Title: Foundations and Interpretation of Quantum Theory - Lecture 1

Date: Jan 12, 2010 02:30 PM

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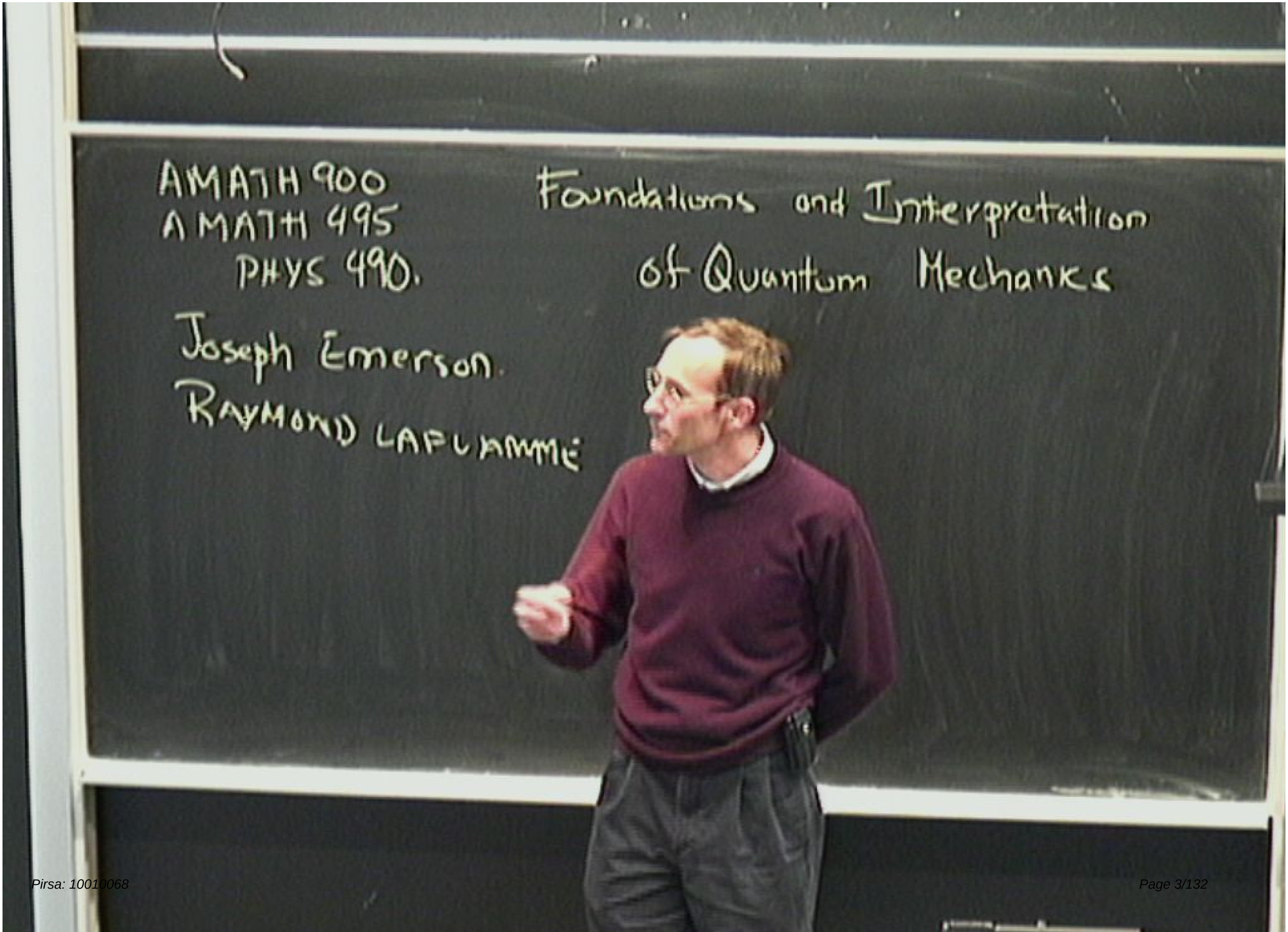
Abstract: After a review of the axiomatic formulation of quantum theory, the generalized operational structure of the theory will be introduced (including POVM measurements, sequential measurements, and CP maps). There will be an introduction to the orthodox (sometimes called Copenhagen) interpretation of quantum mechanics and the historical problems/issues/debates regarding that interpretation, in particular, the measurement problem and the EPR paradox, and a discussion of contemporary views on these topics. The majority of the course lectures will consist of guest lectures from international experts covering the various approaches to the interpretation of quantum theory (in particular, many-worlds, de Broglie-Bohm, consistent/decoherent histories, and statistical/epistemic interpretations, as time permits) and fundamental properties and tests of quantum theory (such as entanglement and experimental tests of Bell inequalities, contextuality, macroscopic quantum phenomena, and the problem of quantum gravity, as time permits).

Outline

1. Introduction and Motivation

2. Axioms for Quantum Theory
   - Ideal Preparations: Hilbert Space Vectors
   - Ideal Measurements: Self-adjoint Operators
   - Composite Systems: Tensor-Product Structure
   - Ideal Transformations 1: Unitary Operators
   - Ideal Transformations 2: Projections

3. Generalized Axioms for Quantum Theory
   - Generalized Preparations: Density Operators
   - Generalized Measurements
   - Composite Systems and Entanglement
   - Generalized Transformations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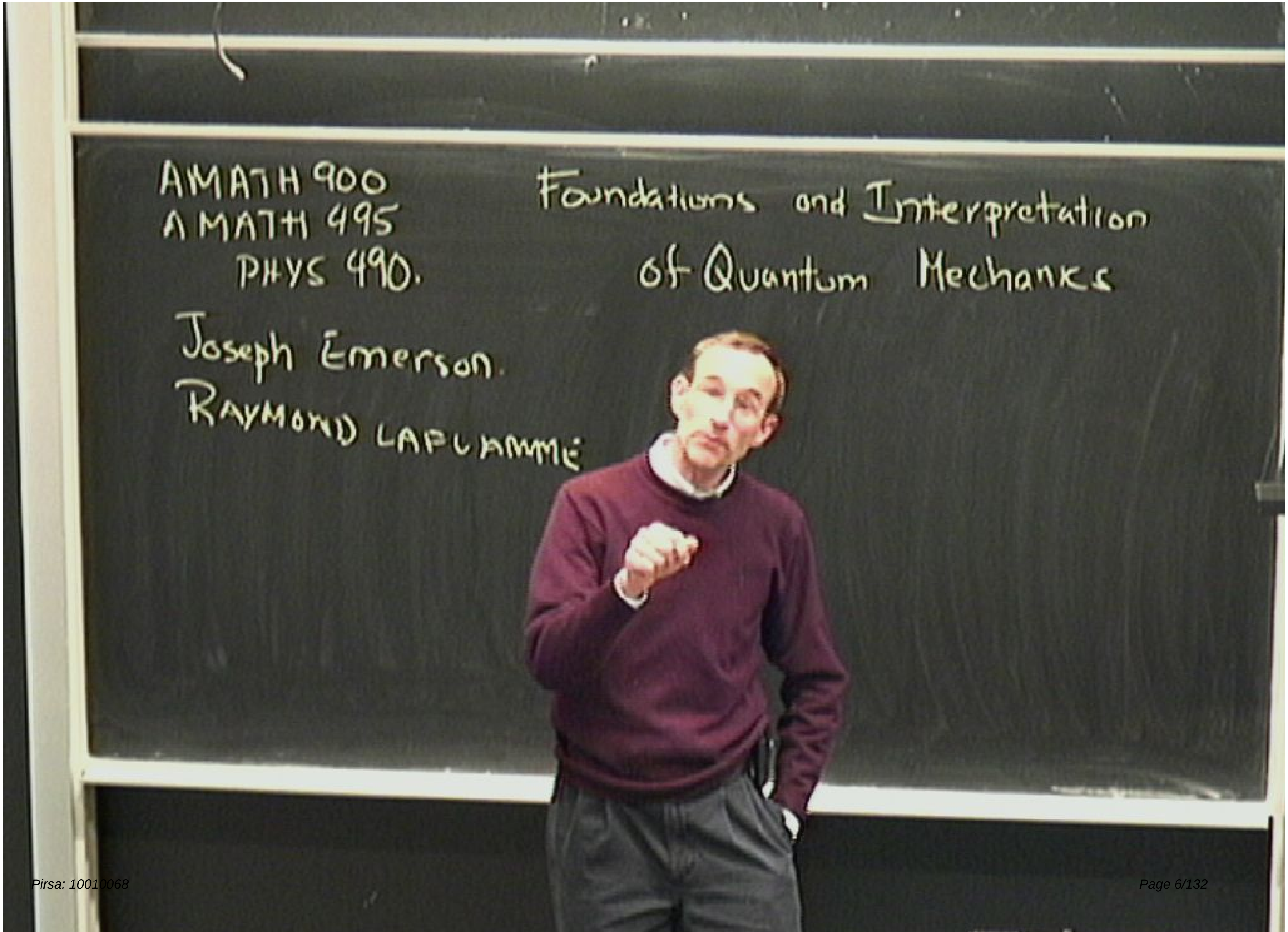
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Foundations and Interpretations of Quantum Theory

