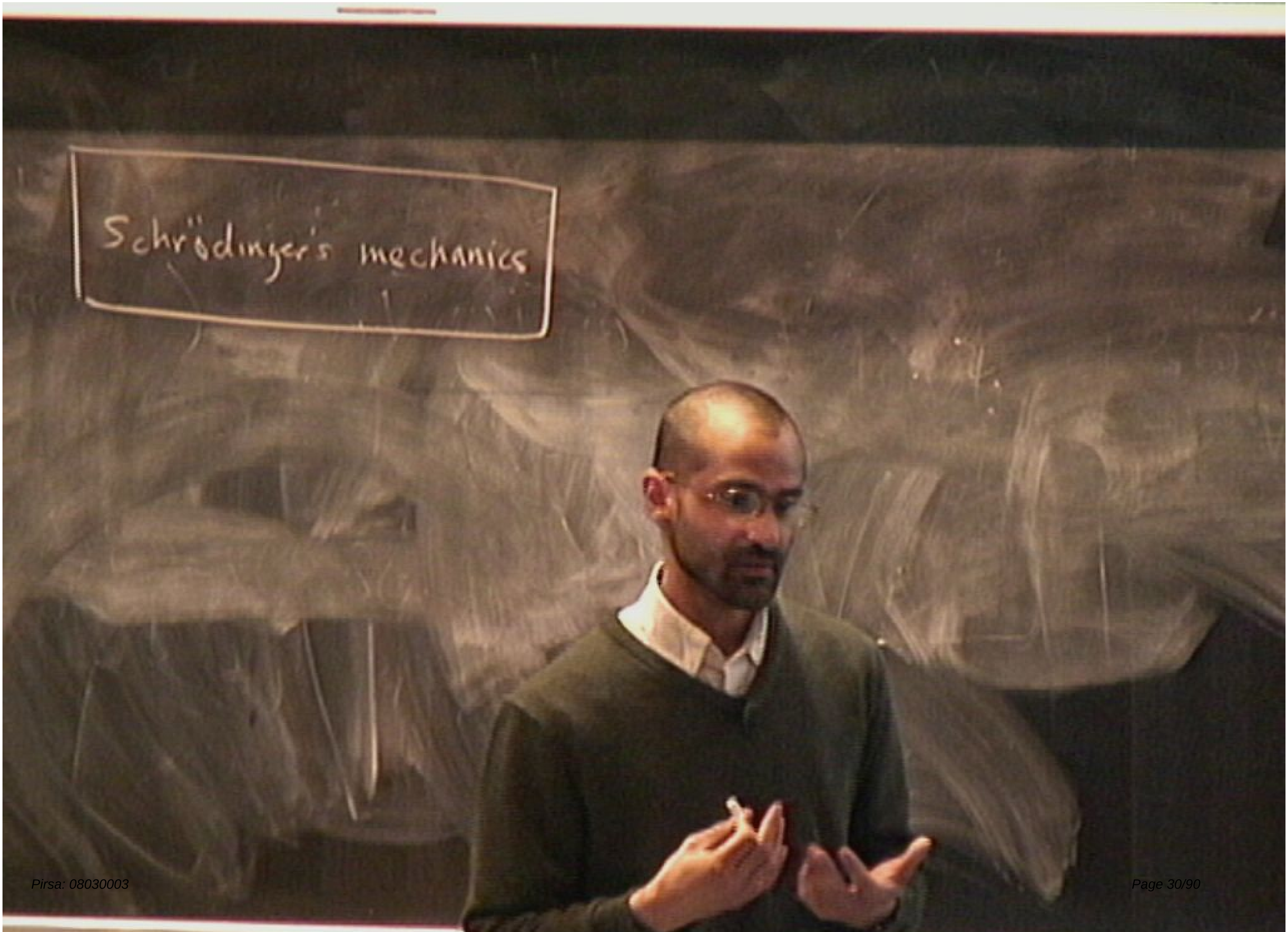
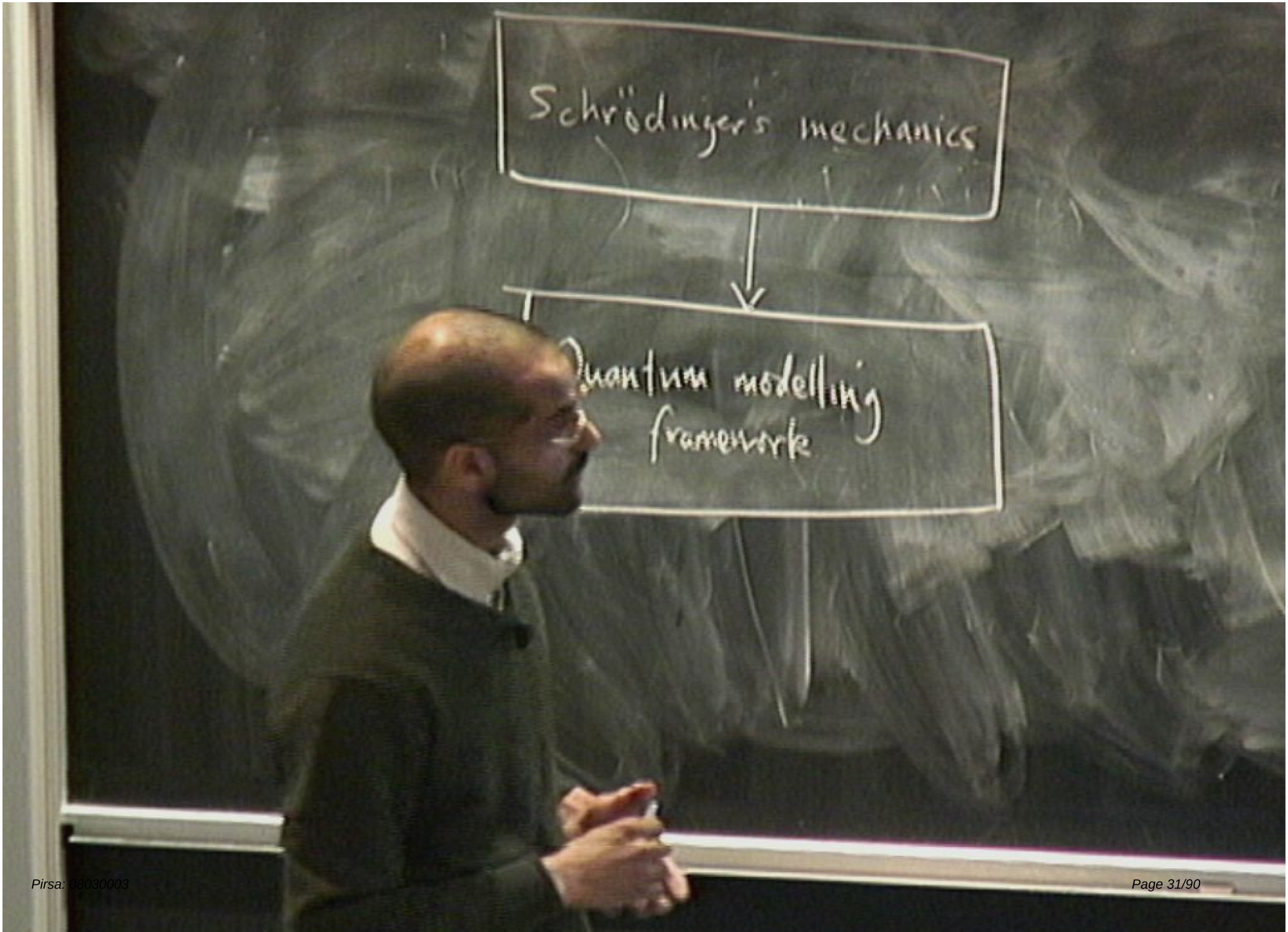

Schrödinger's mechanics


Schrödinger's mechanics
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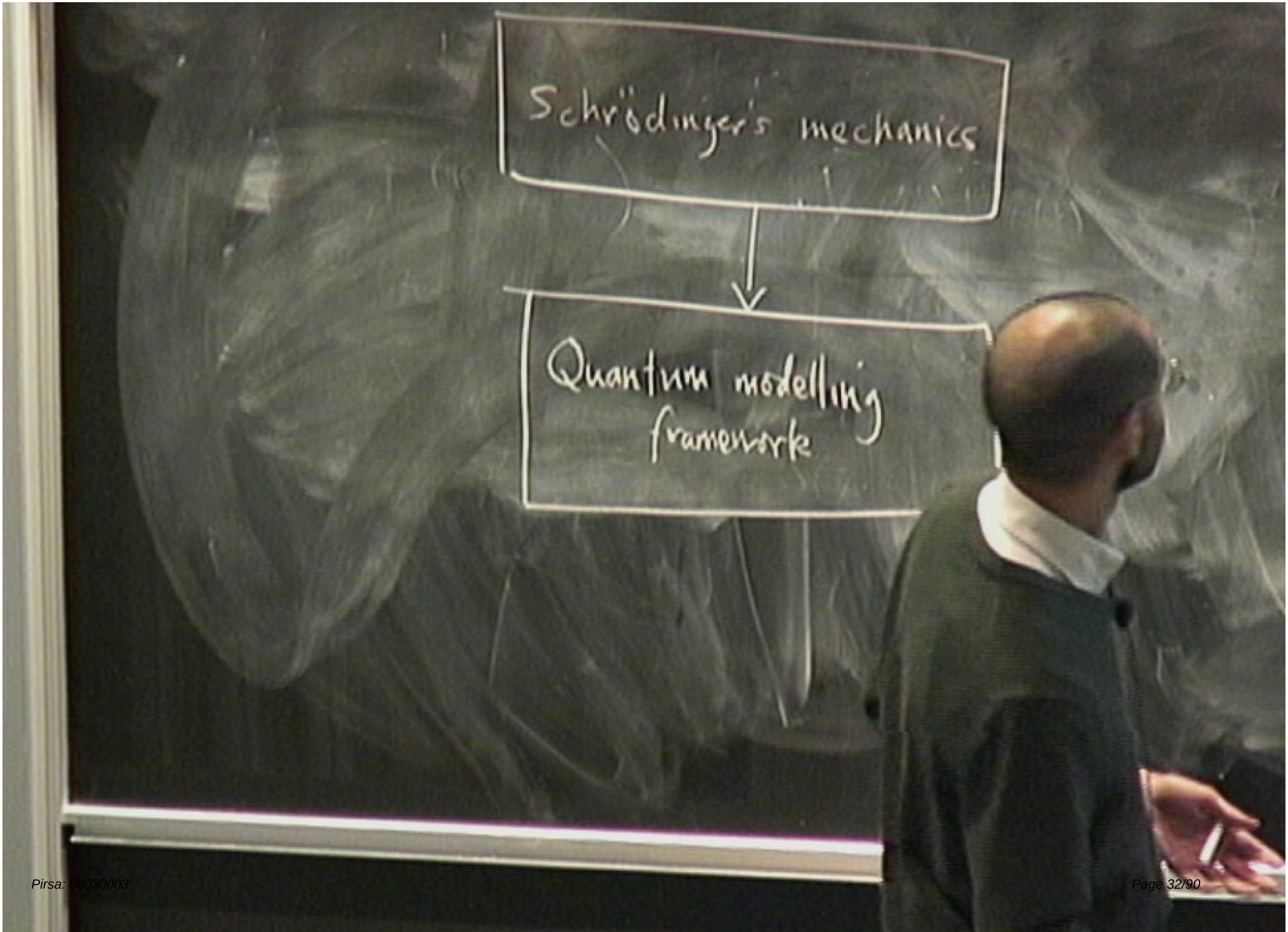
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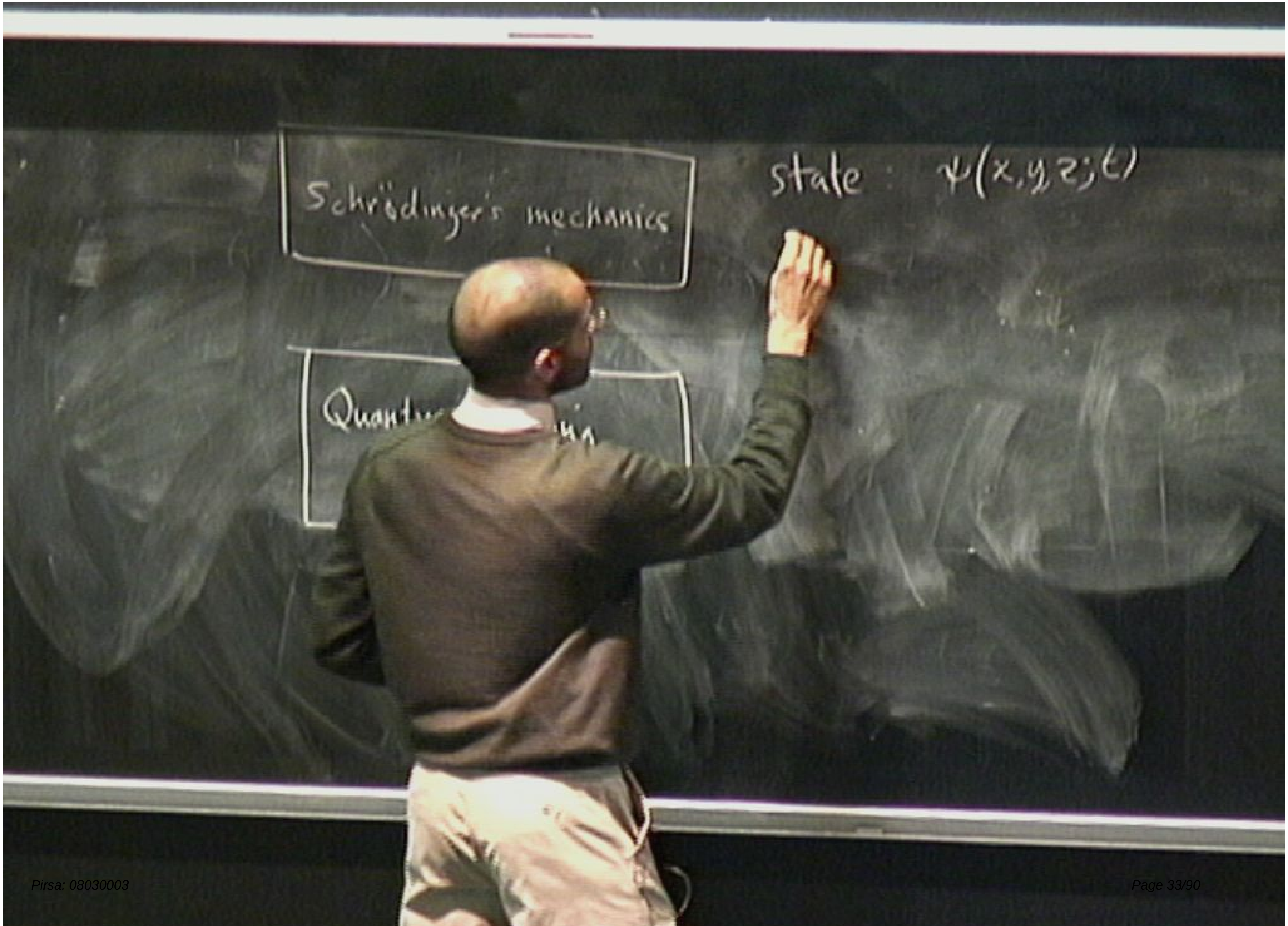
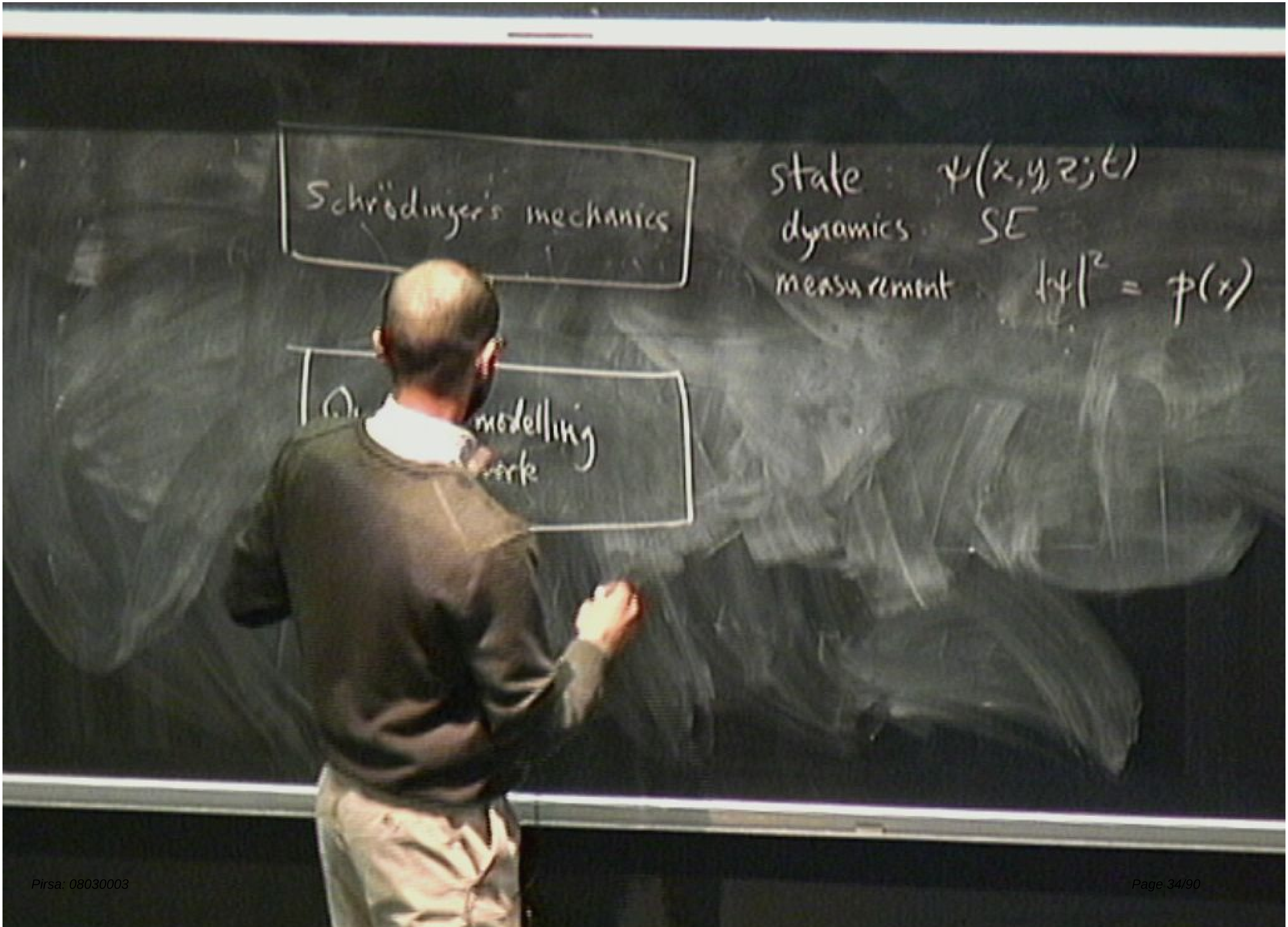