Course Instructors: Joseph Emerson, Ray Laflamme

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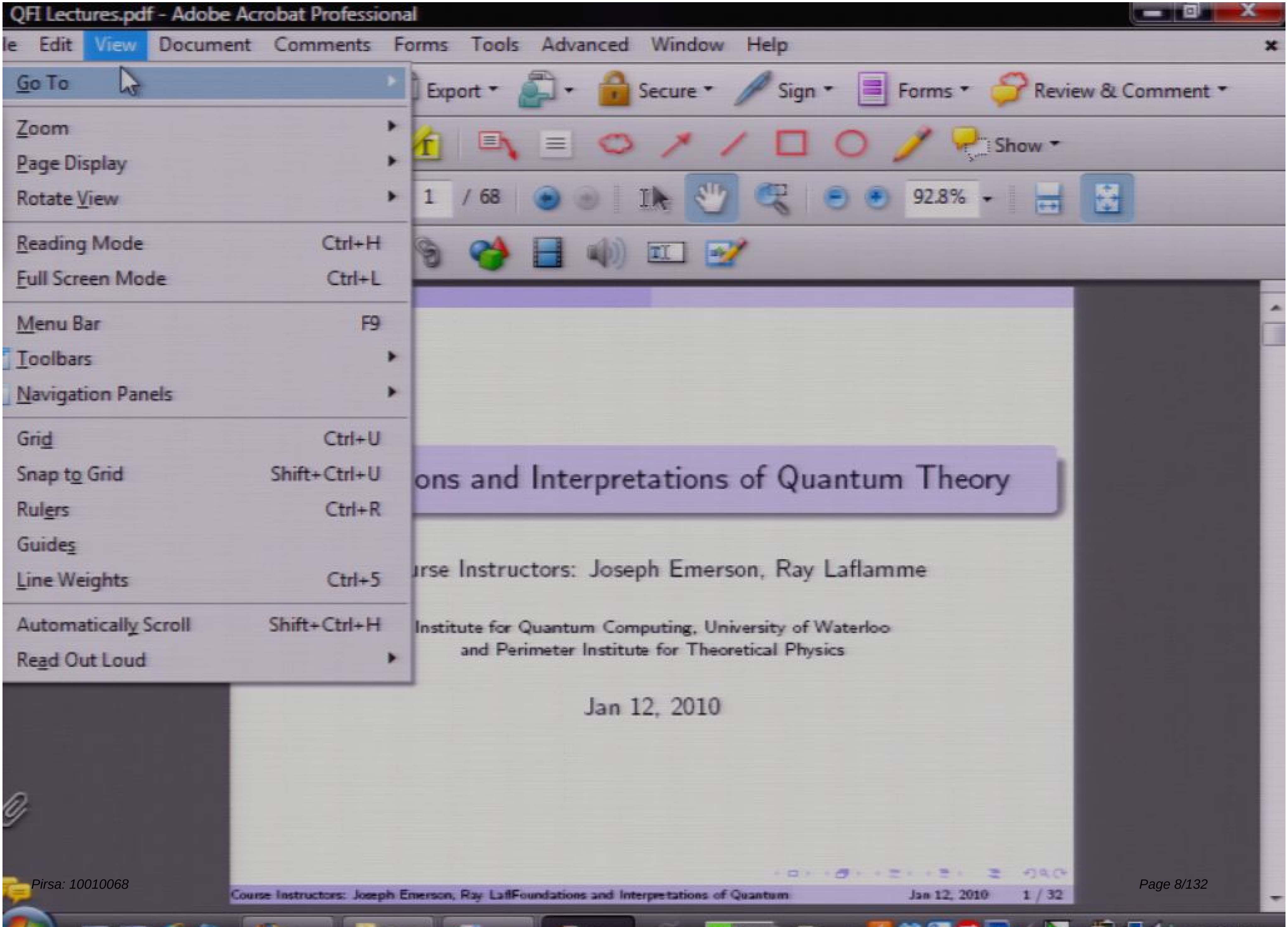
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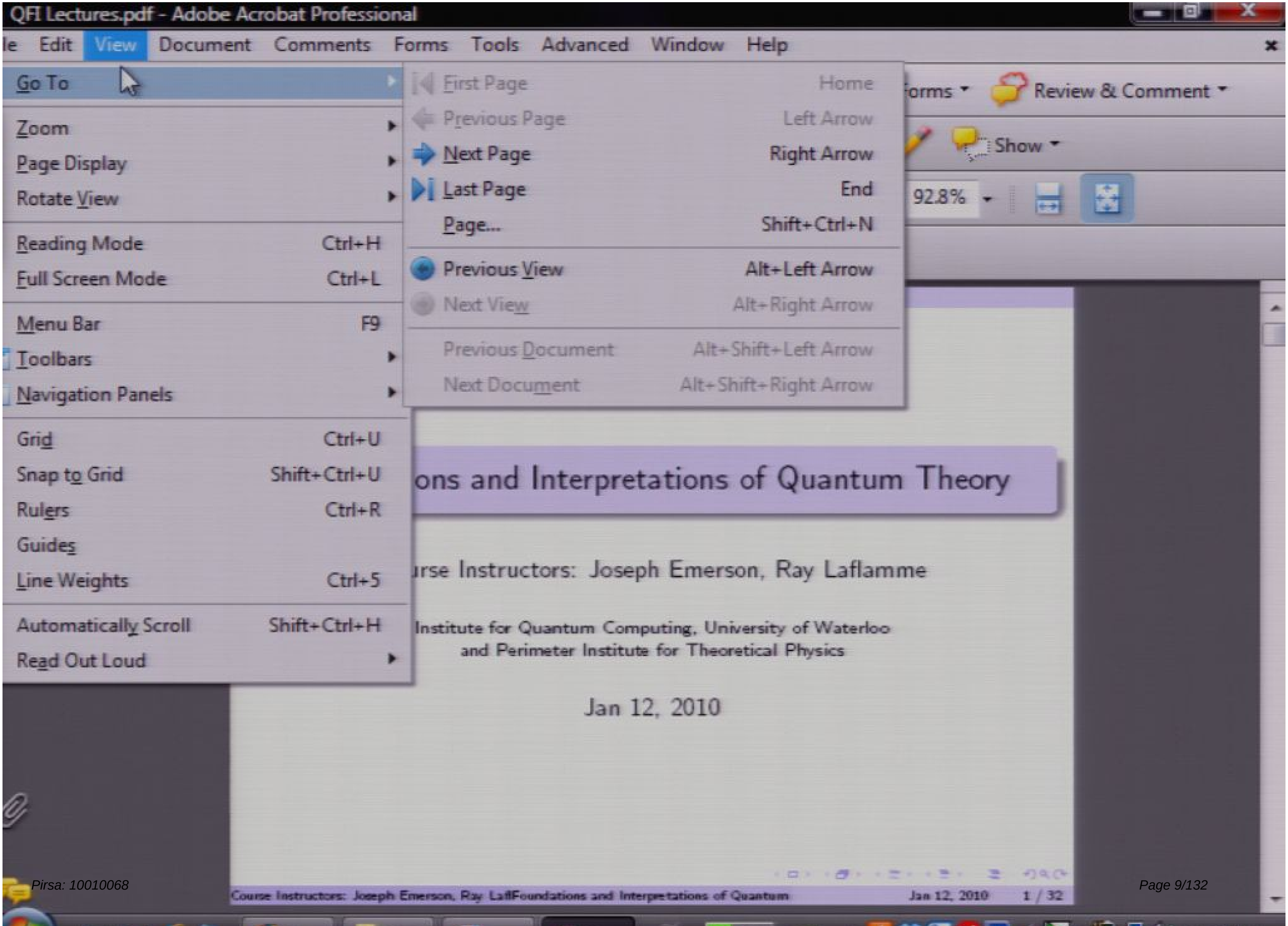
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Description: After a review of the axiomatic formulation of quantum theory, the generalized operational structure of the theory will be introduced (including POVM measurements, sequential measurements, and CP maps). There will be an introduction to the orthodox (sometimes called Copenhagen) interpretation of quantum mechanics and the historical problems/issues/debates regarding that interpretation, in particular, the measurement problem and the EPR paradox, and a discussion of contemporary views on these topics. The majority of the course lectures will consist of guest lectures from international experts covering the various approaches to the interpretation of quantum theory (in particular, many-worlds, de Broglie-Bohm, consistent/decoherent histories, and statistical/epistemic interpretations, as time permits) and fundamental properties and tests of quantum theory (such as entanglement and experimental tests of Bell inequalities, contextuality, macroscopic quantum phenomena, and the problem of quantum gravity, as time permits).

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Foundations and Interpretation of Quantum Theory (Winter 2010)

Code: AMATH 900/AMATH 495/PHYS 490	**Semester/Year Offered:** Winter 2010
Instructors: Joseph Emerson and Raymond Laflamme	
Location: PI and RAC	**Time:** Tuesdays and Thursdays, 2:30-3:50

Calendar Description:
Lecture times and locations: Tuesdays 2:30-3:50 p.m. at Perimeter Institute, Bob Room, Thursdays 2:30-3:50 p.m. at RAC 2009

First lecture: Tuesday, January 12, 2010.

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Motivation: From a practical point of view, quantum theory has been an enormously successful theory. It correctly predicts both non-relativistic and relativistic phenomena to extraordinary precision and has driven major technological developments such as the laser, superconductivity and micro-circuitry. More recently, we have seen the coherence and entanglement of single quantum systems veri ed routinely in todays labs and these distinctive quantum phenomena are now being directly exploited as the basis for emerging quantum technologies. And yet, in spite of these successes, there are questions and controversy surrounding very basic issues about the physical nature of the theory. While such questions are sometimes dismissed as mere philosophy, the study of these foundational issues has played a critical role in conceptual breakthroughs in areas ranging from quantum computation and

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Alex Wilce	Convex sets framework for probabilistic theories	Week of February 22, 2009
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Chris Fuchs	Quantum Bayesian view	Week of March 8, 2009
TBA	TBA	Week of March 15, 2009
Tony Leggett	Fundamental tests of quantum mechanics	Week of March 22, 2009
Michel Devoret	Macroscopic quantum coherence	Week of March 29, 2009

Transportation: Shuttle transportation to/from PI and RAC is available as follows. Priority will be given to students registered in the course. Pick up at EIT will be at the entrace facing DC.