Schrödinger's mechanics
state : ψ(x,y,z;t)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state : ψ(x,y,z;t)
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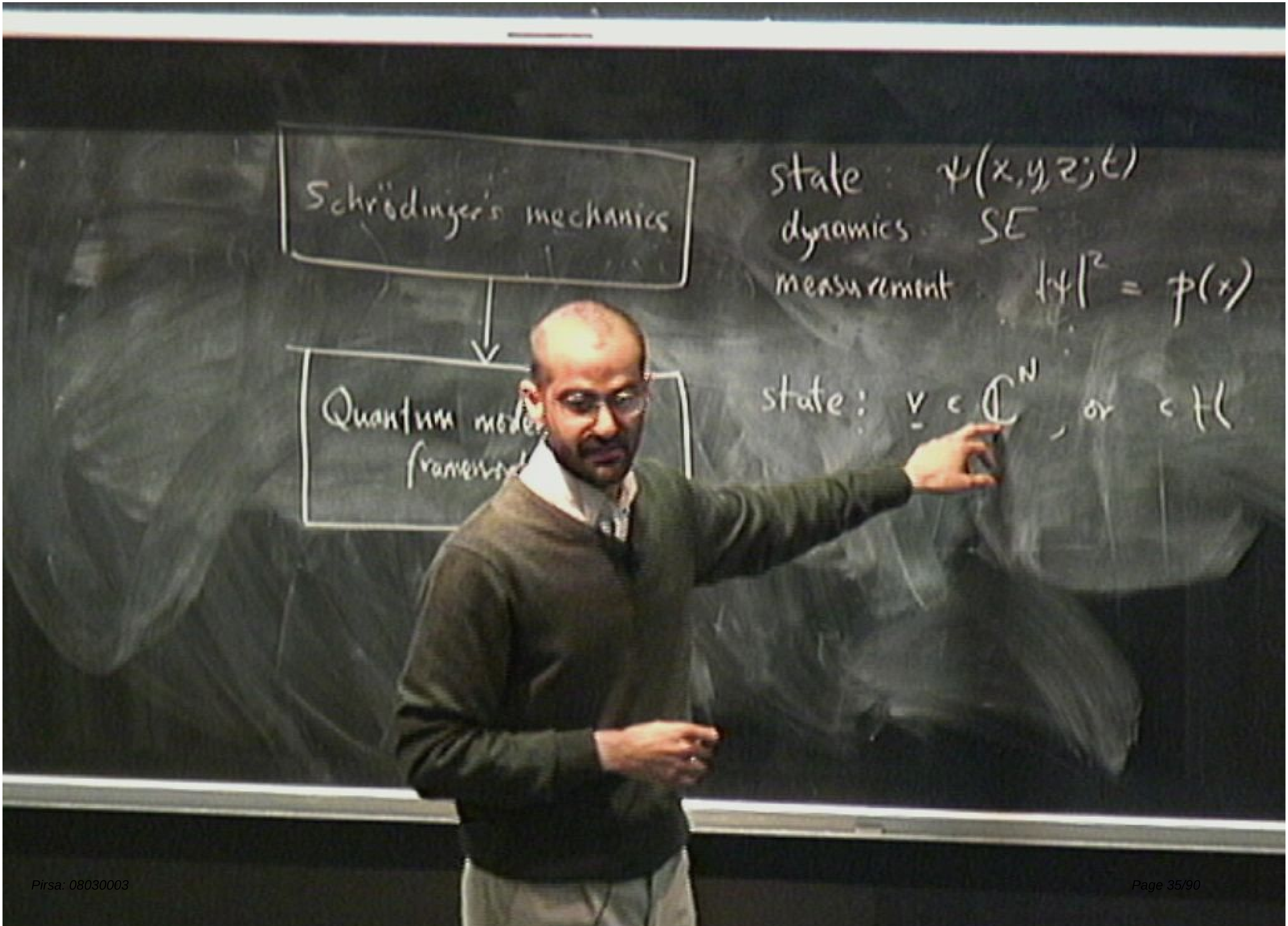
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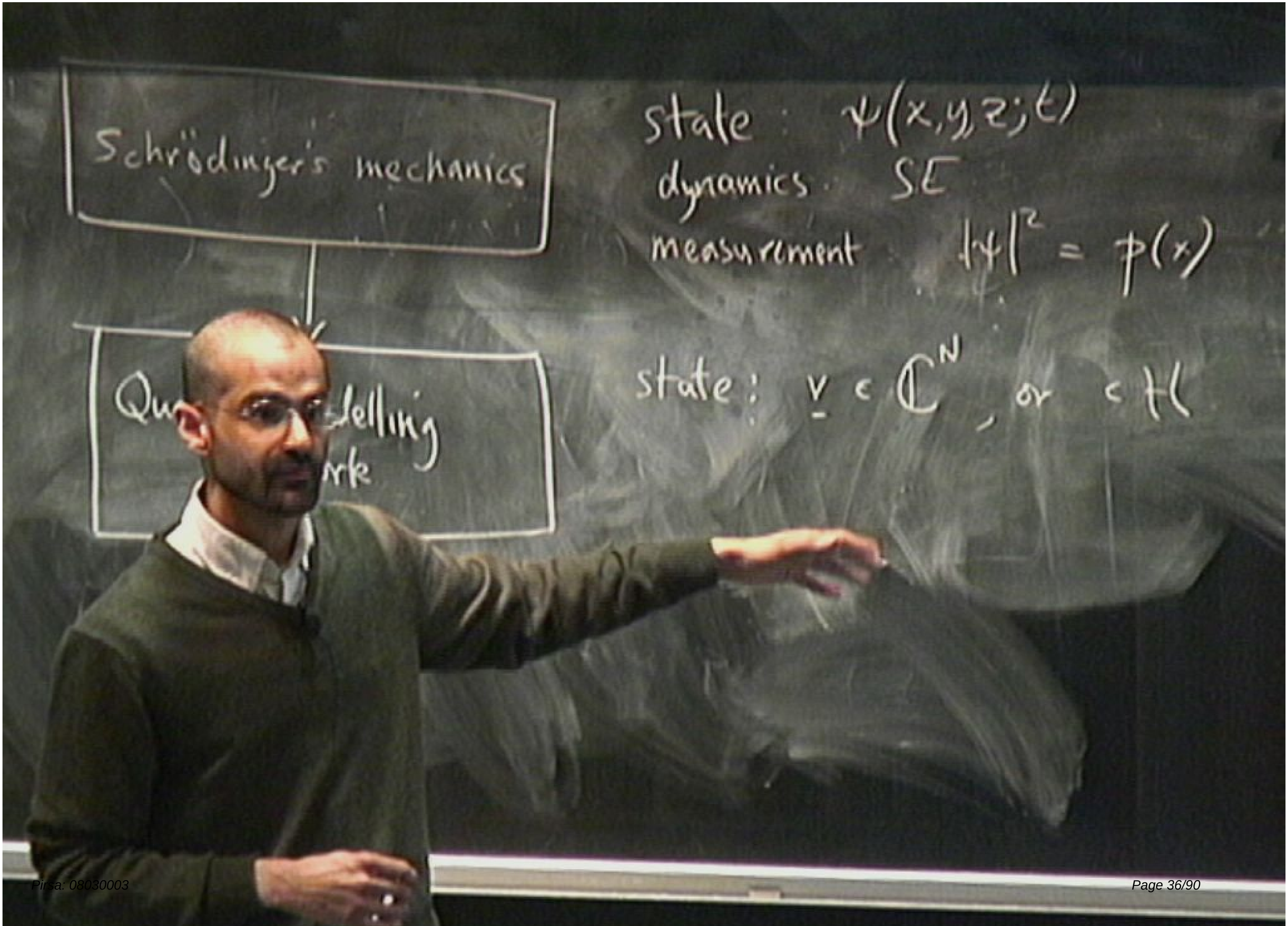

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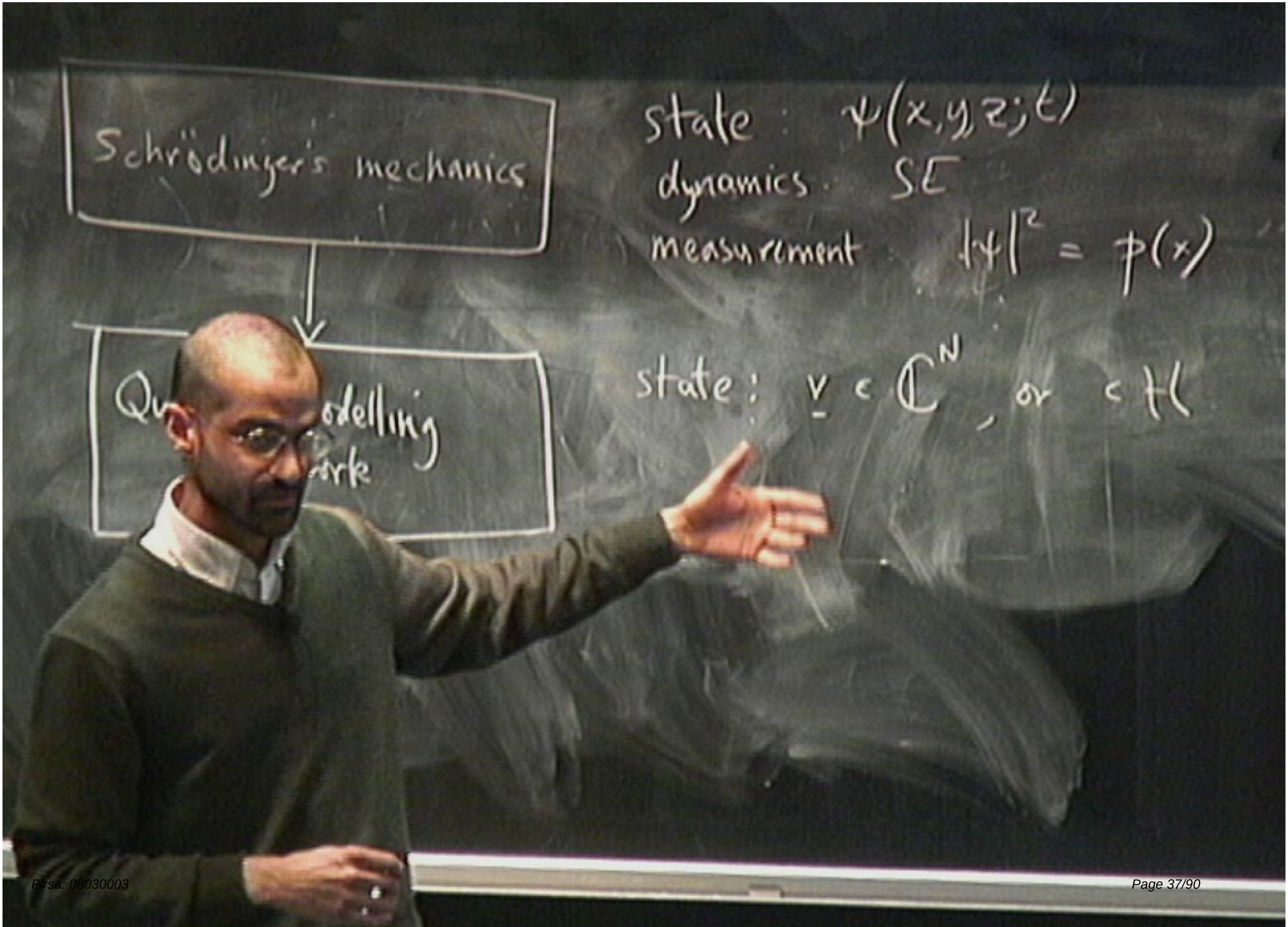
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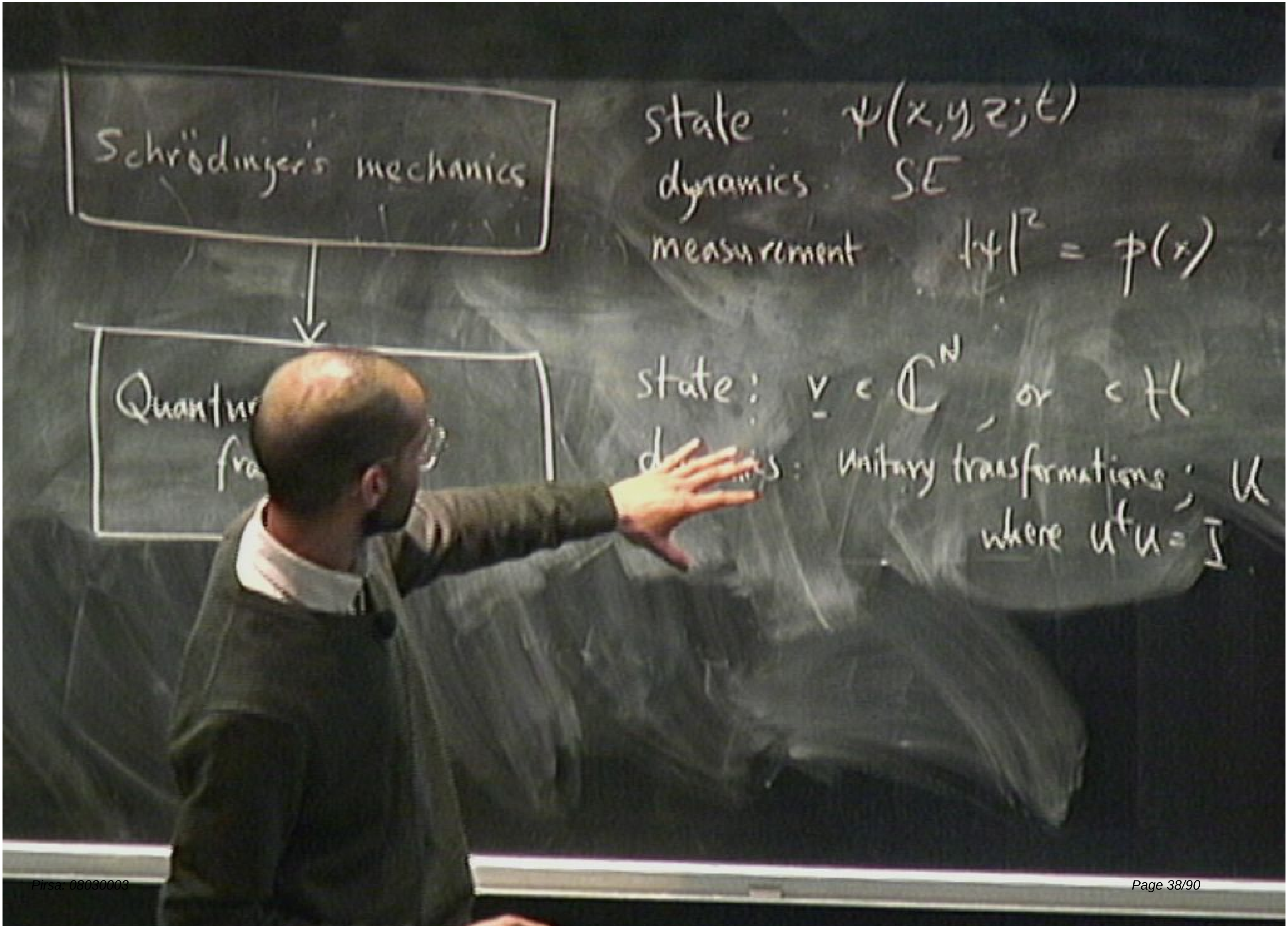