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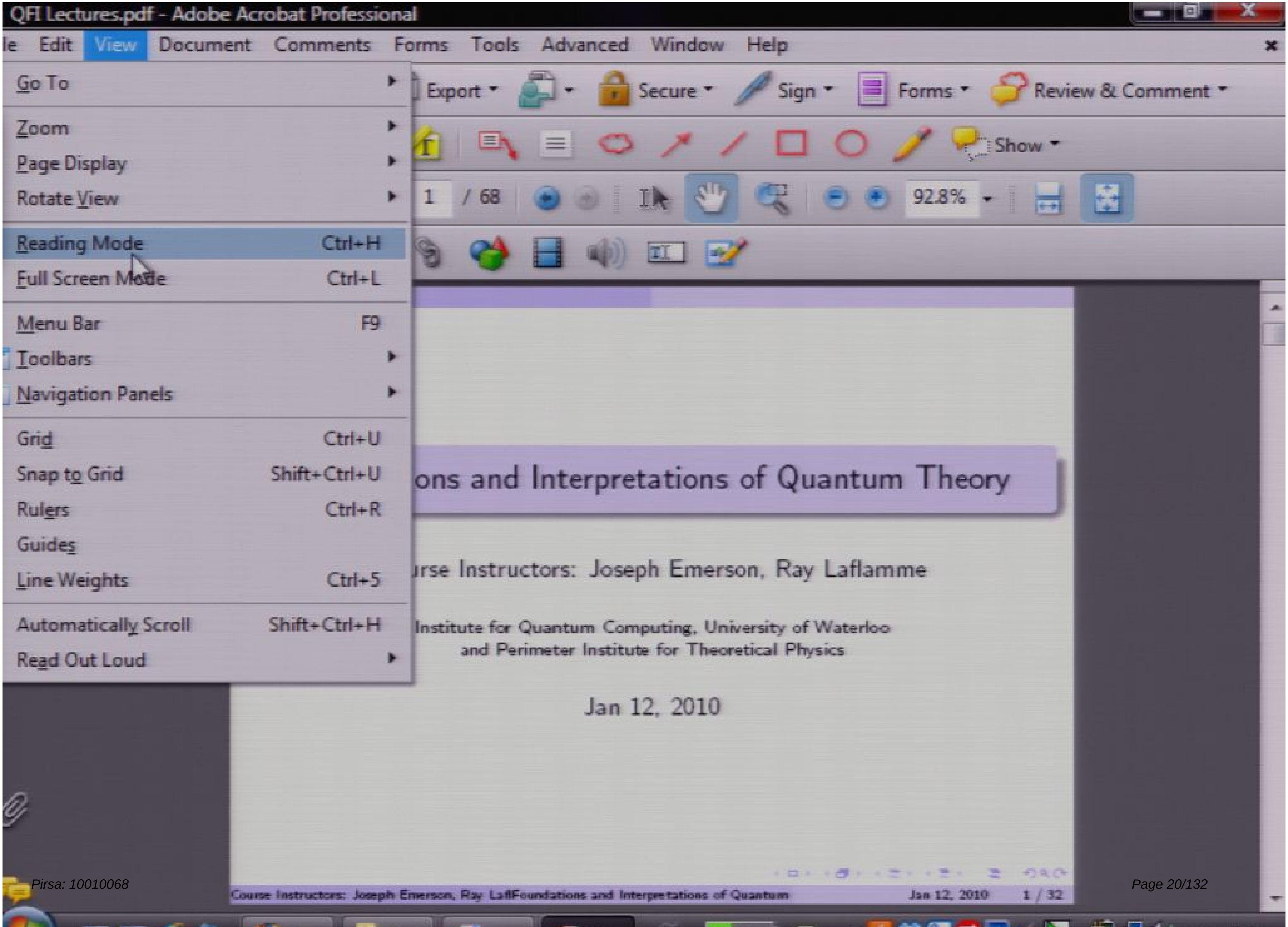
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- A related goal is to understand what we may or may not deduce about "reality", or, to use a more philosophical term, about the fundamental *ontology*, in light of quantum theory.
- Of course, one option is to deny that there is any reality at all, and another is to say that there are infinitely many.
- Somewhat amazingly, we will see that, if you accept that there is "something really going on", ie some unique reality, then irrespective of what ontology you believe in, it must satisfy certain constraints, in particular, *non-locality* and *contextuality*.

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  - Not surprisingly, "users" with a poor understanding of these interpretational issues will often be led to erroneous conclusions about what is, and is not, possible to achieve with quantum theory. There are many historical examples of this.
  - On the flip side, major advances in the application of quantum theory, such as quantum information technology, were born out of concerns about the unusual ontological implications of quantum phenomena such as *superposition* and *entanglement*.

Some Introductory Thoughts

- Finally, after almost a century of efforts, no one has been able to understand how to combine quantum theory and general relativity to construct a single theoretical framework, capable of describing physical phenomena on all scales and with all known forces involved.

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  - Is this because too many researchers have neglected answering *carefully* the simple question: "What is a quantum state?"
- Before we get to these issues, we first we have to be clear that we know how to be practical quantum "users" ...

Ideal Preparations: Hilbert Space Vectors

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- In finite dimensions $\mathcal{H} = \mathbb{C}^d$.
- Normalization implies $||\psi|| = 1$, which prescribes a hypersphere S^{2d-1} in a $2d$-dimensional real vector space.
- Because state vectors have a complex phase which is physically insignificant, distinct preparations are in one-to-one correspondence with elements of the complex projective space $\mathbb{C}P^{d-1}$.

Ideal Measurements: Self-adjoint Operators

- Let $\hat{A}$ be a self-adjoint operator with discrete eigenvalues a_l and eigenvectors $\{|a_l, m_l\rangle\}$, where m_l indexes an orthogonal set of vectors spanning any degenerate subspaces.

Ideal Measurements: Self-adjoint Operators

Axiom 2. An ideal measurement procedure is represented by a self-adjoint operator $\hat{A}$.

(a) **The set of observable outcomes is given by the eigenvalues $\{a_l\}$ of $\hat{A}$.**

(b) **The probability of finding outcome a_l, given preparation $|\psi\rangle$, is** $\Pr(a_l) = \mathrm{Tr}(|\psi\rangle\langle\psi|P_{a_l})$.

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- An important representation of a self-adjoint operator is its *spectral decomposition*. In the case of a discrete spectrum we have

$$\hat{A} = \sum_l a_l \hat{P}_{a_l},$$

where we introduce projectors onto the (possibly degenerate) eigenspaces associated with distinct eigenvalues $P_{a_l} = \sum_{m_l} |a_l, m_l\rangle\langle a_l, m_l|$.

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Composite Systems: Tensor-Product Structure

Suppose we have two systems, A and B, with state spaces $\mathcal{H}_A$ and $\mathcal{H}_B$, both of which are separable Hilbert spaces and hence possess orthonormal bases $\{|a_k\rangle\}$ and $\{|b_\ell\rangle\}$ respectively. We wish to describe these systems *jointly* by a Hilbert space $\mathcal{H}_{AB}$. How is this Hilbert space related to the Hilbert spaces of the subsystems?

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Composite Systems: Tensor-Product Structure

Suppose we have two systems, A and B, with state spaces $\mathcal{H}_A$ and $\mathcal{H}_B$, both of which are separable Hilbert spaces and hence possess orthonormal bases $\{|a_k\rangle\}$ and $\{|b_\ell\rangle\}$ respectively. We wish to describe these systems *jointly* by a Hilbert space $\mathcal{H}_{AB}$. How is this Hilbert space related to the Hilbert spaces of the subsystems?

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Axiom 3. The Hilbert space of a composite system is given by the tensor product of the subsystem Hilbert spaces,

$$\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B.$$

Composite Systems: Tensor-Product Structure

- Remark that $\mathcal{H}_{AB}$ is spanned by $\{|a_k\rangle \otimes |b_\ell\rangle\}$, $\forall\ k, \ell$, and $\dim(\mathcal{H}_A \otimes \mathcal{H}_B) = \dim(\mathcal{H}_A)\dim(\mathcal{H}_B)$. Hence an arbitrary state vector $|\psi_{AB}\rangle \in \mathcal{H}_{AB}$ of the joint system can be obtained from linear combinations of the joint-basis states,

$$|\psi_{AB}\rangle = \sum_{k,\ell} \psi_{k\ell} |a_k\rangle \otimes |b_\ell\rangle, \quad \psi_{k\ell} = (\langle a_k| \otimes \langle b_\ell|)|\psi_{AB}\rangle \in \mathbb{C}.$$

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- In the finite-dimensional case, where $\mathcal{H}_A = \mathbb{C}^M$ and $\mathcal{H}_B = \mathbb{C}^N$, we have

$$\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B = \mathbb{C}^{MN}.$$

- **Terminology:** The state associated with a composition of two subsystems is called *bipartite*; similarly the state associated with a composition of three subsystems is called *tripartite*, and so on. The state space of each subsystem is called a *factor space* of the full Hilbert space.

Ideal Transformations

During the time-interval between the preparation procedure and the measurement procedure the system evolves under a dynamical transformation:

Ideal Transformations

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Axiom 4. Ideal dynamical transformations are generated by a linear operator U,

$$|\psi(t_2)\rangle = \hat{U}(t_2, t_1)|\psi(t_1)\rangle$$

satisfying,

$$i\hbar\frac{\partial \hat{U}(t_2, t_1)}{\partial t_2} = \hat{H}(t_2)\hat{U}(t_2, t_1),$$

where $\hat{H}(t)$ is a self-adjoint operator representing the system energy function and $t \in \mathbb{R}$ is time, subject to the initial condition $\hat{U}(t_1, t_1) = \mathbb{1}$.