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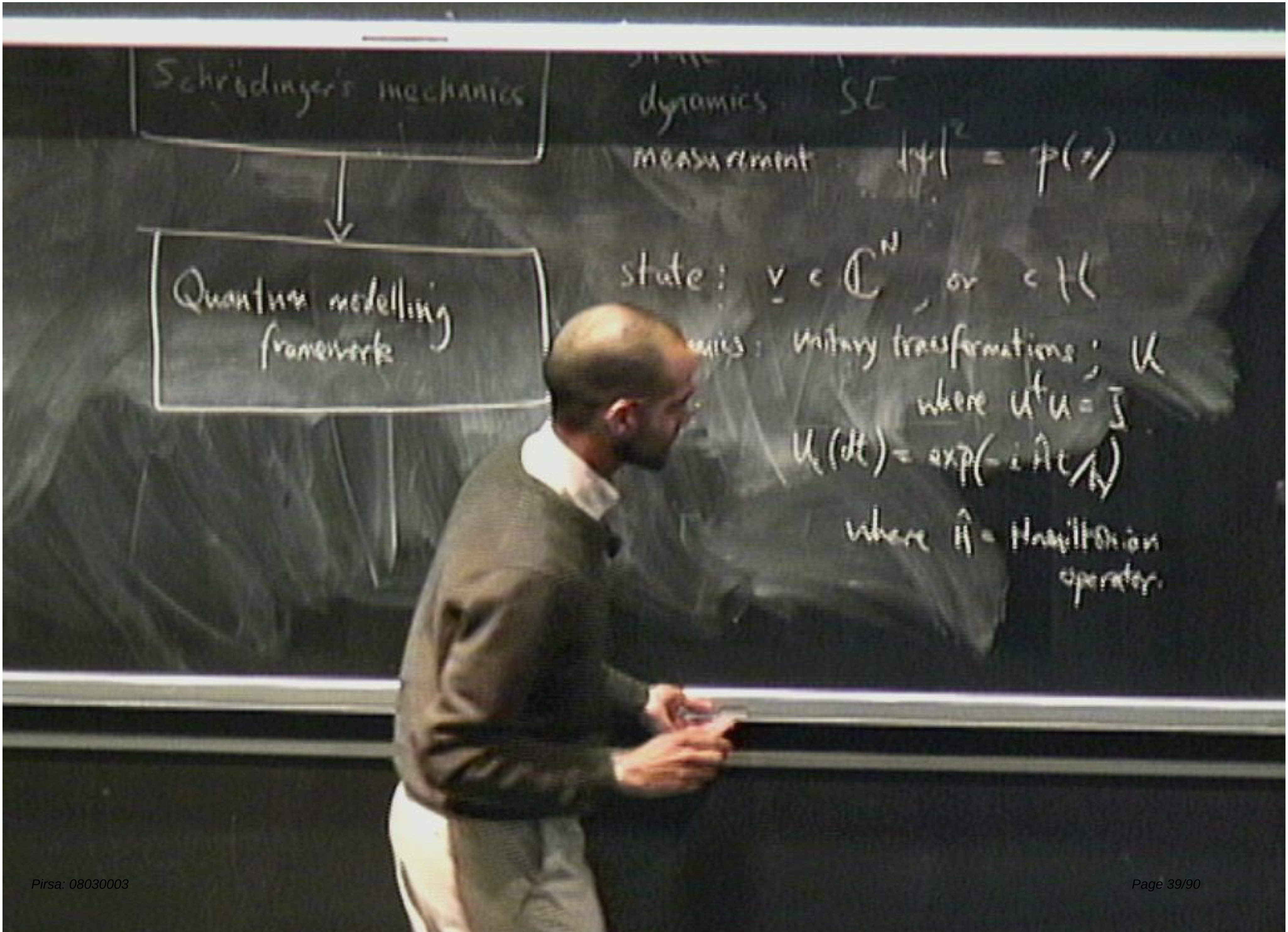
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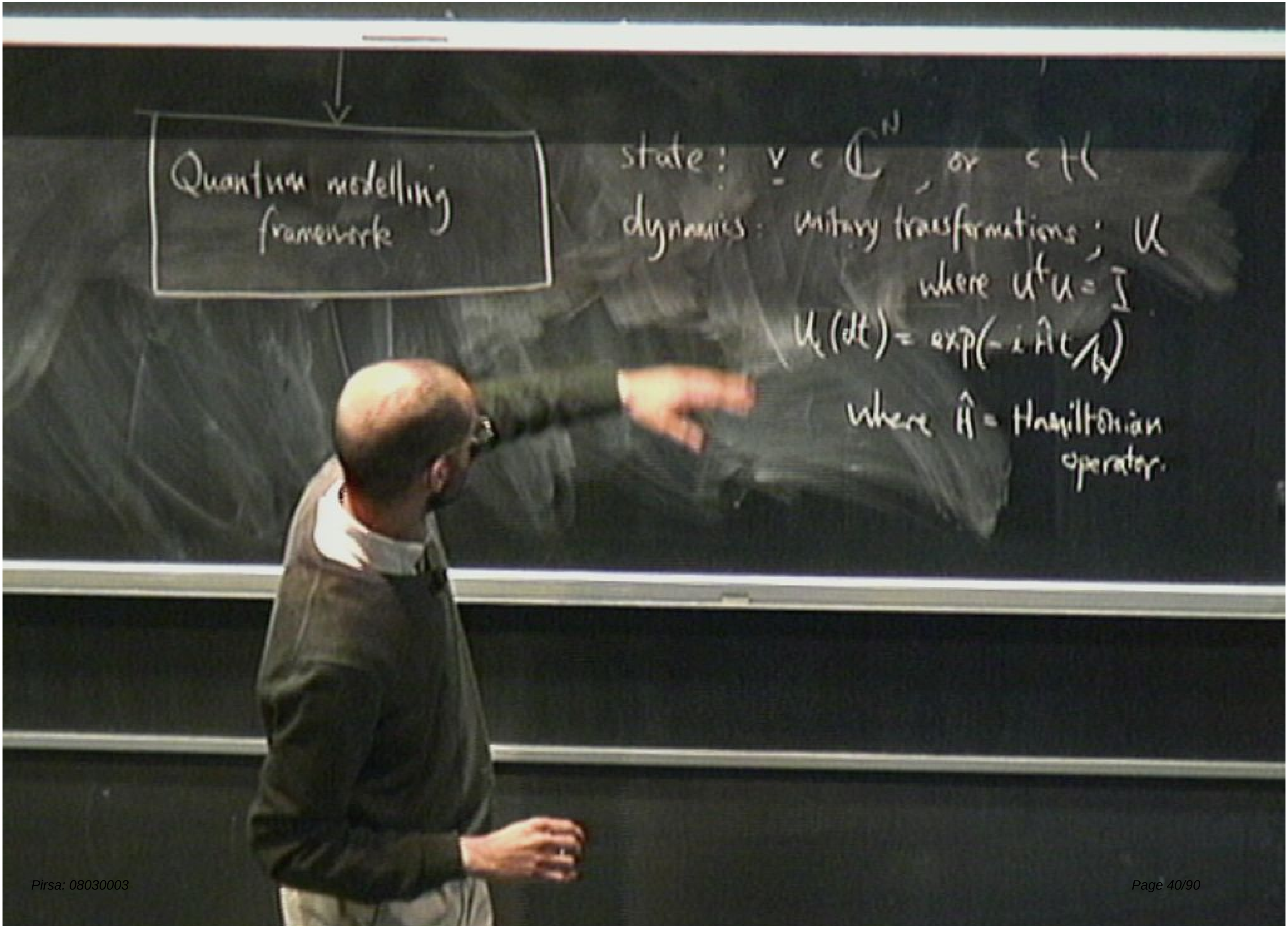
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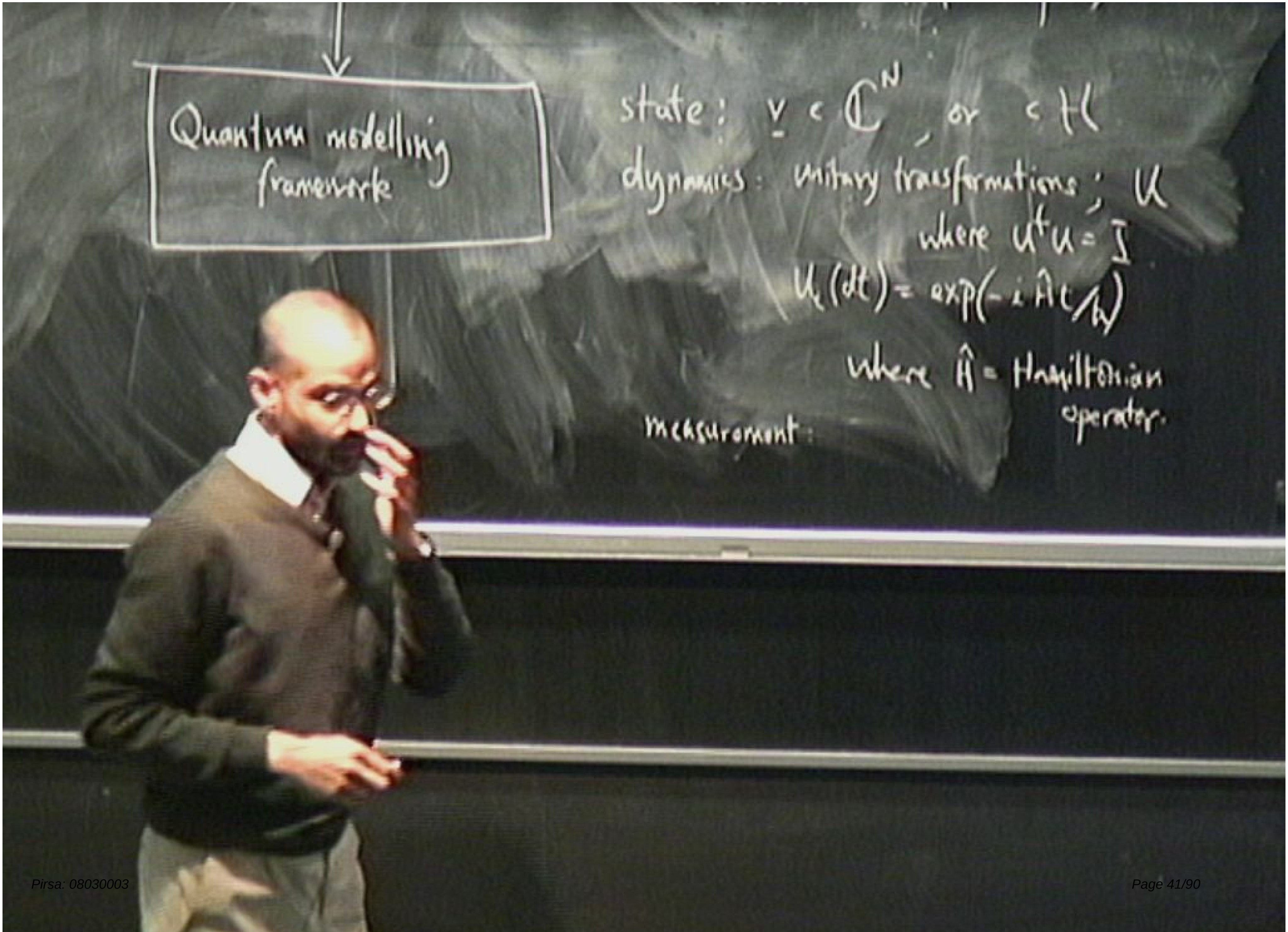
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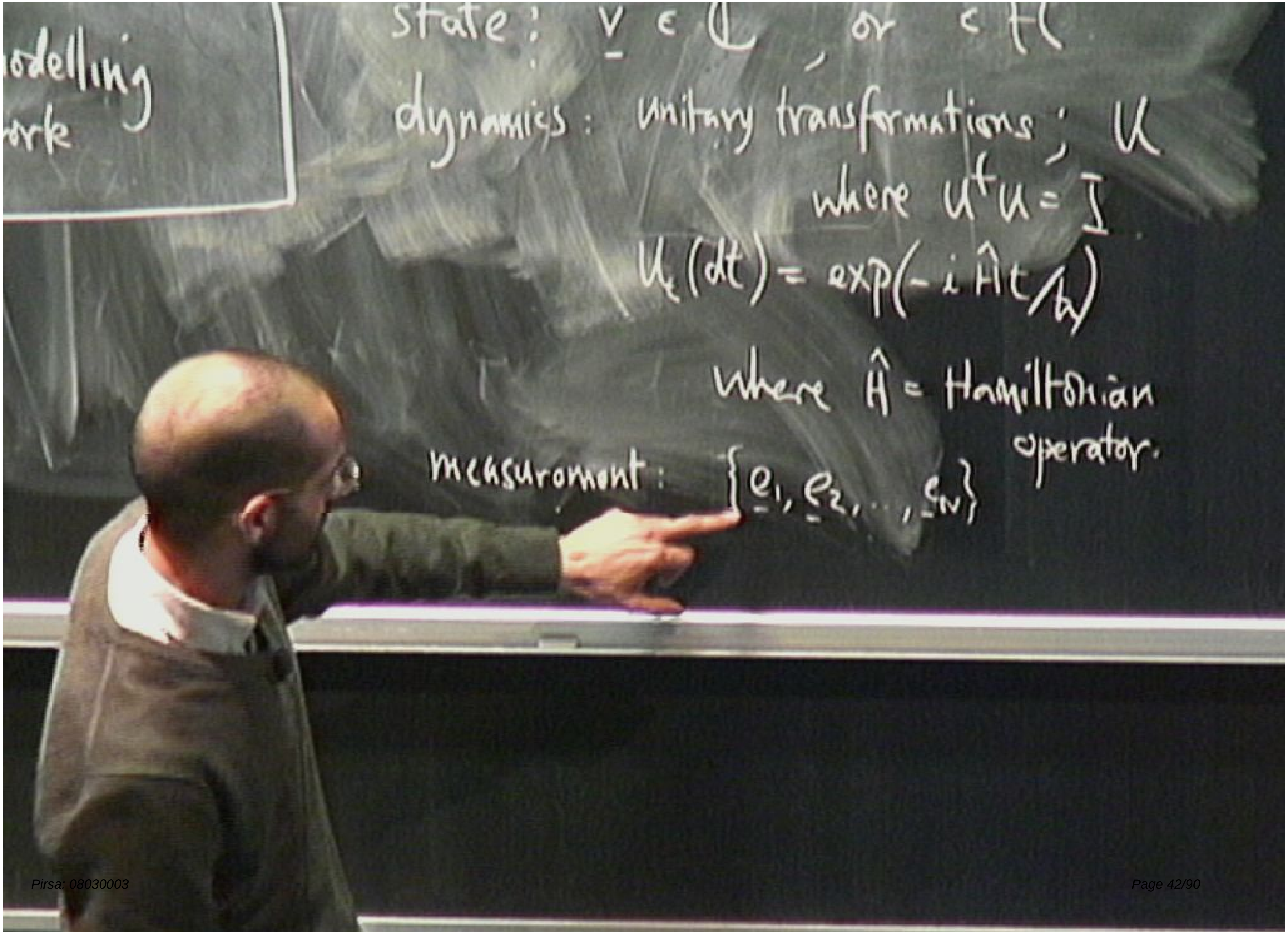
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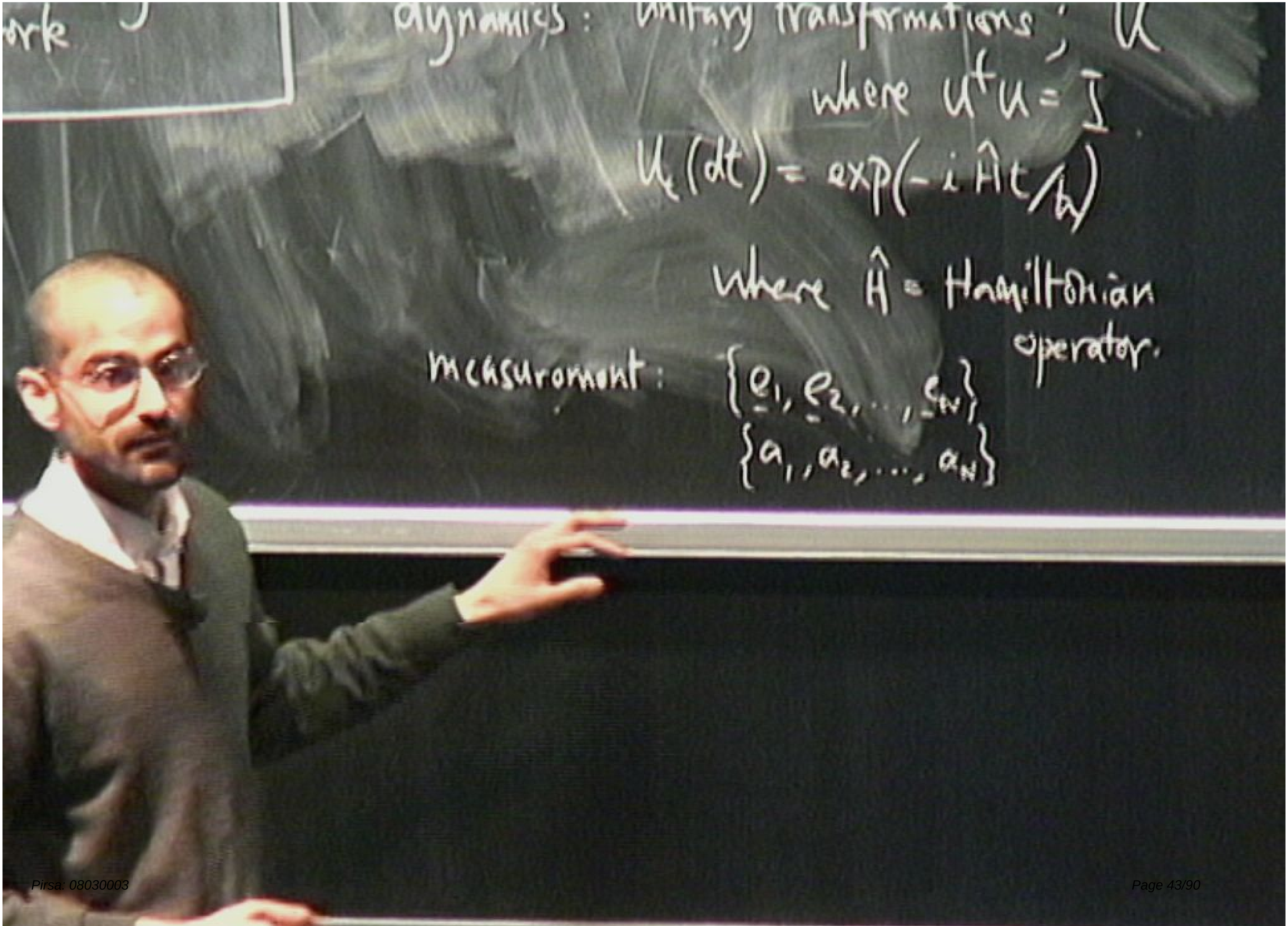
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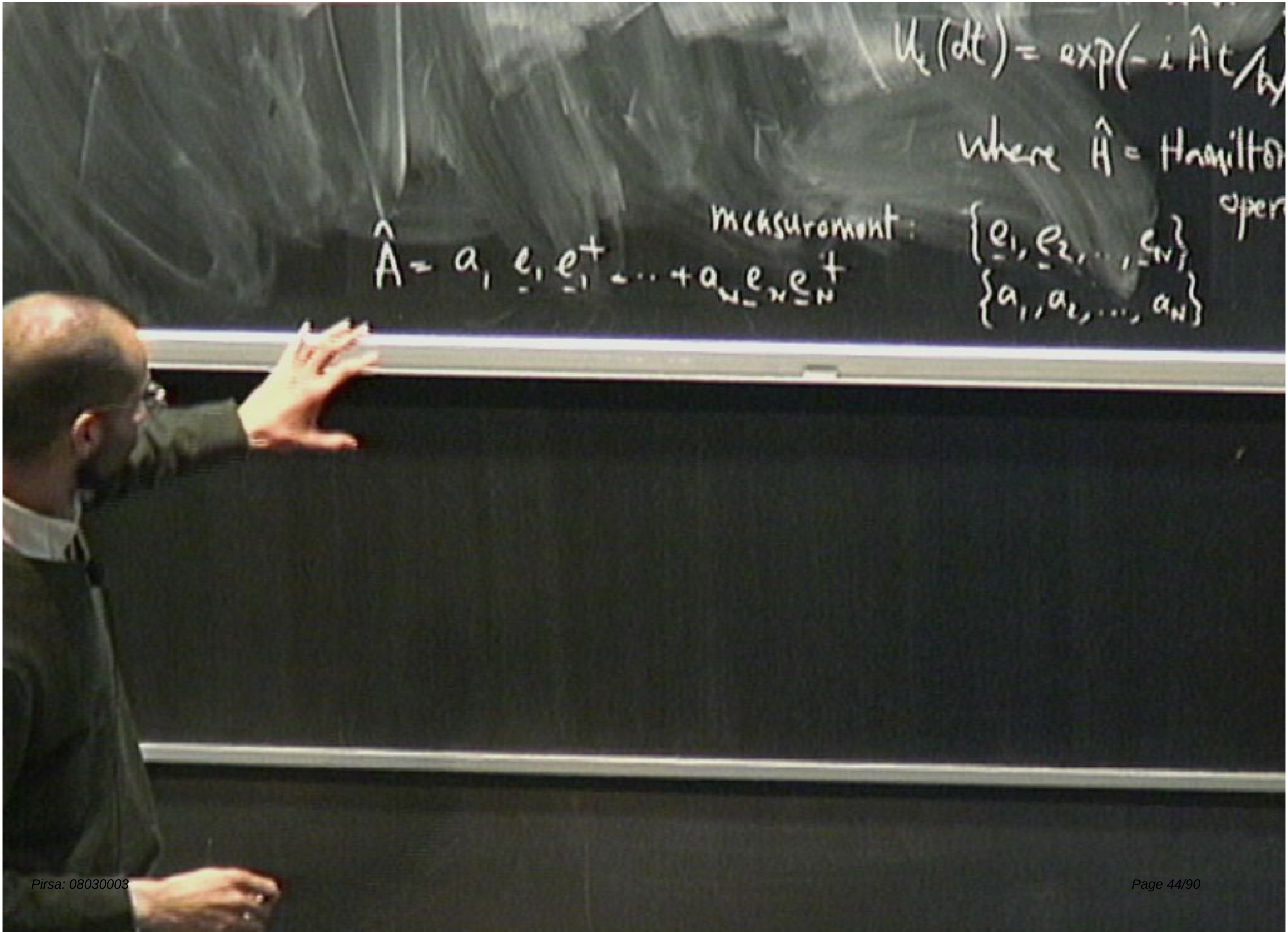
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Schrödinger's mechanics