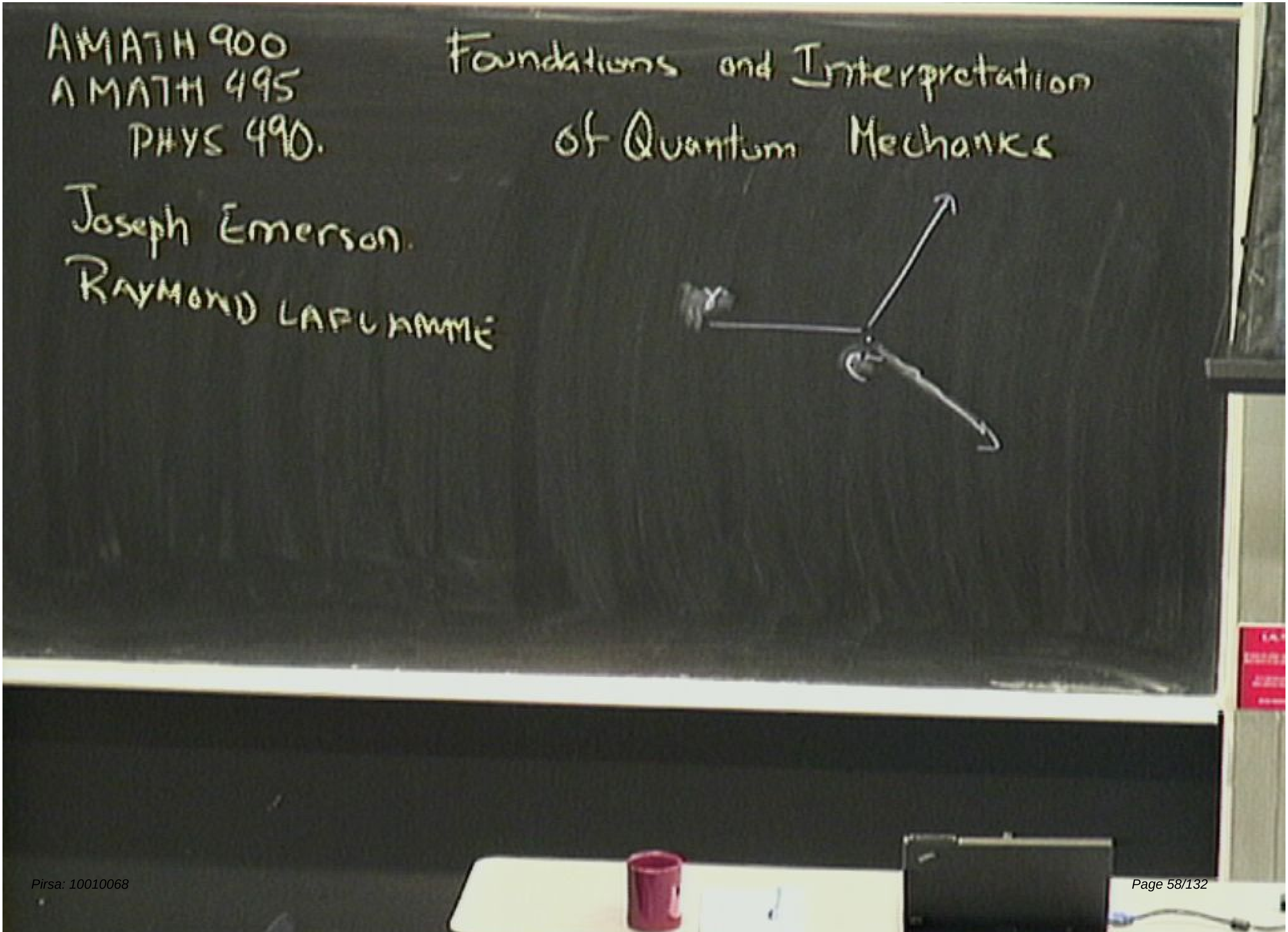
Ideal Transformations

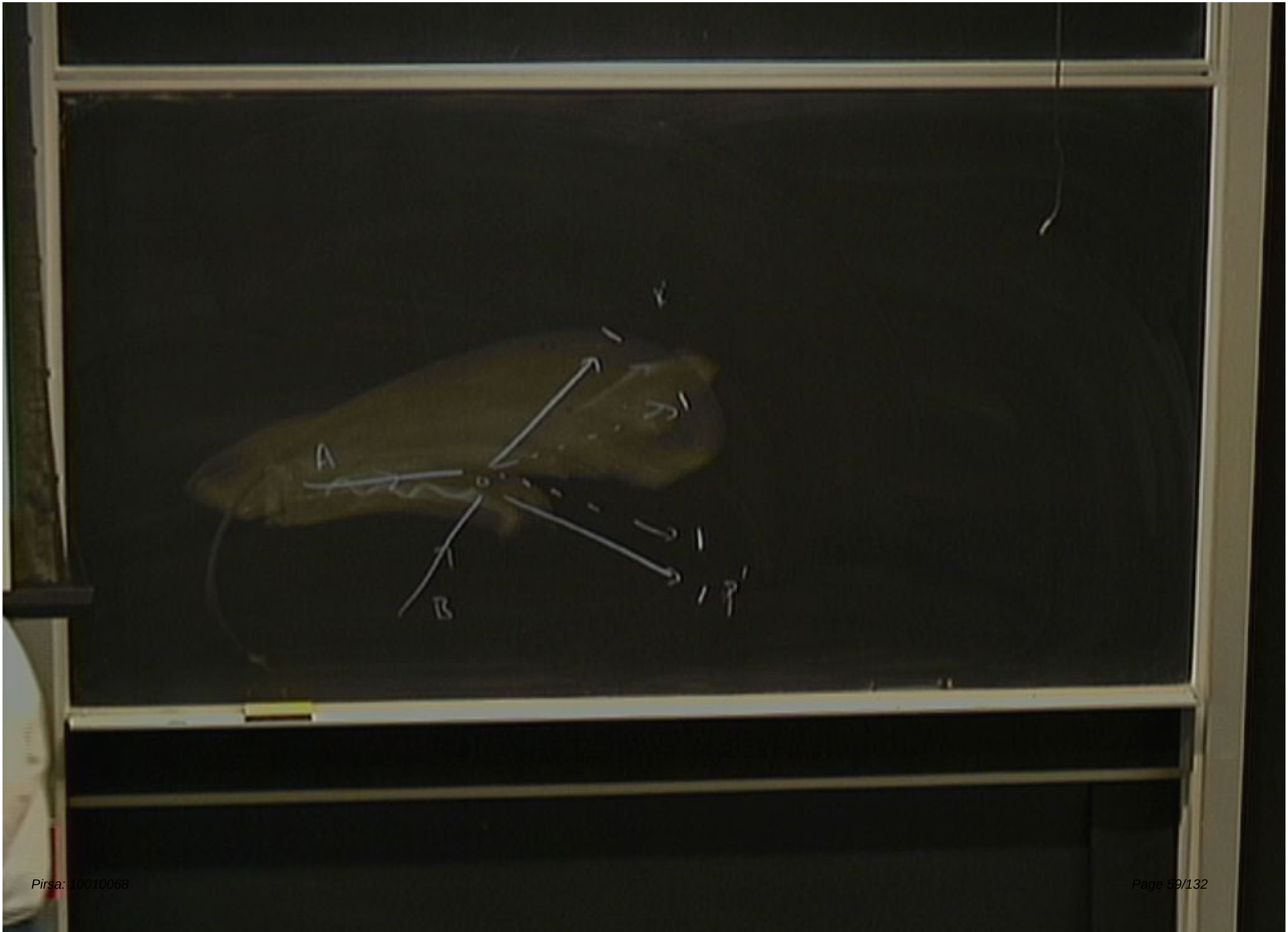
From Axiom 4 we can deduce *Schrödinger's equation*,

$$i\hbar\frac{d}{dt}|\psi(t)\rangle = \hat{H}(t)|\psi(t)\rangle.$$

What is the state after an ideal filtering measurement?

- In order to understand how to describe the state of a quantum system after an ideal filtering measurement, von Neumann considered the Compton experiment where photons are scattered off electrons that are initially at rest.


AMATH 900
AMATH 495
PHYS 490.
Foundations and Interpretation
of Quantum Mechanics
Joseph Emerson.
RAYMOND LAFLAMME


A
B

What is the state after an ideal filtering measurement?

- von Neumann then imagined a scenario where there is a finite time difference Δt between the measurement of the electron and of the photon, i.e., a time-delay between the detection times of these particles.
  - **Forward reference:** note the similarity to the EPR and Bell-type arguments involving entangled states.
- Because, after measurement of the electron, the photon's momentum can be predicted with certainty (within some finite precision) this means that, after the electron momentum has been observed, the state describing the photon must be somehow "updated" (to within the same finite precision) to a new state that is consistent with the observed outcome for the electron momentum.

Another kind of Transformation

- The transformation taking the quantum state accorded just before measurement of the electron to that just after measurement is **not** consistent with the usual unitary (Schrodinger) evolution. We will prove this later, but for now consider that:

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  - After measurement, the state update must be indeterministic - it is conditional on the random outcome of the measurement of the electron momentum.
  - After measurement, the state update must be discontinuous - an instantaneous update of the photon's state is required.

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  - After measurement, the state update must be discontinuous - an instantaneous update of the photon's state is required.
- This practical consideration of the ideal filtering type measurements that were possible with "entangled" systems forced von Neumann to formally introduce a second kind of dynamical transformation into quantum theory: the projection postulate.

Evolution under Sequential Measurements

- von Neumann realized from his analysis of sequential measurements that two kinds of transformation were required in quantum mechanics (von Neumann, 1932):

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  - **Process 1.** After observation/measurement of an outcome a_k, the system is left in the eigenstate $|a_k\rangle$ associated with the detected eigenvalue a_k. We have the map,

$$|\psi\rangle = \sum_k c_k |a_k\rangle \rightarrow |a_k\rangle.$$

Projection Postulate

Axiom 5. After observation/measurement of an outcome a_k, the system is left in the eigenstate $|a_k\rangle$ associated with the detected eigenvalue a_k, that is,

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- **Terminology:** the projection postulate is also known as the "reduction of the wavepacket" and "the collapse of the wavefunction".

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- **Terminology:** the projection postulate is also known as the "reduction of the wavepacket" and "the collapse of the wavefunction".
- von Neumann imagined "Process 1" as an essential randomness in nature, and he considered it grounds for abandoning the "principle of sufficient cause", which I take to mean "causal determinism."

General states as mixtures of pure states

- Suppose we want to describe a quantum system which is prepared according to one procedure, represented by state $|\psi_1\rangle$, with probability p_1 and according to a distinct procedure, represented by state $|\psi_2\rangle$, with probability p_2. How can we do this?
- If we are measuring the operator $A = \sum_a a\hat{P}_a$ which possesses non-degenerate eigenvalues $a \in \mathbb{R}$ associated with orthogonal eigenspaces $\hat{P}_a$, then the probability of obtaining outcome a given preparation ψ_1 is

$$\Pr(a|\psi_1) = \mathrm{Tr}(\hat{P}_a|\psi_1\rangle\langle\psi_1|).$$

and similarly for preparation 2.

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- If we do not know which preparation took place then the net probability of finding outcome a is simply

$$\mathrm{Pr}(a) = p_1 \mathrm{Pr}(a|\psi_1) + p_2 \mathrm{Pr}(a|\psi_2).$$

By linearity of the trace we deduce that,

$$\mathrm{Pr}(a) = \mathrm{Tr}(\hat{P}_a \rho)$$

where

$$\rho = p_1 |\psi_1\rangle\langle\psi_1| + p_2 |\psi_2\rangle\langle\psi_2|$$

is non-negative operator called a *density operator* satisfying the normalization condition $\mathrm{Tr}(\rho) = 1$ (which ensures that probabilities are conserved).

General states as mixtures of pure states

- In this way we can construct general quantum states from probabilistic mixtures (convex combinations) of pure states as follows:
- (i) Discrete case: $\rho = \sum_i p_i|\psi_i\rangle\langle\psi_i|$ with $\sum_i p_i = 1$ and $p_i \geq 0$.
- (ii) Continuous case: $\rho = \int d\lambda p(\lambda)|\psi(\lambda)\rangle\langle\psi(\lambda)|$ for $\lambda \in \mathbb{R}$, with $\int d\lambda p(\lambda) = 1$ and $p(\lambda) \geq 0$.