↓

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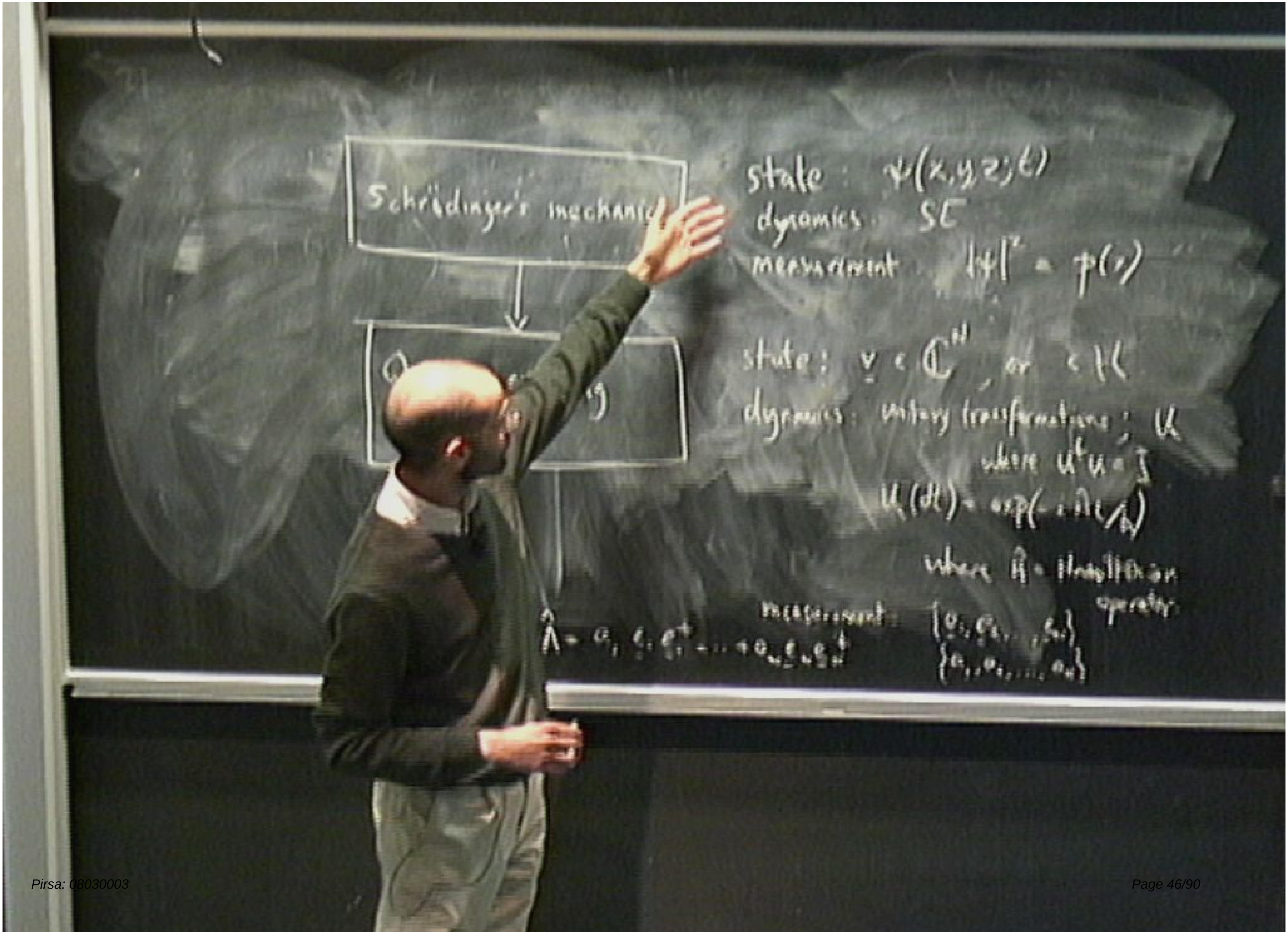
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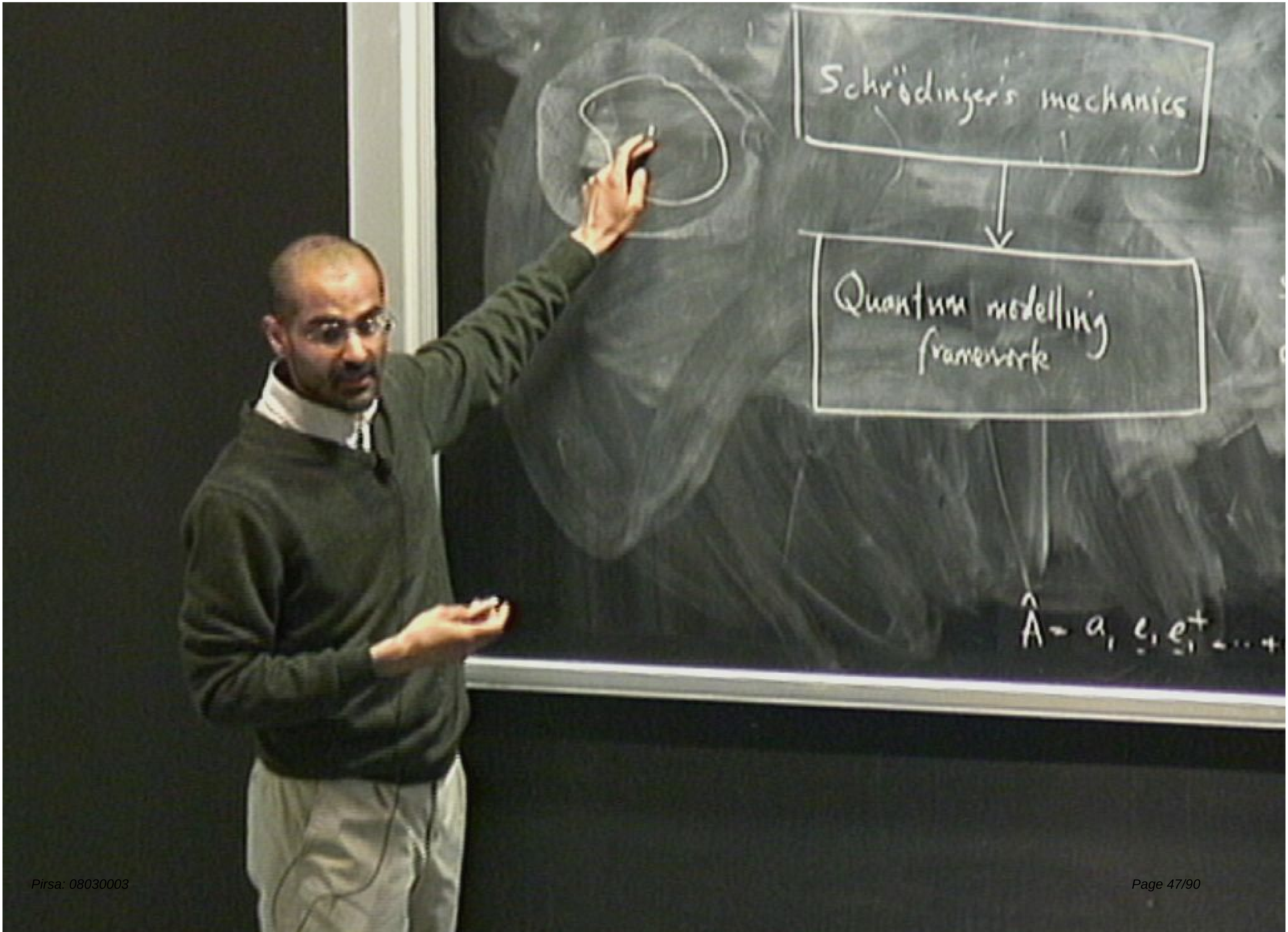
Schrödinger's mechanics
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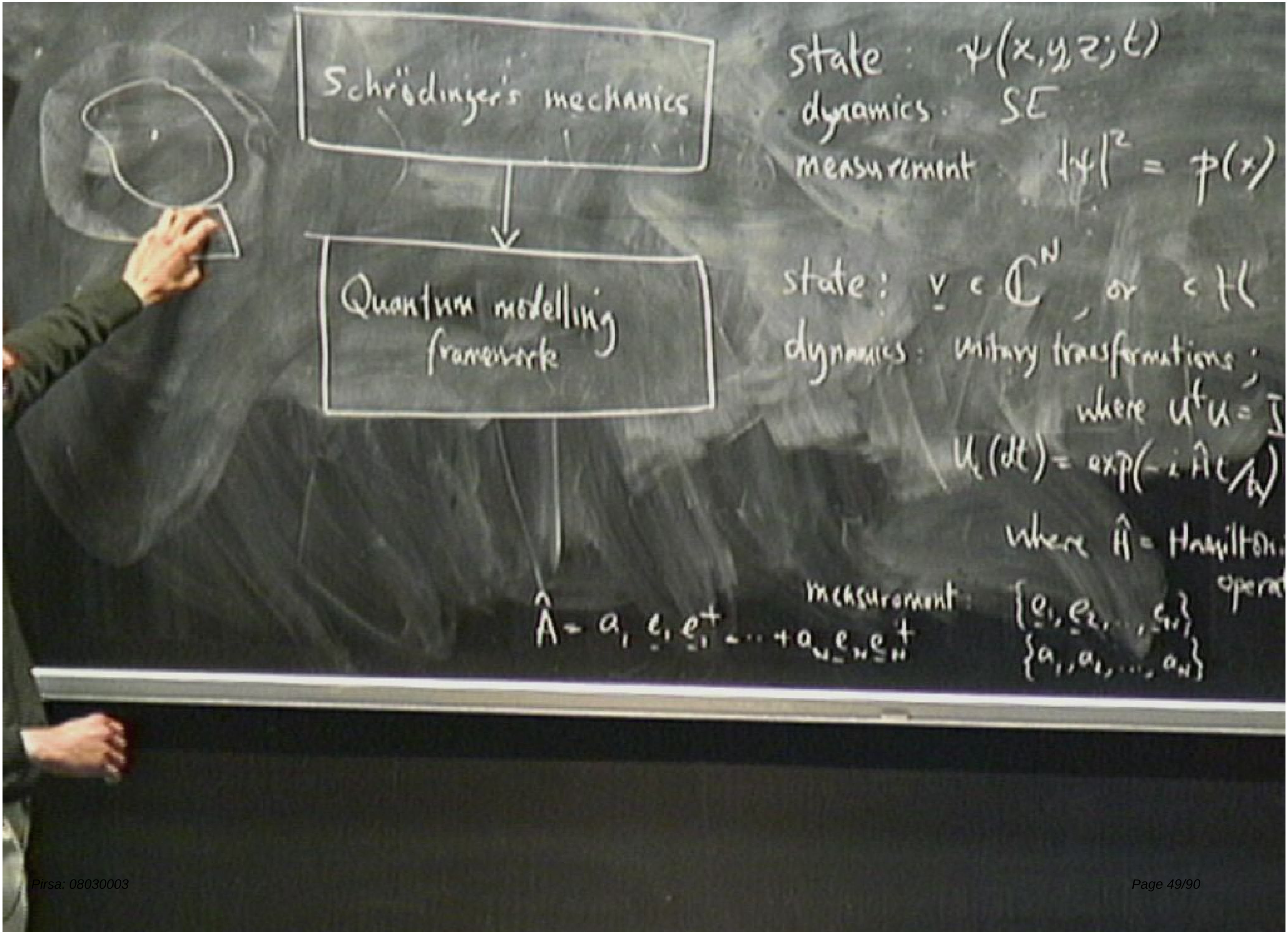
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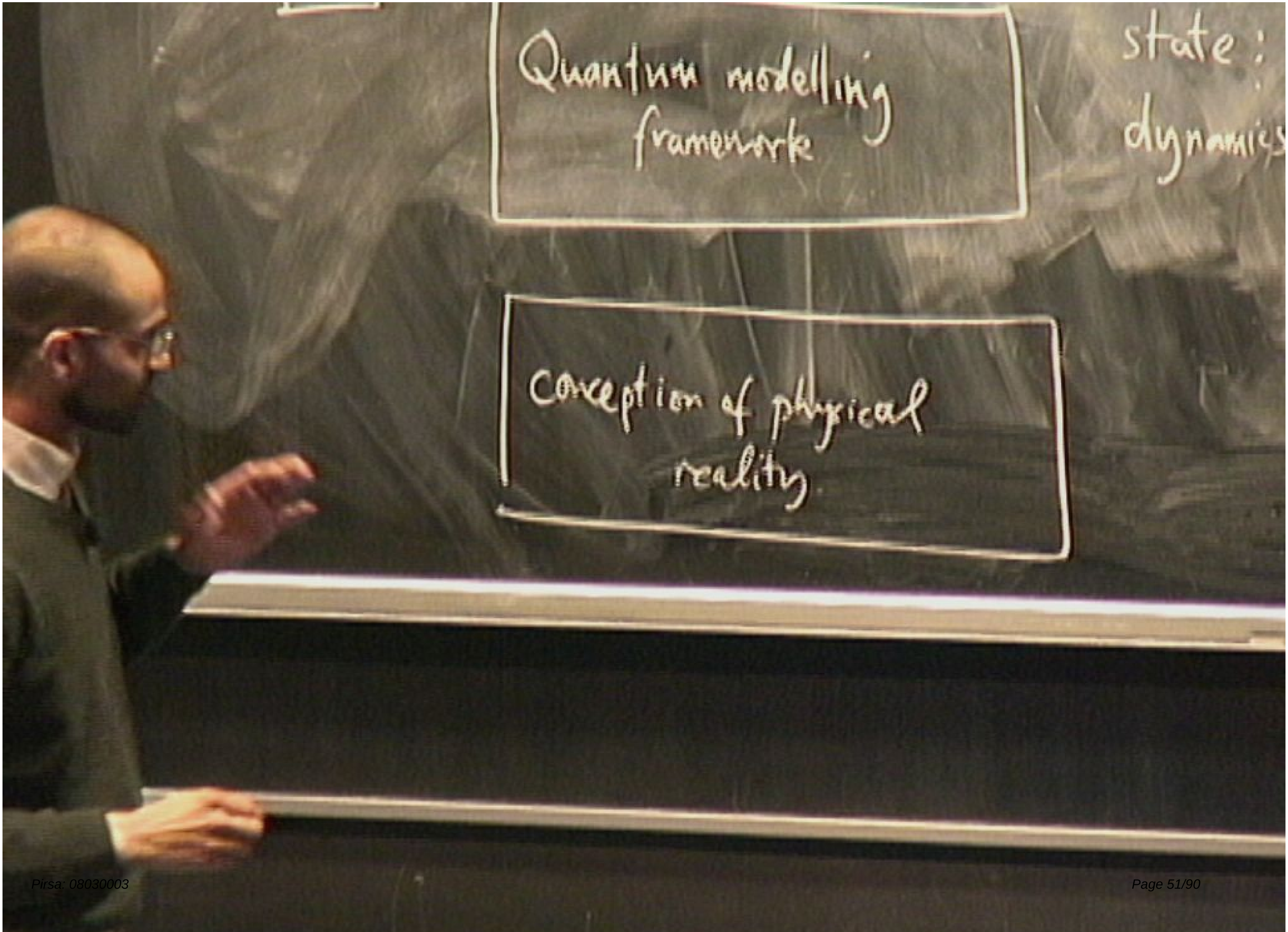
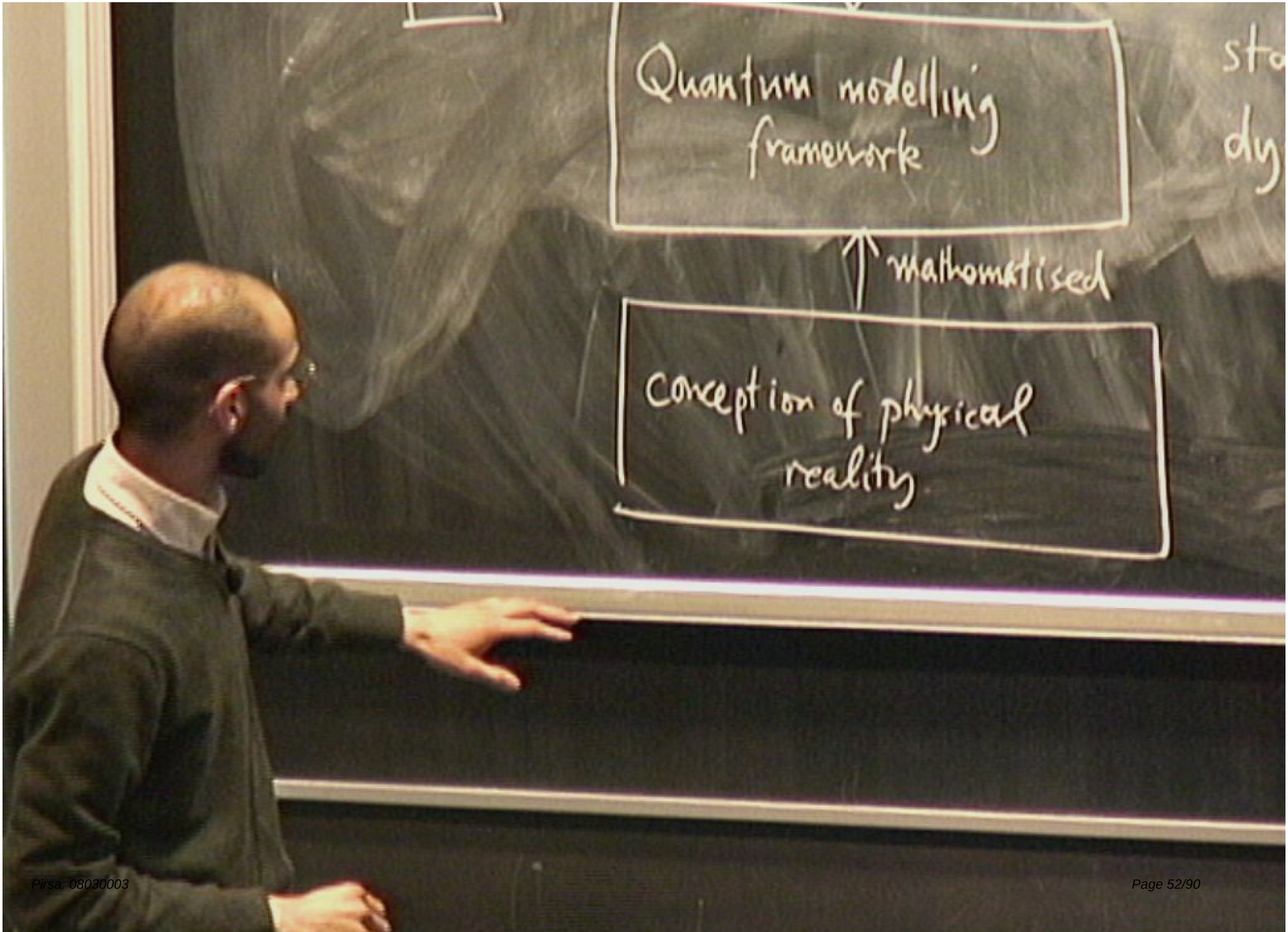
So, what is lacking in our understanding?

- We lack a clear conception of reality which underpins the quantum modelling framework.
- In particular, in the quantum modelling framework itself:
  - We do not understand the physical basis of many of the key mathematical features of the formalism.
  - We do not understand the presupposition of the existence of a classical world of definiteness.


Quantum modelling framework
conception of physical reality
state :
dynamics


Quantum modelling framework
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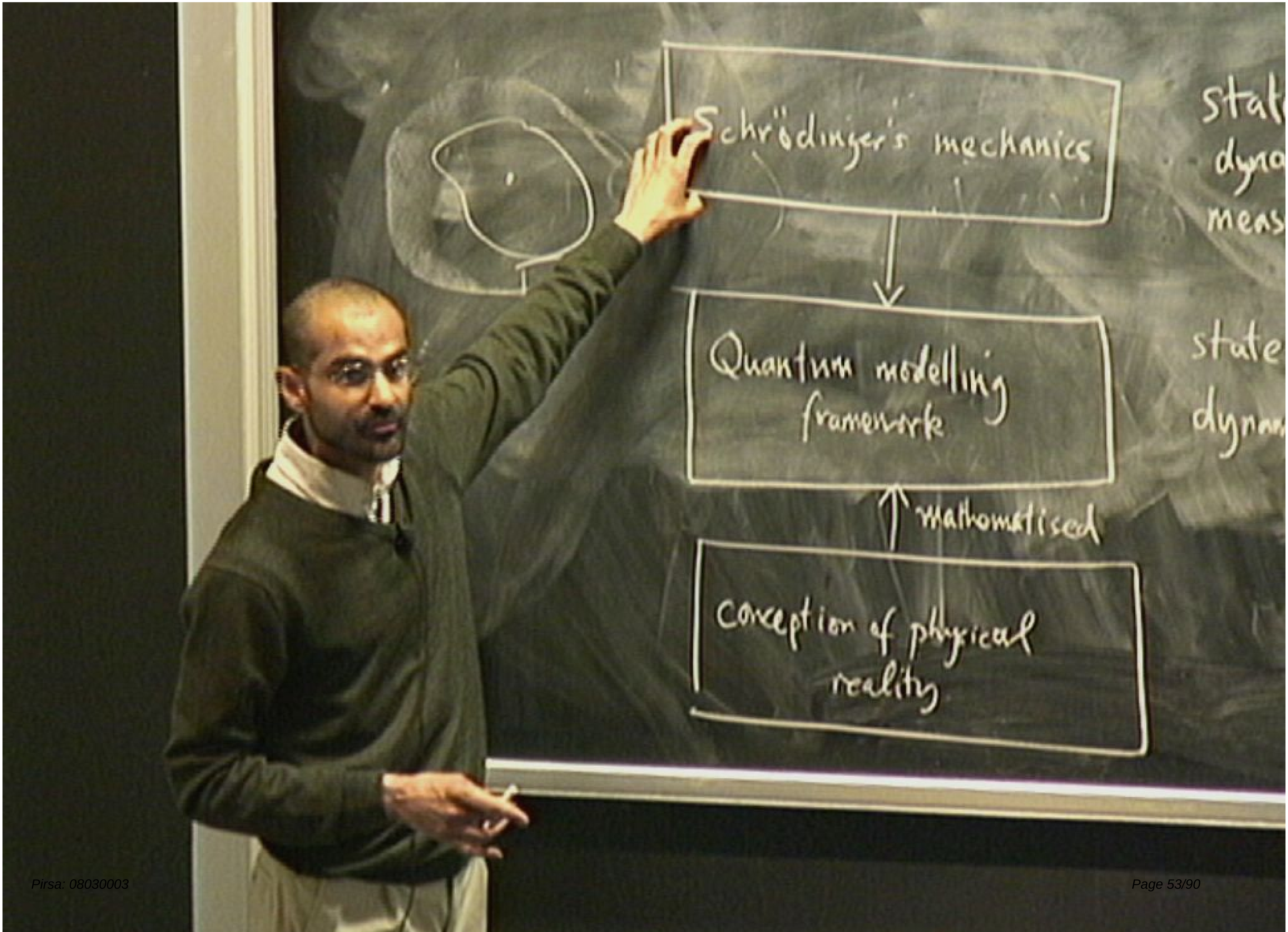
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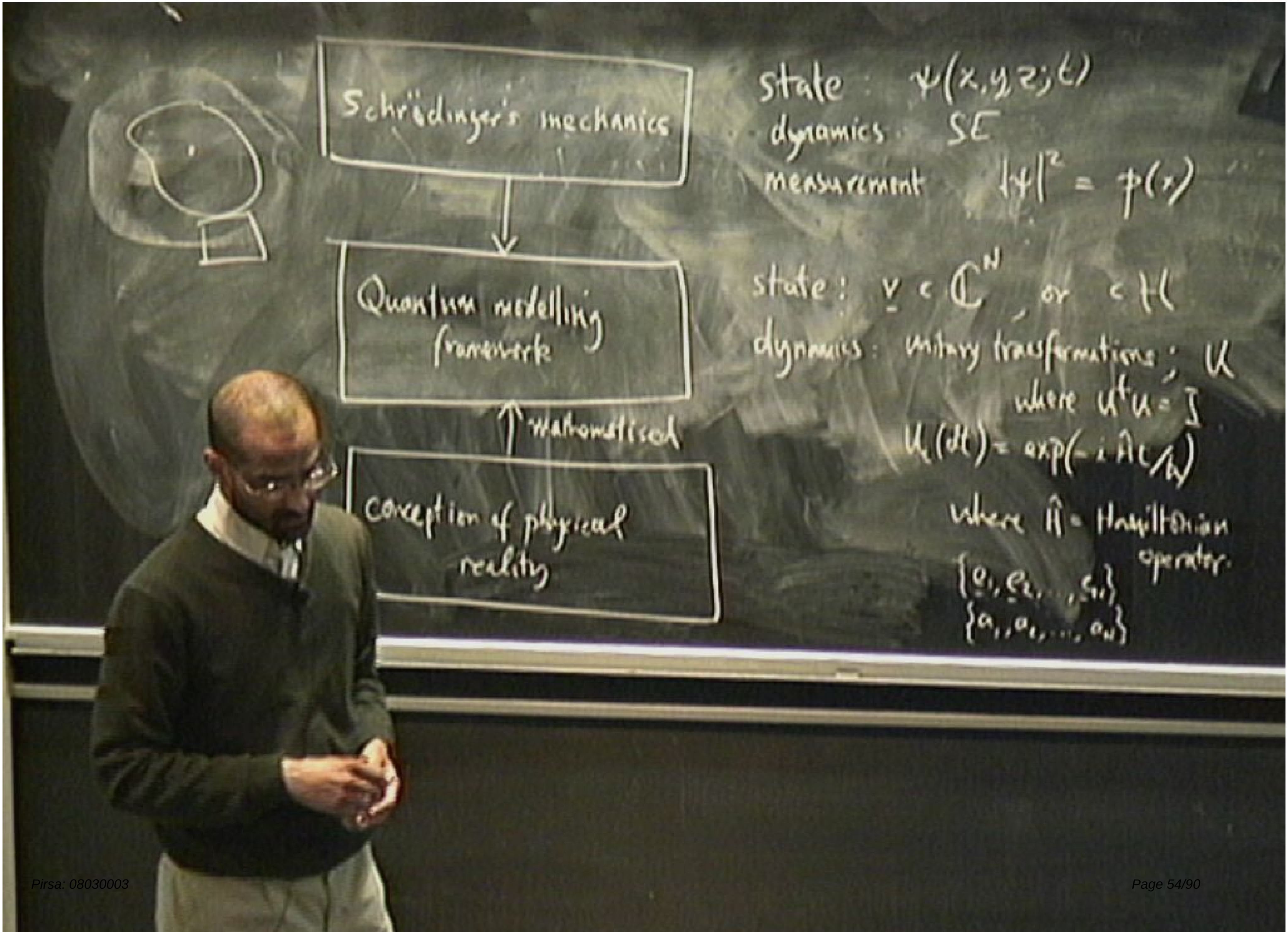
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What obstacles stand in our way?

Ideally, we would like a clear conception of reality which, when mathematised, leads to the quantum modelling framework.

The main obstacles to forming such a conception are:

- Lack of conceptual access to the full mathematical content of the quantum modelling framework.
- Unclear understanding of the presupposition of the classical world in the formulation.
- Sheer conceptual difficulty of grasping the non-classical properties of quantum reality from a single unifying perspective.

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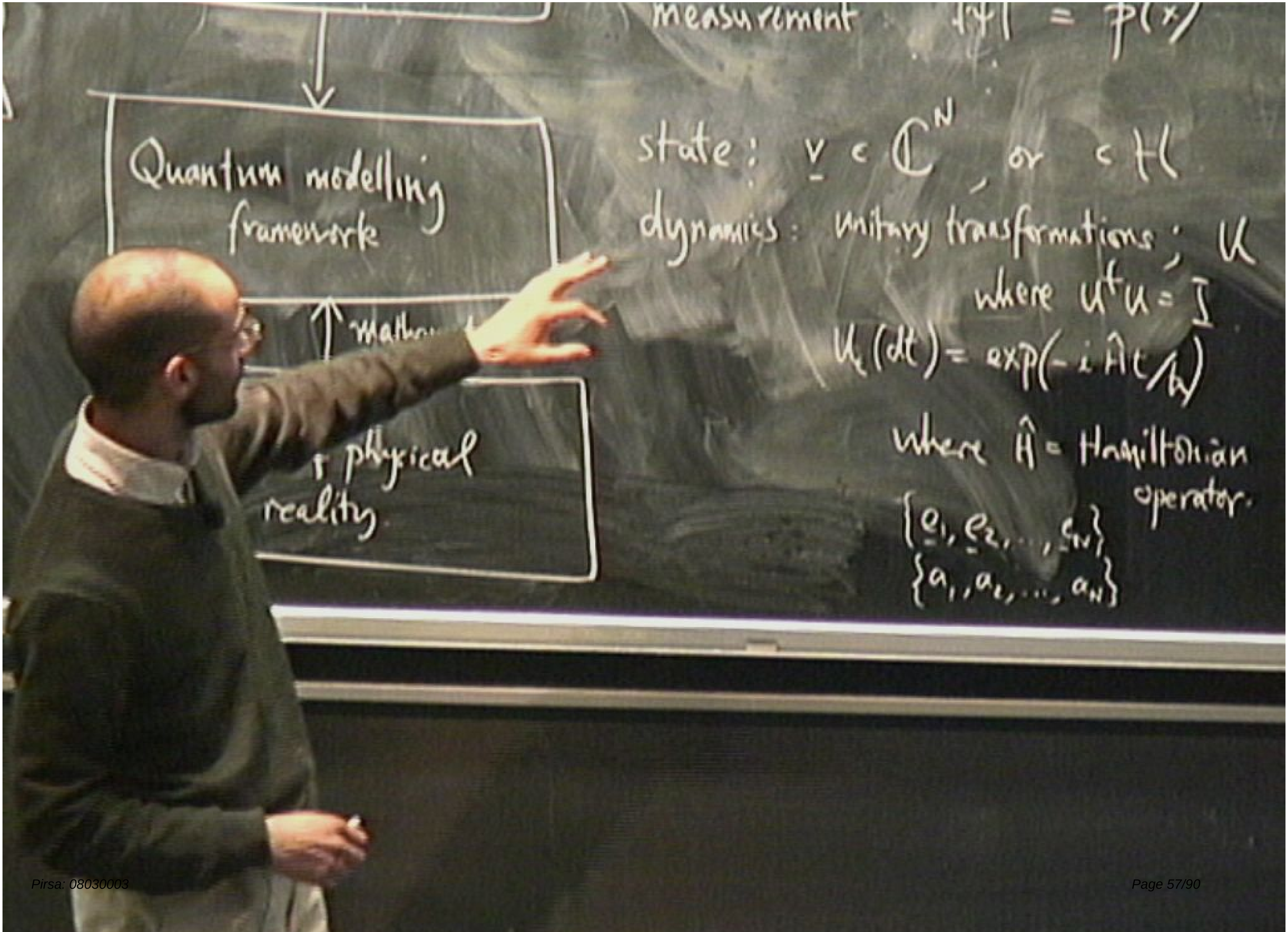

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What is needed to overcome these obstacles?

- We need to know what physical ideas underpin the quantum modelling framework.
- We need as many clues as possible of what the quantum world 'looks like' (i.e. what properties it has).
- We need the philosophical imagination and philosophical resources to form a conception of reality that provides a unified understanding of the various properties

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What has been done?

1. Interpretations: provide a conception of reality which makes sense of some features of the quantum modelling framework.
   - Copenhagen Interpretation
     - Argues for necessity of classicality assumption.
   - Many Worlds Interpretation
     - Attempts to dispense with classicality assumption altogether.
     - Argues for a universal wavefunction, and that, via decoherence, measurements as interactions with all possible outcomes occuring can be made sense of.
     - Argues that probability still makes sense, and that the usual probability rules of quantum theory can be derived from reasonable assumptions.

What has been done?

1. Interpretations: provide a conception of reality which makes sense of some features of the quantum modelling framework.

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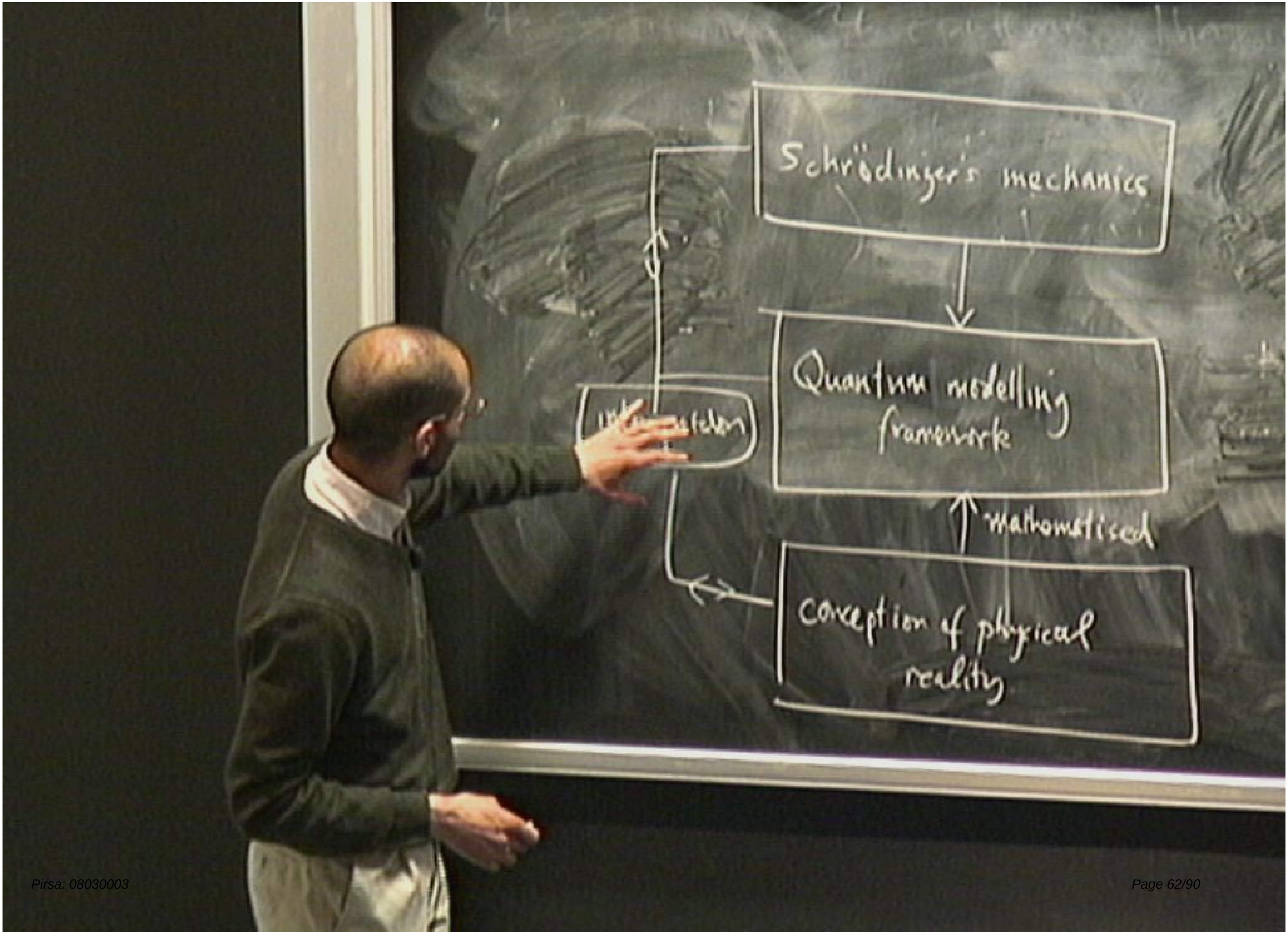
Schrödinger's mechanics
Quantum modelling framework
mathematised
conception of physical reality

2. Reformulations: mathematically re-express the quantum modelling framework or quantum mechanics in a new, physically suggestive way.

- Feynman path-integral reformulation
  - Quantum mechanics re-expressed in a Lagrangian form.
  - A Classical limit of quantum mechanics becomes transparent.
  - Powerful aid to intuition in many situations.
- Bohm reformulation
  - Schroedinger equation re-written in form closely resembling the Hamilton-Jacobi equation.
  - Makes sharply apparent the non-local, instantaneous influences between particles.
  - Inspired Bell's exploration of non-locality.

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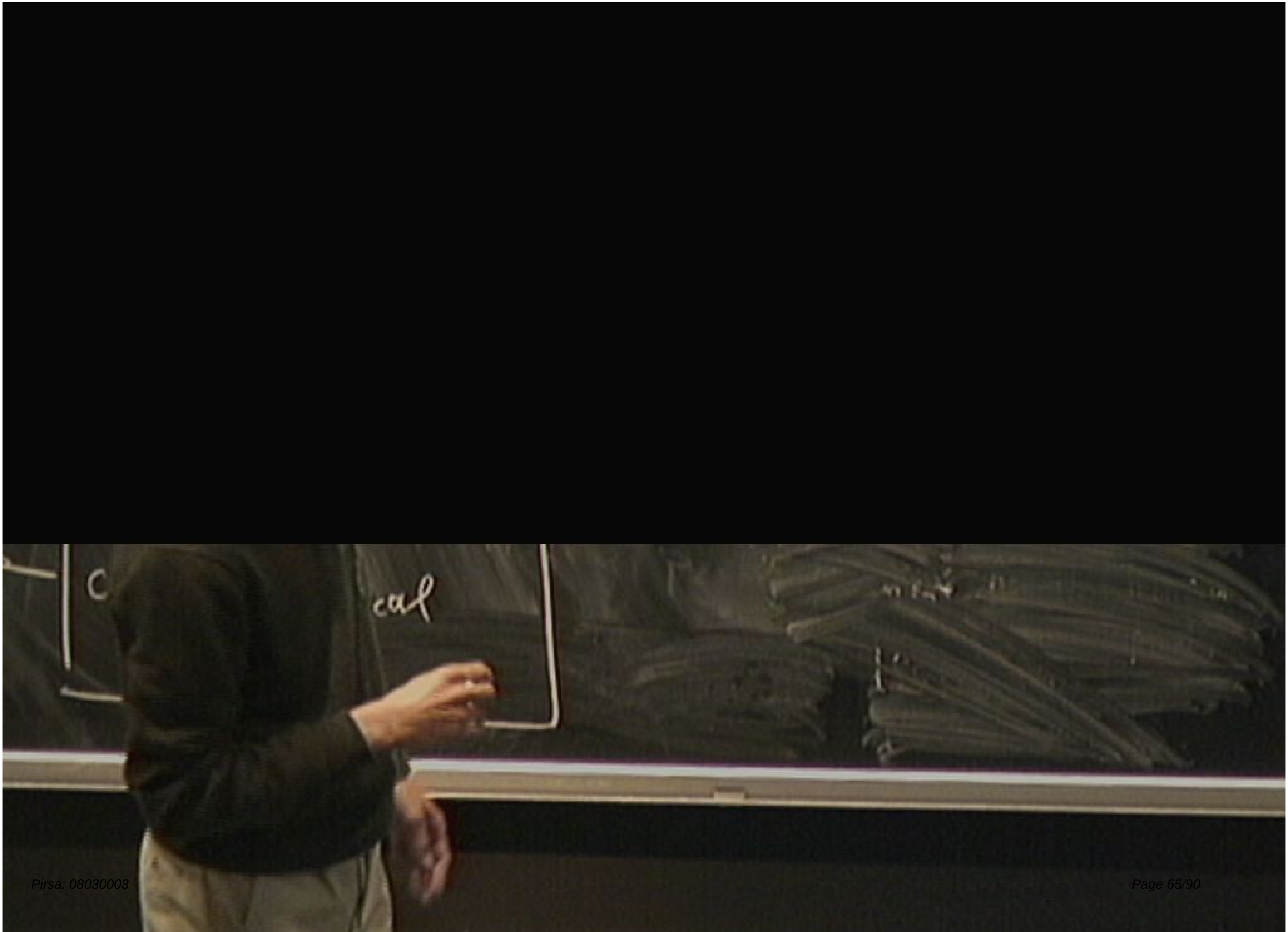