General states from the partial trace

- Suppose we have a quantum state (density operator) $\rho = \rho_{AB}$ on a composite Hilbert space $\mathcal{H}_{AB}$, where in general ρ need not correspond to a pure state $\rho = |\psi\rangle\langle\psi|$ but may be a probabilistic mixture of pure states. How does one describe the state of subsystem A alone (with a state ρ_A) or B alone (with a state ρ_B) ?
- The relationship between ρ_A and ρ_{AB} is generated by the *partial trace* operation:

$$\rho_A = \mathrm{Tr}_B(\rho_{AB}).$$

- The state ρ_A is called the *reduced state* associated with ρ_{AB}.

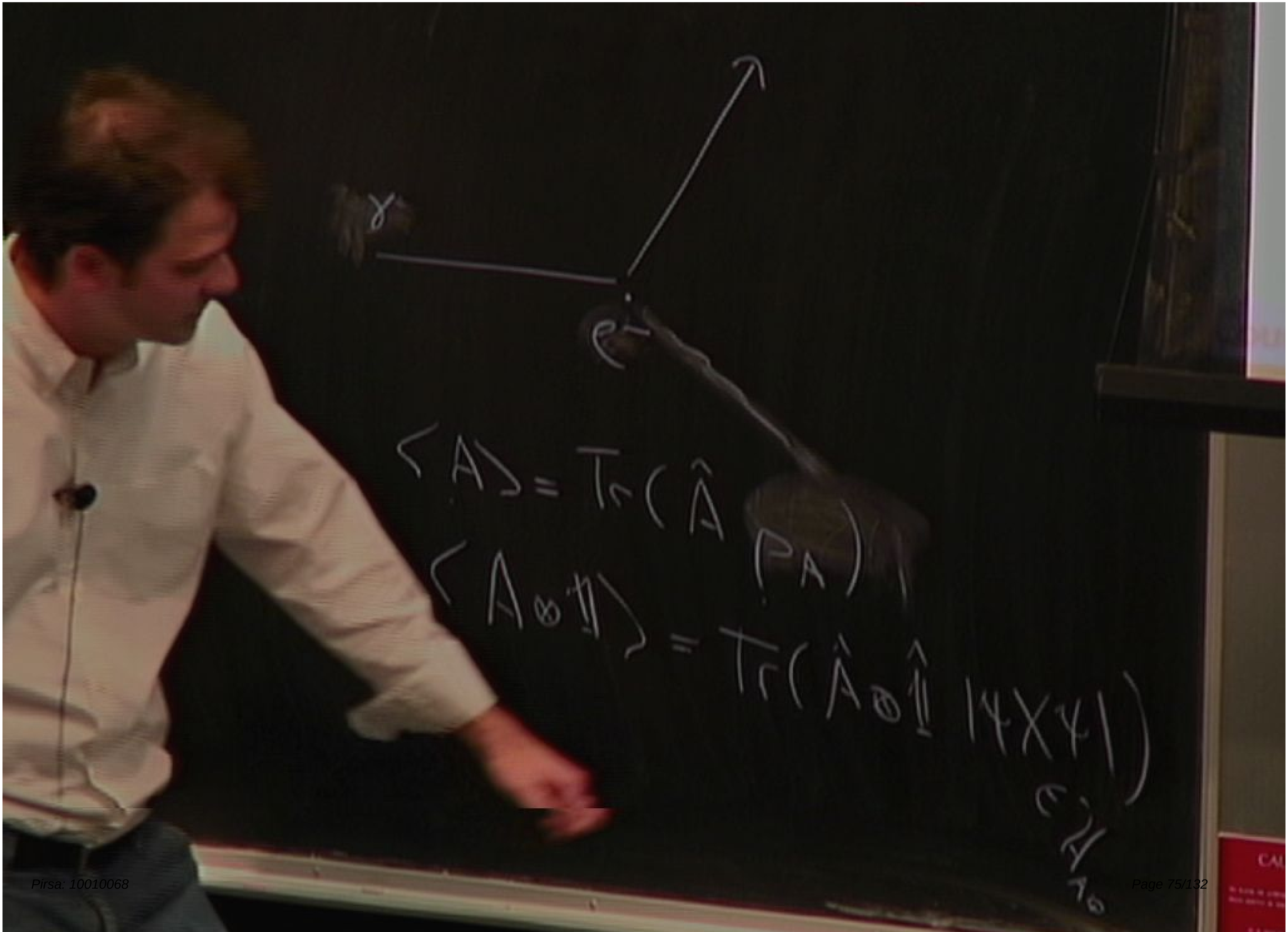
- This relationship can be deduced from physical consistency of *demanding* that

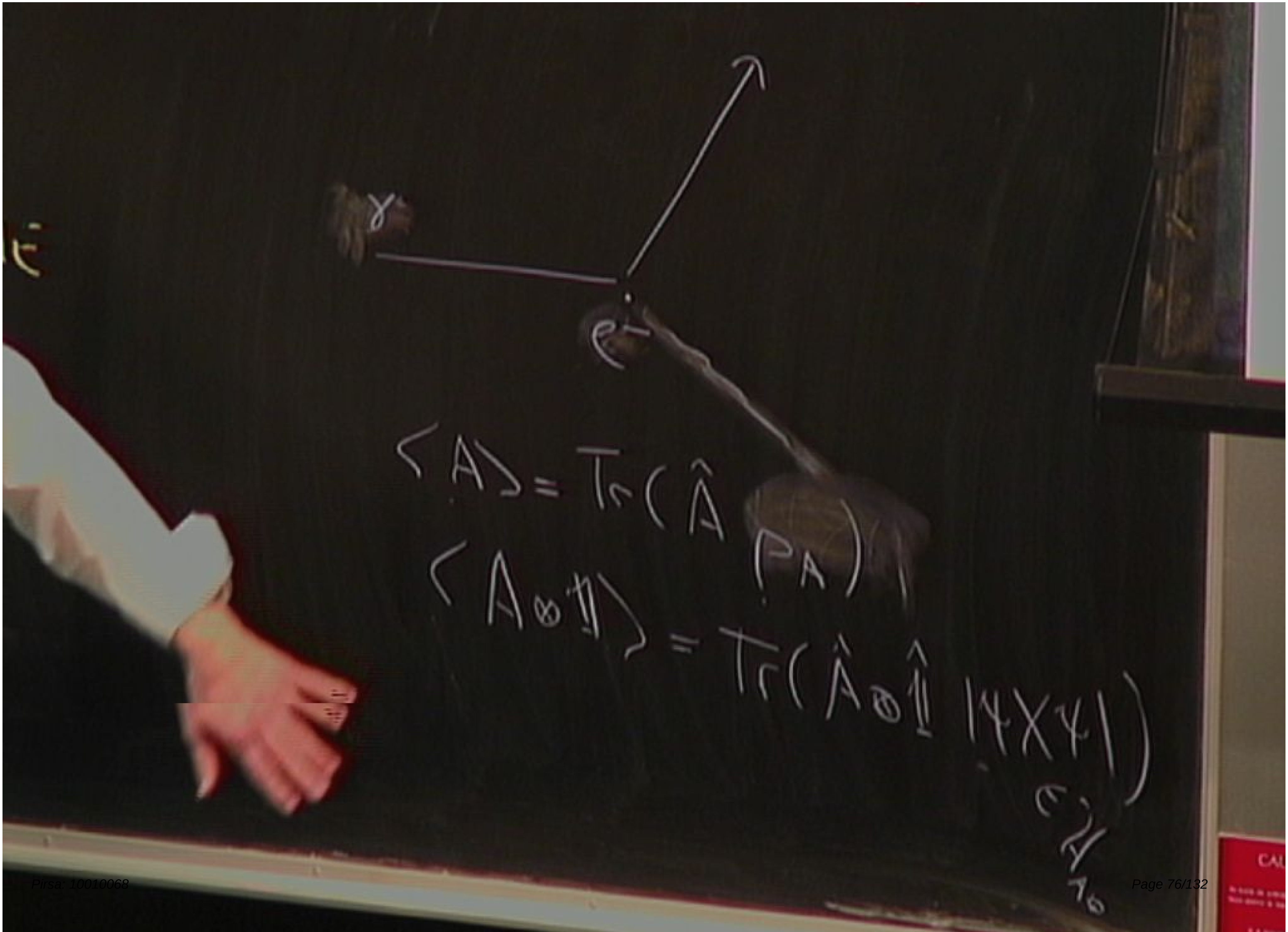
$$\langle \hat{A} \otimes \mathbb{1}_B \rangle = \langle \hat{A} \rangle$$

for all Hermitian operators $\hat{A}$ and states $\hat{\rho}_{AB}$. Hence,

$$(\rho_A)_{\ell\ell'} = \sum_k (\rho_{AB})_{\ell k \ell' k},$$

which gives us an explicit *matrix representation* of $\hat{\rho}_A$ in terms of the matrix elements of ρ_{AB} via the partial trace.