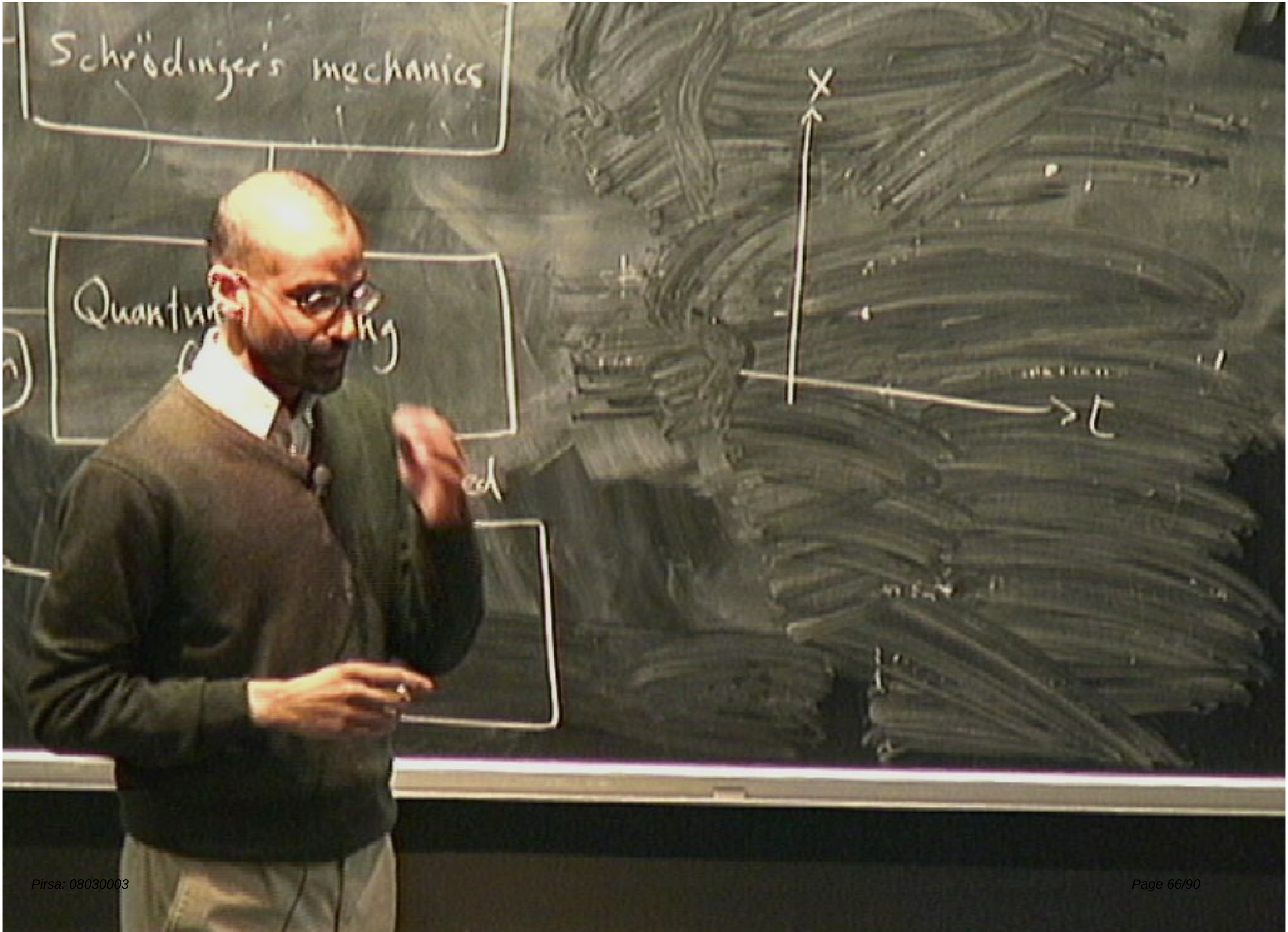
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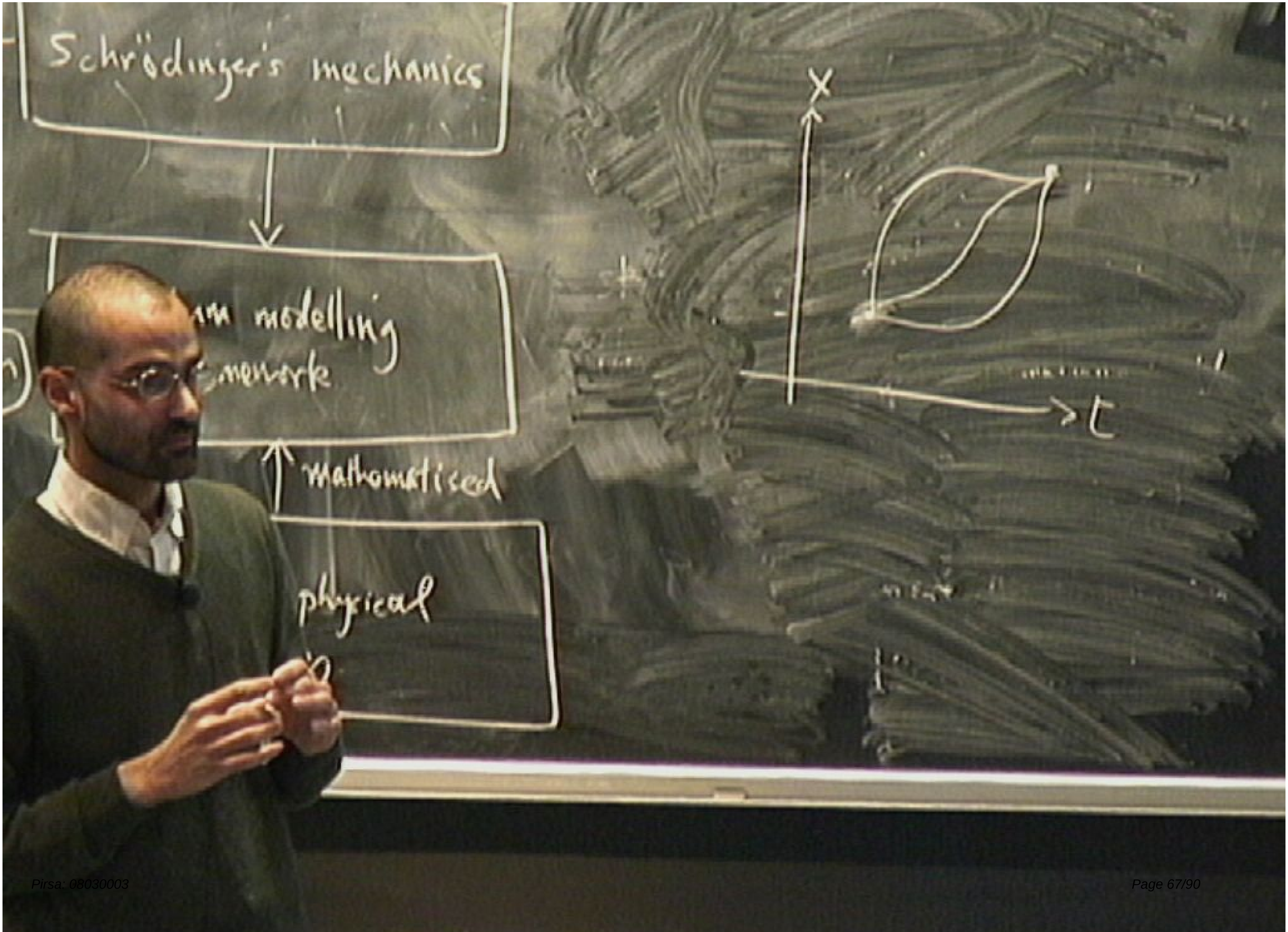
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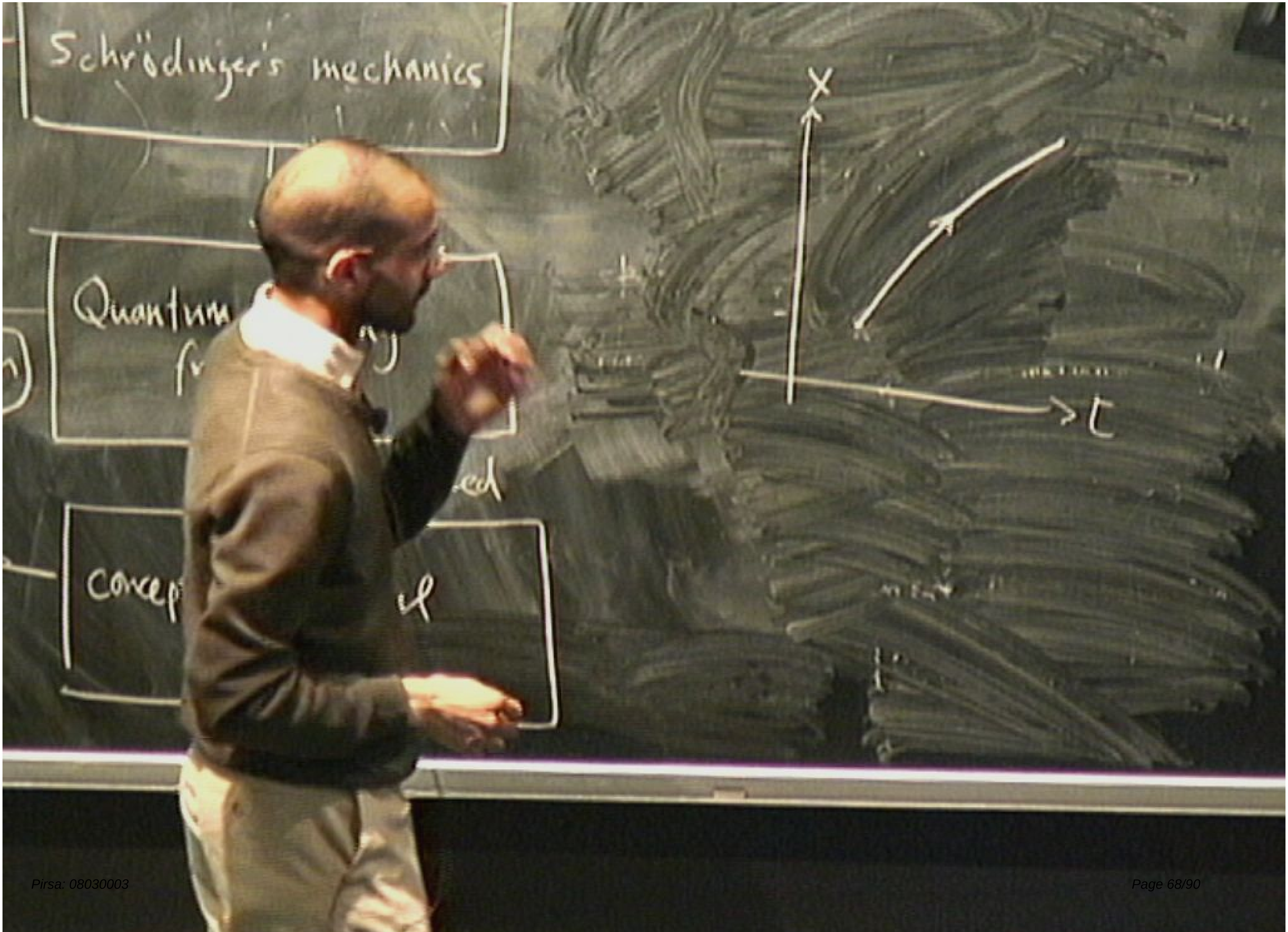
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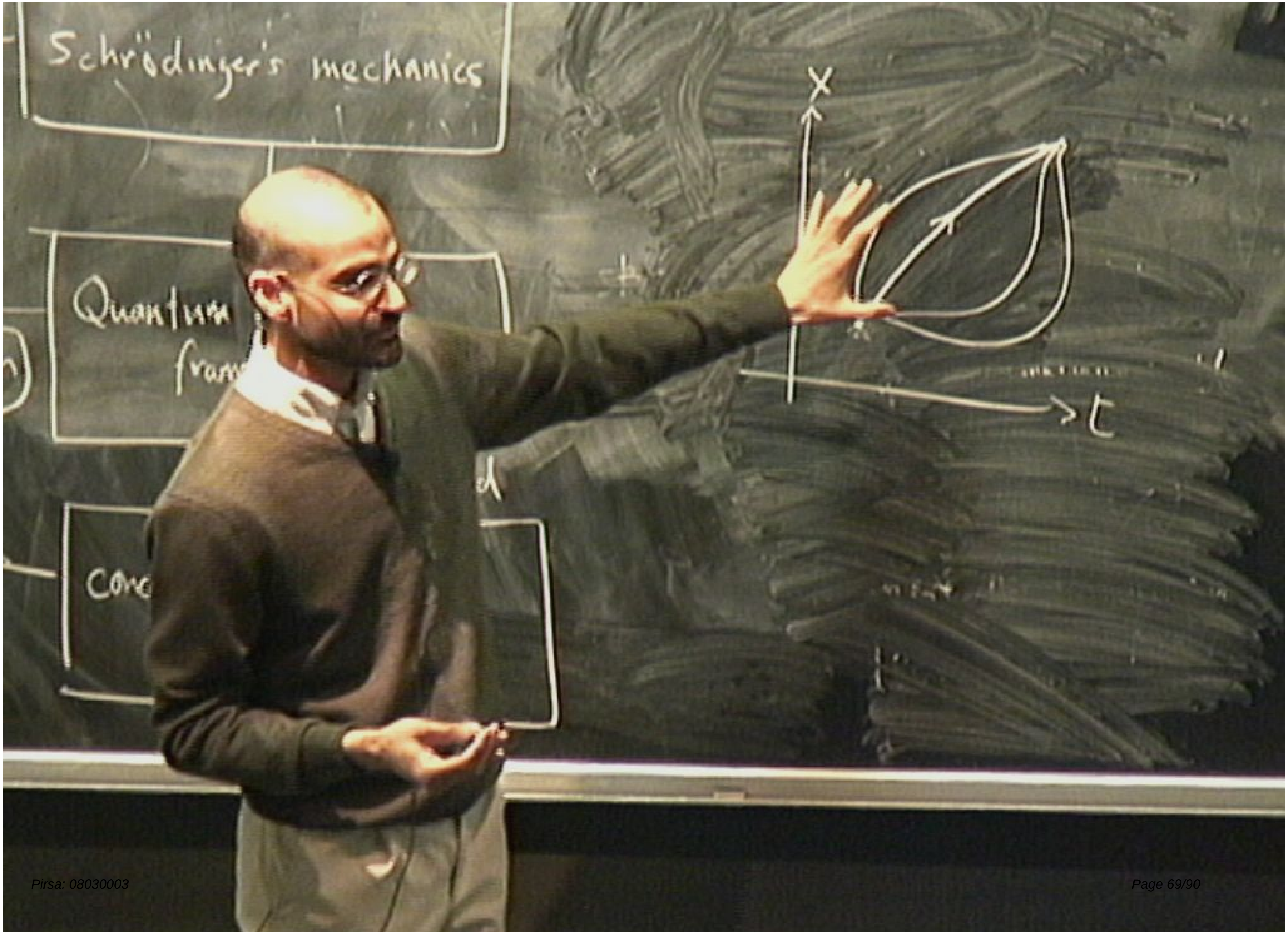
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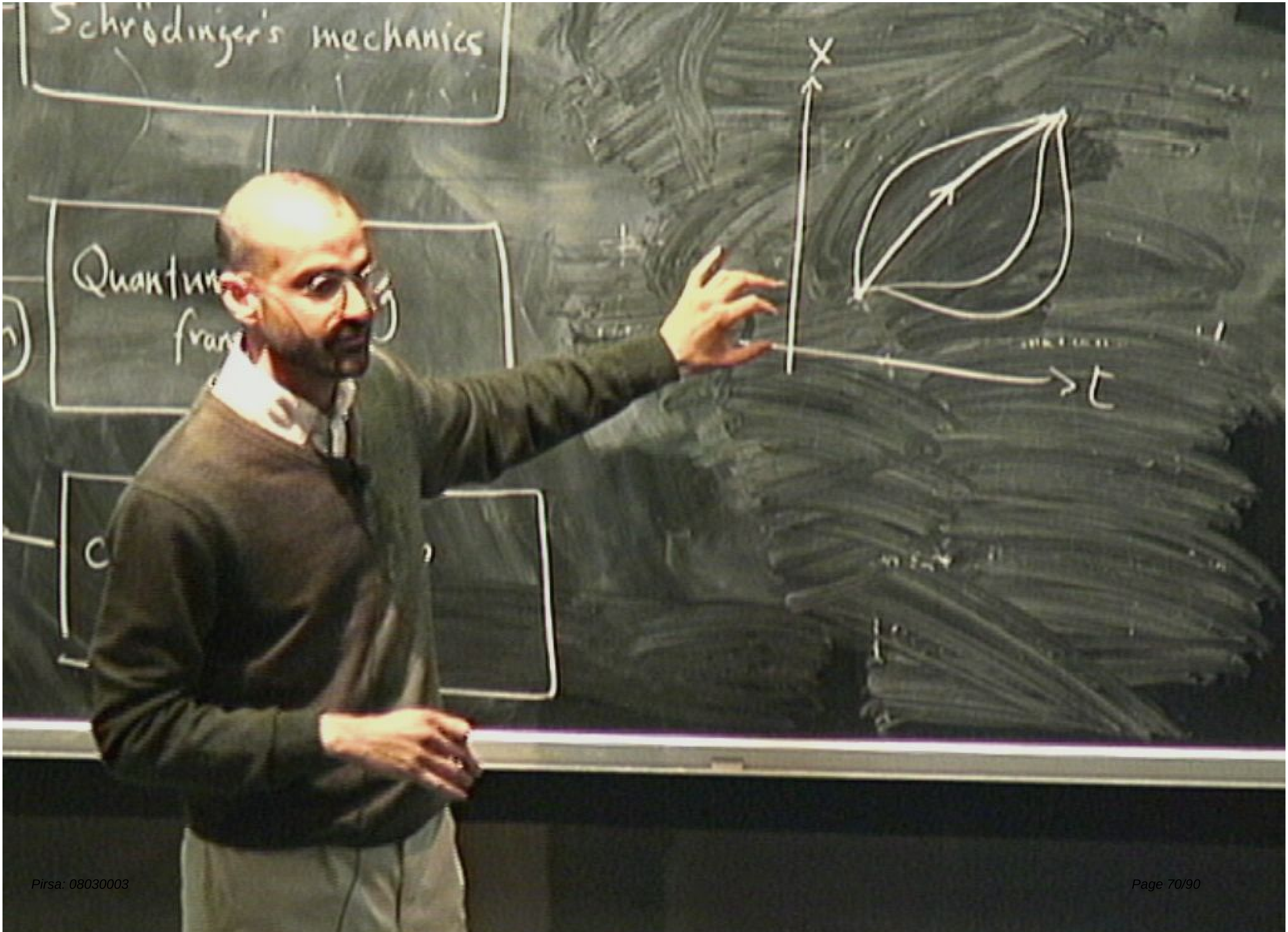
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- Complementarity: Bohr formulated a general philosophical notion of complementarity.
- Potentiality & Actuality: Heisenberg and Bohm developed the connections between these Aristotelian notions and complementarity.