γ
e⁻
⟨A⟩ = Tr(Â ρ_A)
⟨A⊗𝟙⟩ = Tr(Â⊗𝟙̂ |ψ⟩⟨ψ|)
∈ ℋ_A ⊗ ℋ_B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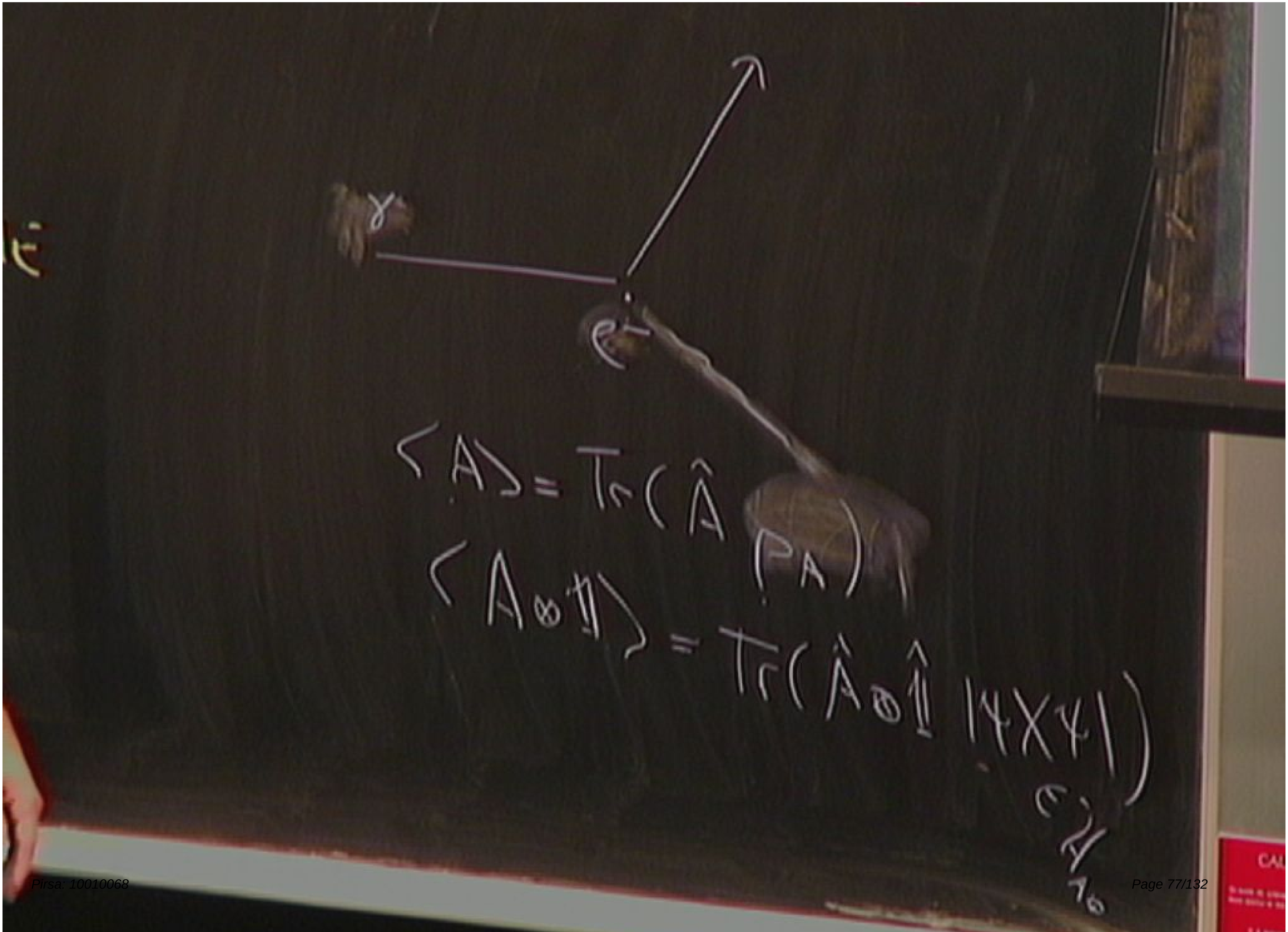
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⟨A⟩ = Tr(Â ρA)
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General states from the partial trace

Definition: The *partial trace* over a subsystem B of an operator O acting on the composite space $\mathcal{H}_{AB}$,

$$\hat{O}_A = \mathrm{Tr}_B[\hat{O}_{AB}],$$

can be defined in terms of the matrix representation,

$$(\hat{O}_A)_{\ell\ell'} = \langle \ell|\hat{O}_A|\ell'\rangle = \sum_k \langle \ell| \otimes \langle k|\hat{O}_{AB}|\ell'\rangle \otimes |k\rangle.$$

- It should be understood that the operation $\mathrm{Tr}_B(\cdot)$ takes as input *any* linear operator on $\mathcal{H}_{AB}$ (not necessarily a density operator) and generates a linear operator on $\mathcal{H}_A$.

Generalized states

Generalized Axiom 1: The physical configuration of a system positive semidefinite operator ρ subject to the normalization constraint $\mathrm{Tr}(\rho) = 1$

- An operator P is positive semi-definite iff it is self-adjoint and satisfies $\langle u|P|u\rangle \geq 0$ for every vector u in the Hilbert space.
- A positive semidefinite operator is sometimes just called a *positive operator* or a *non-negative operator*.

Pure States vs Mixed States

- For a state operator $\hat{\rho}$ subject to the normalization condition $\mathrm{Tr}(\hat{\rho}) = 1$ there are three equivalent definitions of *purity*:
  i) $\hat{\rho}^2 = \hat{\rho}$, which means that ρ is projector.
  ii) $\mathrm{Tr}(\hat{\rho}^2) = 1$.
  iii) $\hat{\rho} = |\psi\rangle\langle\psi|$, defining a projector onto a one-dimensional subspace of $\mathcal{H}$.

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Definition: If ρ can not be expressed in the form $\rho = |\psi\rangle\langle\psi|$ for any $\psi \in \mathcal{H}$, *i.e.*, if ρ is not a *pure state*, then it is called a *mixed state*.

Pure States vs Mixed States

General states obtained via partial trace are sometimes called *improper mixtures*, whereas the term *proper mixtures* refers to general states obtained from probabilistic mixing of pure states. These two conceptual classes of mixed states are mathematically equivalent. The justification for this claim comes from the mixed state purification theorem we will prove later as well the following theorem.

Theorem

Any general state operator can be expressed as a convex combination of pure states.

Purification of Mixed States

We have already seen how any mixed state can always be decomposed as a infinite number of different convex combination of pure states. It is also the case that:

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Any mixed state can be realized as the reduced state associated with a pure state on an extended Hilbert space.

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The pure state on the extended Hilbert space is called the *purification* of ρ_A.
If the reduced state has finite rank m, then clearly $m \leq M = \dim(\mathcal{H}_A)$.
From the proof we see that the ancilla factor space $\mathcal{H}_B$ must have dimension greater than or equal to m.
This purification of a mixed state is never unique. Indeed any state $|\psi'\rangle = (\mathbb{1} \otimes U)|\psi\rangle$, where U is an arbitrary unitary operator acting on $\mathcal{H}_B$, provides a valid purification of ρ_A.

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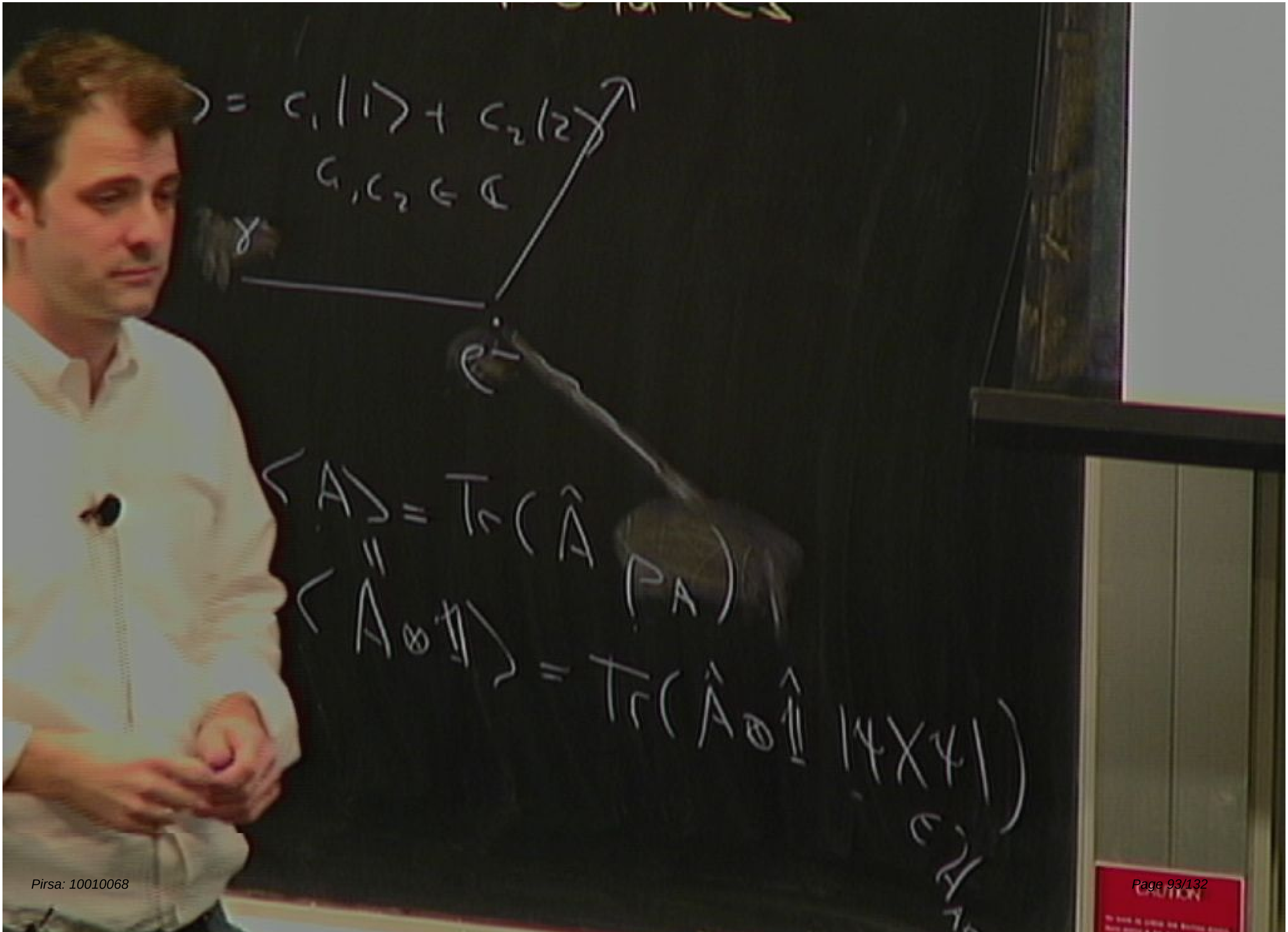
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c₁, c₂ ∈ ℂ
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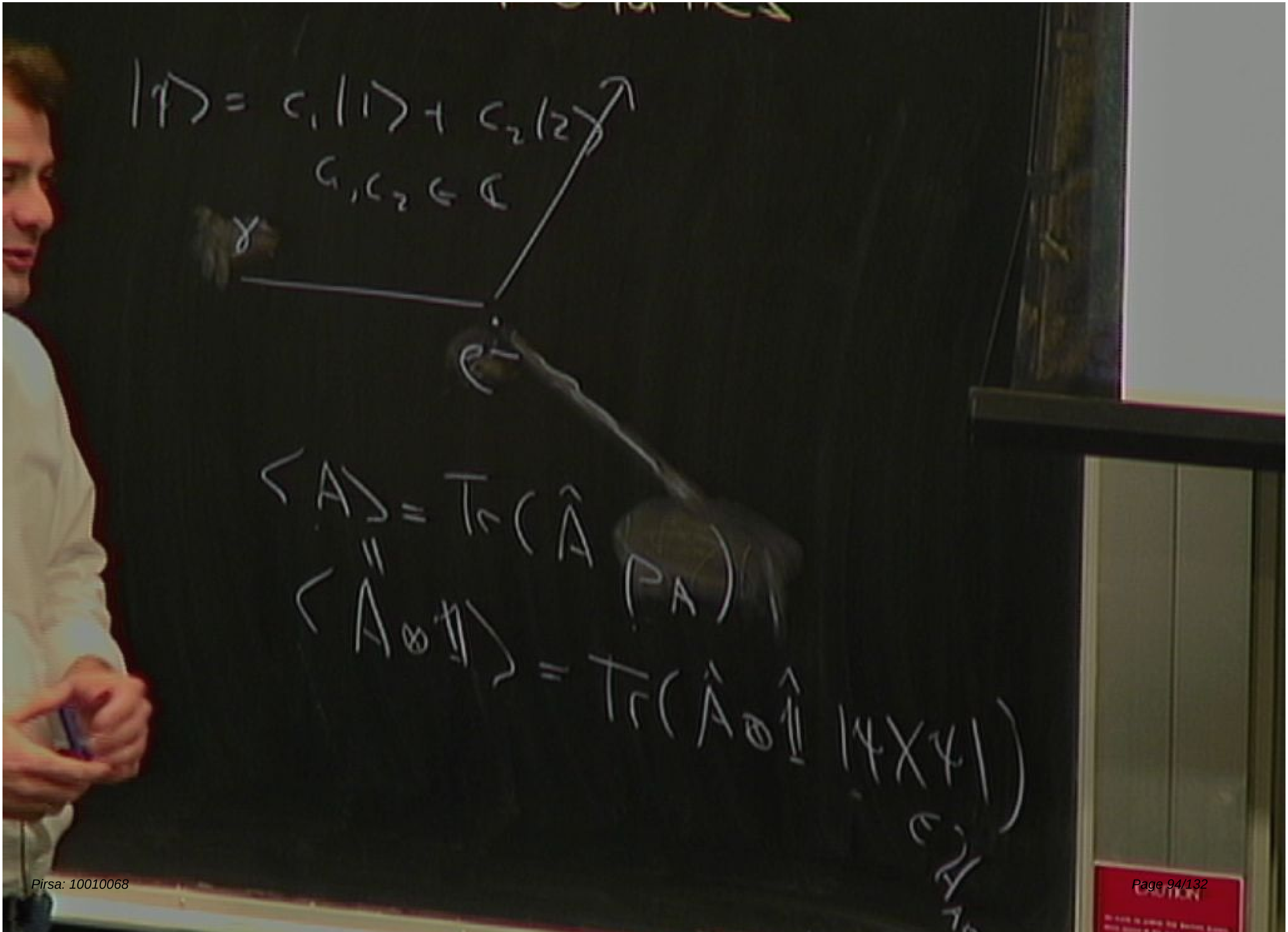
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⟨Â ⊗ 𝟙⟩ = Tr(Â ⊗ 𝟙 |ψ⟩⟨ψ|)
e⁻

Ideal Preparations: Hilbert Space Vectors

Axiom 1. An ideal preparation procedure is described by a Hilbert space vector $\psi \in \mathcal{H}$**.**

- Ideal preparations are often called "pure states".
- In discussions of interpretation, calling preparations "states" can lead to confusion, because the word state can connote ontological status.
- In finite dimensions $\mathcal{H} = \mathbb{C}^d$.
- Normalization implies $||\psi|| = 1$, which prescribes a hypersphere S^{2d-1} in a $2d$-dimensional real vector space.
- Because state vectors have a complex phase which is physically insignificant, distinct preparations are in one-to-one correspondence with elements of the complex projective space $\mathbb{C}P^{d-1}$.

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experimental tests of Bell inequalities, contextuality, macroscopic quantum phenomena, and the problem of quantum gravity, as time permits).

Schedule:

Lecturer	Tentative Lecture Title	Date
Joseph Emerson	Axioms for quantum mechanics	Week of January 11, 2009
Joseph Emerson	Basic problems of interpretation	Week of January 18, 2009
Joseph Emerson	Constraints on hidden variable models	Week of January 25, 2009
Robin Blume-Kohout	Probability and its interpretation	Week of February 1, 2009
Gregor Weihs	Experimental tests of Bell inequality	Week of February 8, 2009
Alex Wilce	Convex sets framework for probabilistic theories	Week of February 22, 2009
Roderich Tumulka	deBroglie-Bohm interpretation	Week of March 1, 2009
Chris Fuchs	Quantum Bayesian view	Week of March 8, 2009
TBA	TBA	Week of March 15, 2009
Tony Leggett	Fundamental tests of quantum mechanics	Week of March 22, 2009
Michel Devoret	Macroscopic quantum coherence	Week of March 29, 2009

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permits) and fundamental properties and tests of quantum theory (such as entanglement and experimental tests of Bell inequalities, contextuality, macroscopic quantum phenomena, and the problem of quantum gravity, as time permits).

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2:25 EIT to PI (this trip is reserved for those who have class on main campus until 2:20)
3:55 PI to EIT

Thursdays
2:05 EIT to RAC
2:25 EIT to RAC (this trip is reserved for those who have class on main campus until 2:20)
3:55 RAC to EIT

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Course Information

Winter 2005 - PHYS 490 / PHYS 773

Course Outline (in .doc format)

Instructors:

Joseph Emerson jemerson ["at"] perimeterinstitute ["dot"] ca

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January through April, 2005 (Winter Term).

Location:

Perimeter Institute, Room 405.
(Note: Thursday, 3 March, the lecture will be at UW in BFG 2125 at the usual time.)

Lectures

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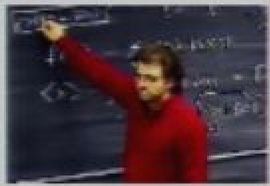
WEEK 1: Postulates of Quantum Theory **Joseph Emerson**

4 January - Lecture 1: Postulates of Quantum Theory I

6 January - Lecture 2: Postulates of Quantum Theory II



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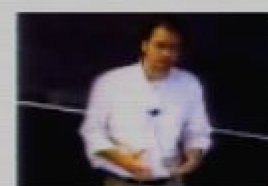

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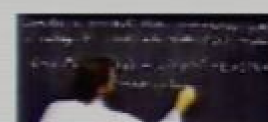
Bibliography for Week 1

WEEK 2: Measurement & Interpretation **Joseph Emerson**



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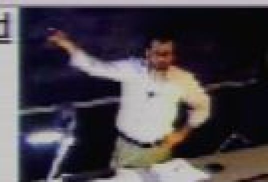
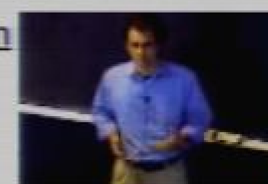


Bibliography for Week 2

WEEK 3: State Collapse & Hidden Variables **Joseph Emerson**

18 January - Lecture 5: Problems for the Orthodox Interpretation

20 January - Lecture 6: Incompleteness and Constraints on Hidden Variables



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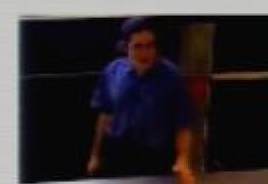
WEEK 4: The Many Worlds Interpretation **David Wallace**



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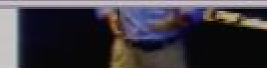

[Bibliography for Week 3](#)

WEEK 4: The Many Worlds Interpretation **David Wallace**

25 January - [Lecture 7: Many Worlds I](#)

27 January - [Lecture 8: Many Worlds II](#)

[Assigned Reading for Week 4](#)

WEEK 5: The de Broglie-Bohm Interpretation **Sheldon Goldstein**

1 February - [Lecture 9: de Broglie-Bohm I](#)

3 February - [Lecture 10: de Broglie-Bohm II](#)

[Assigned Reading for Week 5](#)

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Location:

Perimeter Institute, Room 405.
(Note: Thursday, 3 March, the lecture will be at UW in BFG 2125 at the usual time.)

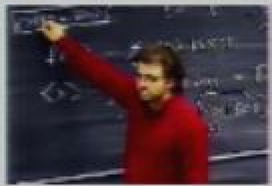
Lectures

Click on the image to view the lecture in Mediasite Live format, which requires Microsoft Internet Explorer (for Windows or Mac) and Windows Media Player. Macromedia Flash versions of the lectures are also available here.

WEEK 1: Postulates of Quantum Theory **Joseph Emerson**

4 January - Lecture 1: Postulates of Quantum Theory I

6 January - Lecture 2: Postulates of Quantum Theory II



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WEEK 1: Postulates of Quantum Theory **Joseph Emerson**

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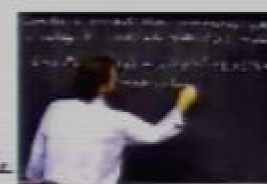
6 January - Lecture 2: Postulates of Quantum Theory II

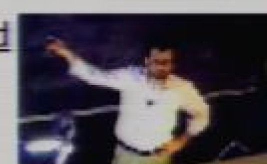
Bibliography for Week 1

WEEK 2: Measurement & Interpretation **Joseph Emerson**



11 January - Lecture 3: Generalized States, Measurements, Transformations

13 January - Lecture 4: Interpretations of Bohr, von Neumann, and Dirac



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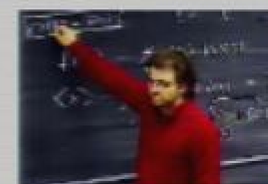
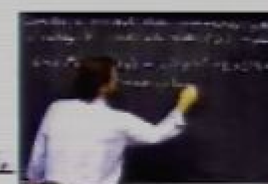


Bibliography for Week 1

WEEK 2: Measurement & Interpretation **Joseph Emerson**



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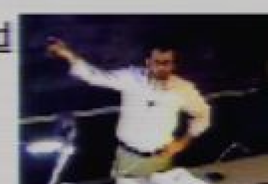
13 January - Lecture 4: Interpretations of Bohr, von Neumann, and Dirac



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WEEK 1: Postulates of Quantum Theory **Joseph Emerson**

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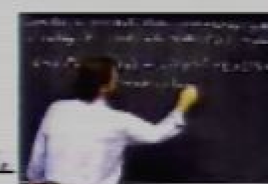

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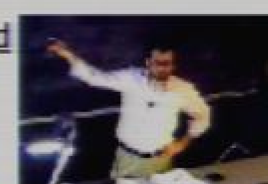