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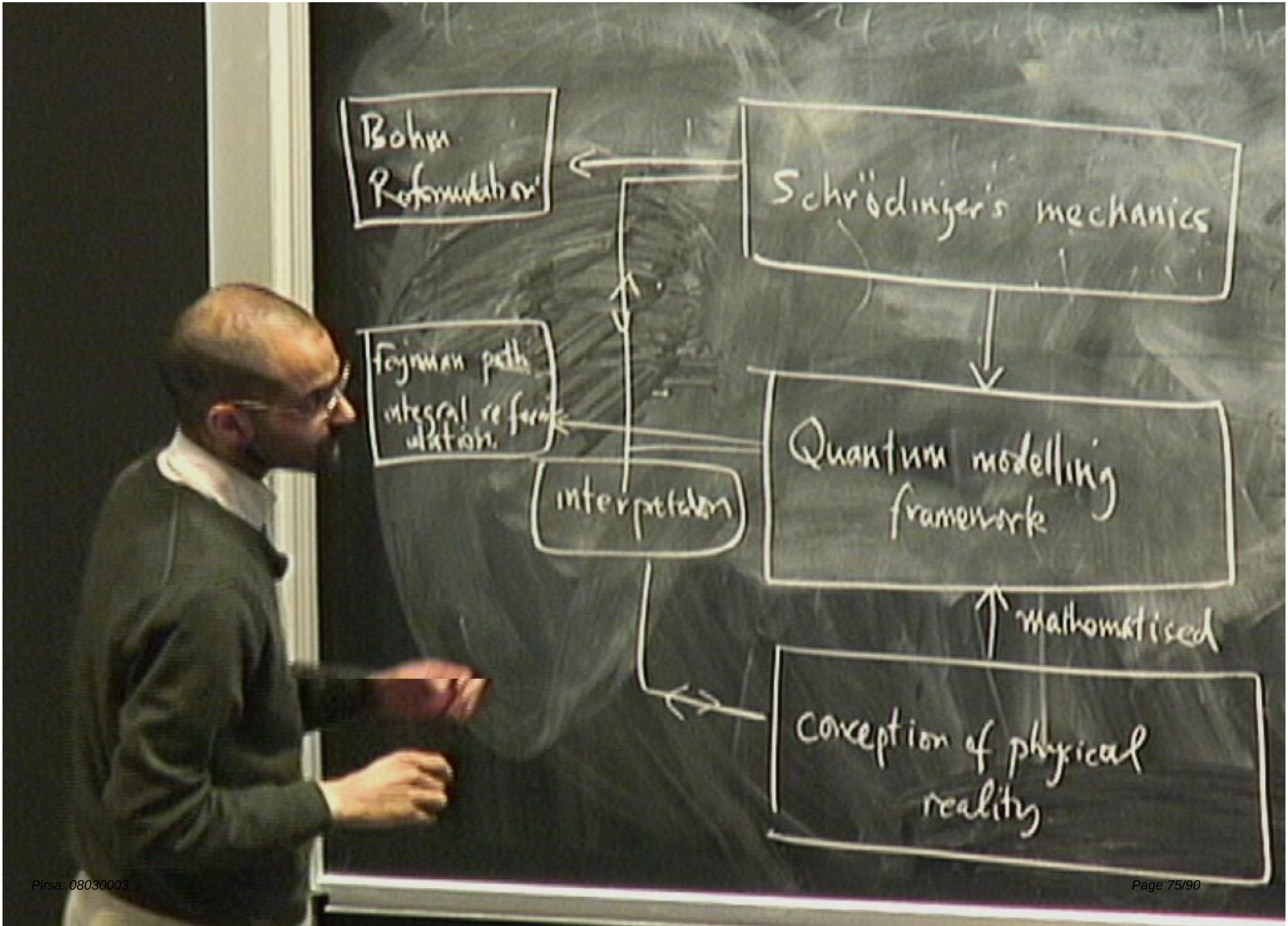
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4. Properties: discover properties (especially non-classical) of the quantum world, and explore their interrelations in general probabilistic frameworks and toy models.

- no-signalling: in spite of entanglement, it is not possible to use entangled states to transmit signals instantaneously.
- classical limit behaviour: Ehrenfest's theorem. Decoherence.
- non-locality: Bell's theorem.
- no non-contextuality: Kocken-Specker theorem.
- no-cloning: "no universal quantum photocopier" (Wootters and Zurek)
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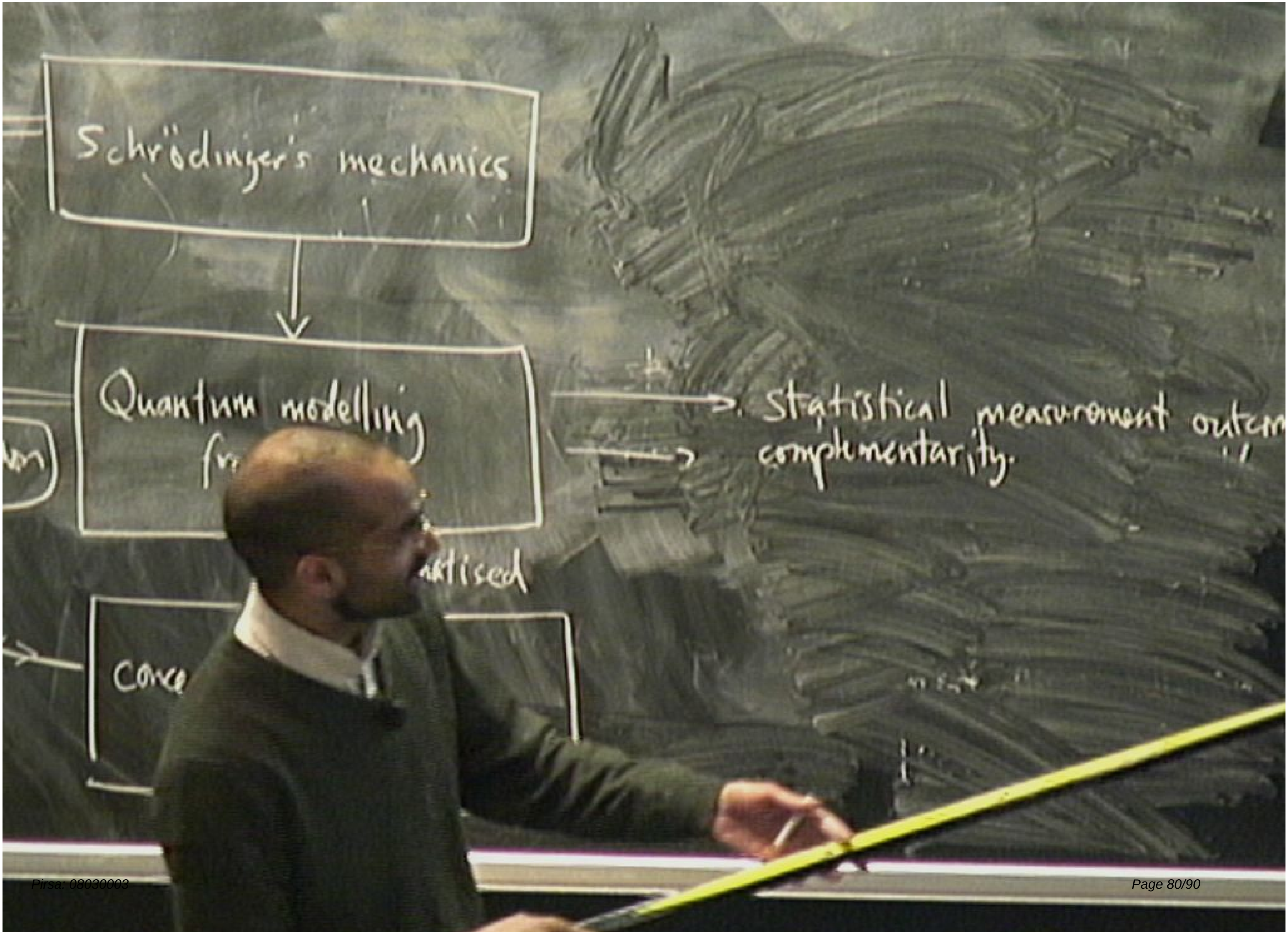
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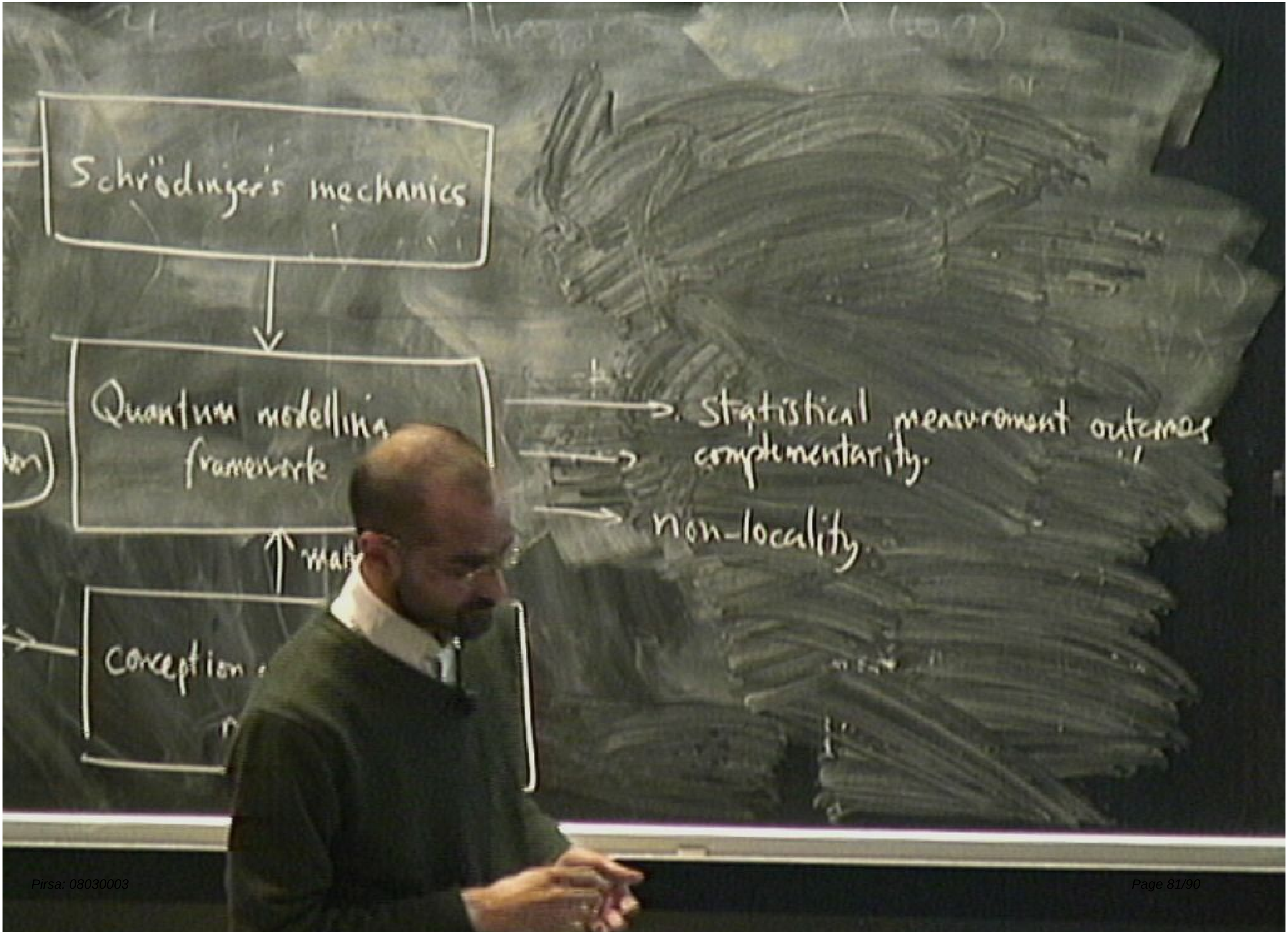
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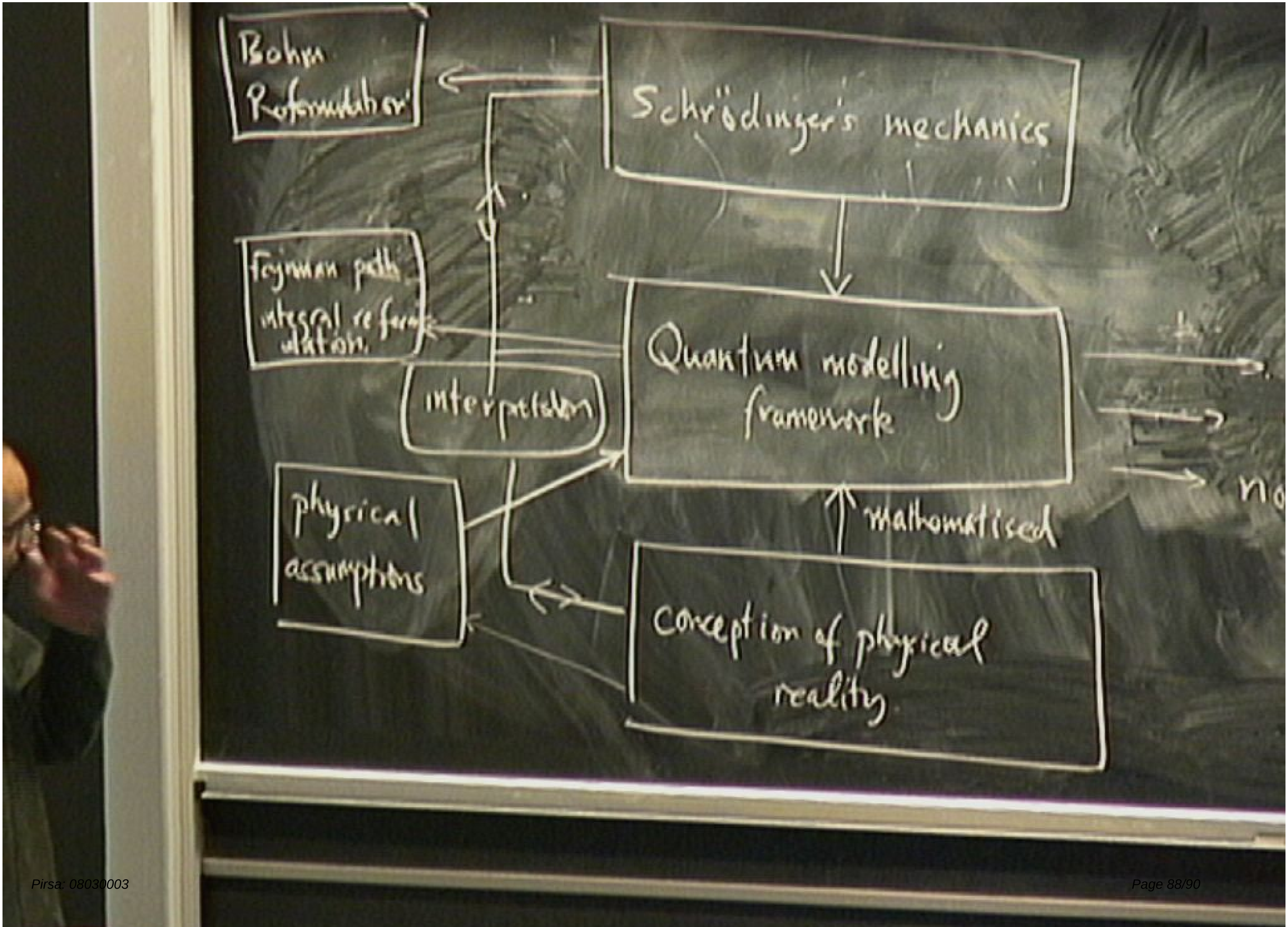
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