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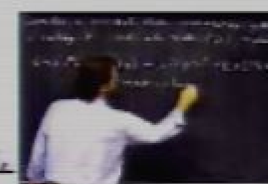

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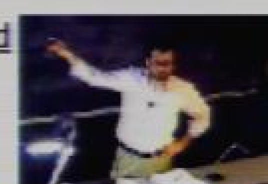

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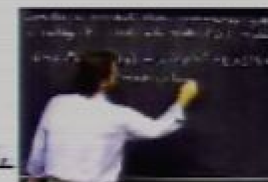

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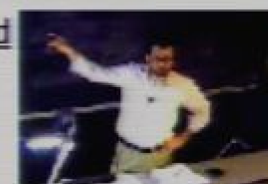

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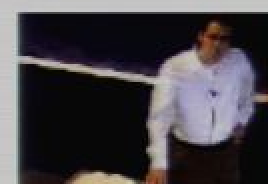
WEEK 3: State Collapse & Hidden Variables **Joseph Emerson**



18 January - Lecture 5: Problems for the Orthodox Interpretation

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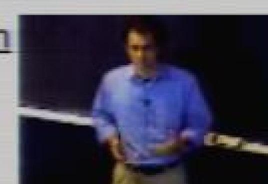

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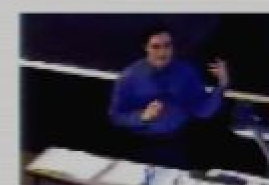
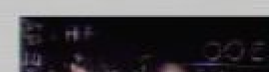


Assigned Reading for Week 4

WEEK 5: The de Broglie-Bohm Interpretation **Sheldon Goldstein**

1 February - Lecture 9: de Broglie-Bohm I

3 February - Lecture 10: de Broglie-Bohm II



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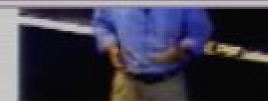

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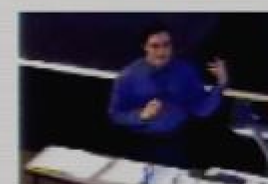

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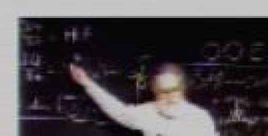

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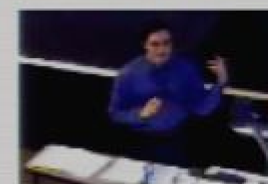

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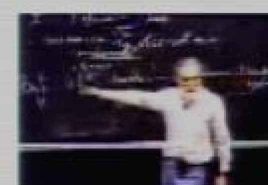

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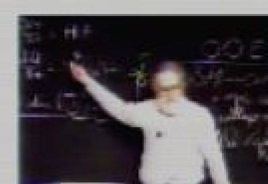

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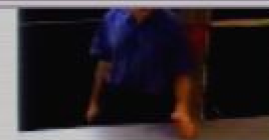

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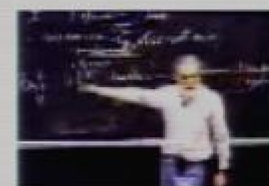

1 February - Lecture 9: de Broglie-Bohm I

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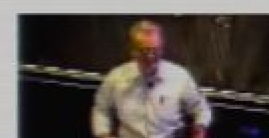
Assigned Reading for Week 5

WEEK 6: The Statistical Interpretation **Leslie Ballentine**



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27 January - Lecture 8: Many Worlds II

Assigned Reading for Week 4

WEEK 5: The de Broglie-Bohm Interpretation **Sheldon Goldstein**

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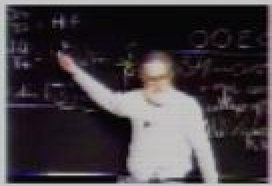
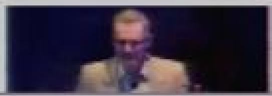


Assigned Reading for Week 5

WEEK 6: The Statistical Interpretation **Leslie Ballentine**

8 February - Lecture 11: Statistical I

10 February - Lecture 12: Statistical II



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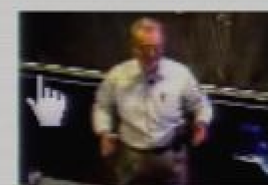
WEEK 6: The Statistical Interpretation **Leslie Ballentine**



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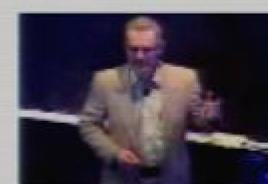
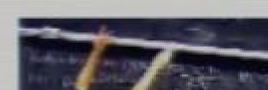


Assigned Reading for Week 6

WEEK 7: Spontaneous Collapse Models **Philip Pearle**

15 February - Lecture 13: Continuous Spontaneous Localization "Lite"

17 February - Lecture 14: Continuous Spontaneous Localization



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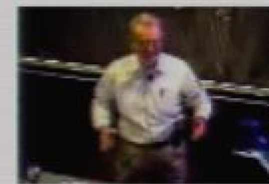

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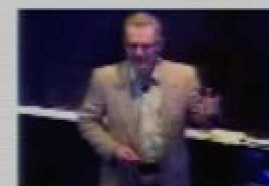

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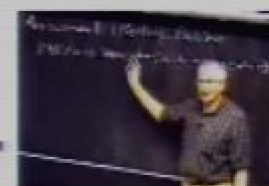

15 February - Lecture 13: Continuous Spontaneous Localization "Lite"

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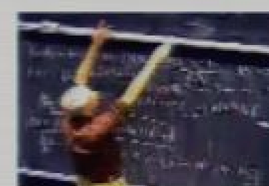

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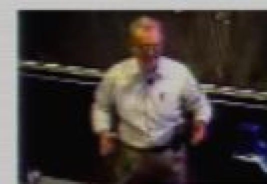
WEEK 6: The Statistical Interpretation **Leslie Ballentine**



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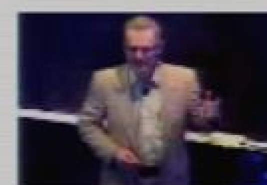

Assigned Reading for Week 6

WEEK 7: Spontaneous Collapse Models **Philip Pearle**

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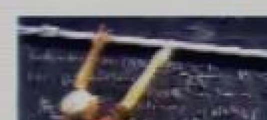

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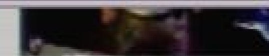
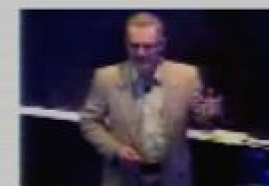
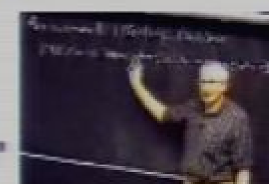


10 February - Lecture 12: Statistical II



Assigned Reading for Week 6

WEEK 7: Spontaneous Collapse Models **Philip Pearle**



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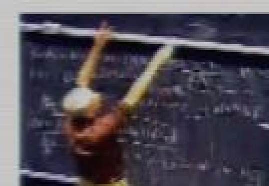
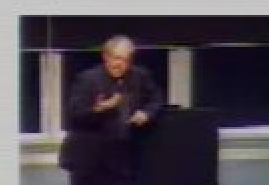


Assigned Reading for Week 7

WEEK 8: Experimental Interlude I **Anton Zeilinger**



1 March - Lecture 15: Interference of Macromolecules

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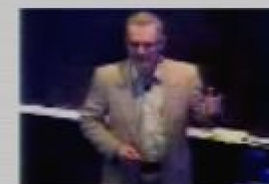
10 February - Lecture 12: Statistical II

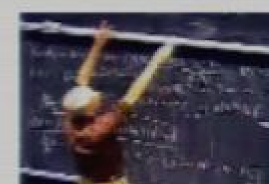


Assigned Reading for Week 6

WEEK 7: Spontaneous Collapse Models **Philip Pearle**

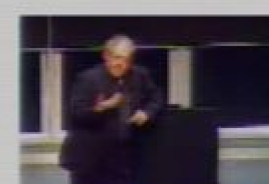
15 February - Lecture 13: Continuous Spontaneous Localization "Lite"

17 February - Lecture 14: Continuous Spontaneous Localization



Assigned Reading for Week 7

WEEK 8: Experimental Interlude I **Anton Zeilinger**



1 March - Lecture 15: Interference of Macromolecules

3 March - Lecture 16: Complementarity and Which-Path Information

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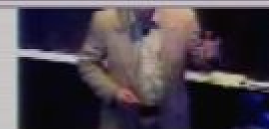

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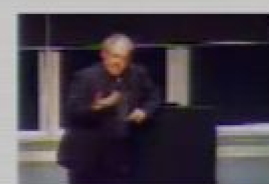

1 March - Lecture 15: Interference of Macromolecules

3 March - Lecture 16: Complementarity and Which-Path Information

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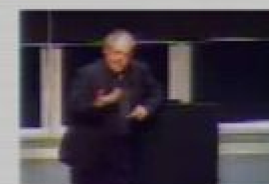
Assigned Reading for Week 7

WEEK 8: Experimental Interlude I **Anton Zeilinger**

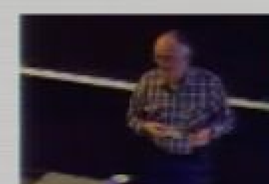


1 March - Lecture 15: Interference of Macromolecules

3 March - Lecture 16: Complementarity and Which-Path Information

Assigned Reading for Week 8

WEEK 9: The Consistent Histories Interpretation **Robert Griffiths**



8 March - Lecture 17: Consistent Histories I

10 March - Lecture 18: Consistent Histories II

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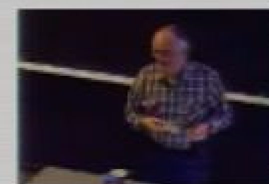
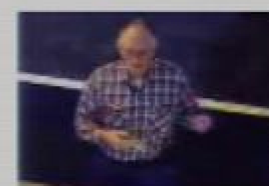


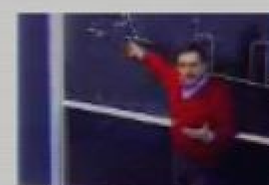
8 March - Lecture 17: Consistent Histories I

10 March - Lecture 18: Consistent Histories II



Assigned Reading for Week 9

WEEK 10: Experimental Interlude II **Alain Aspect**



15 March - Lecture 19: Bell's Theorem & Non-Locality

17 March - Lecture 20: Entanglement & Superluminal Signaling

Assigned Reading for Week 10

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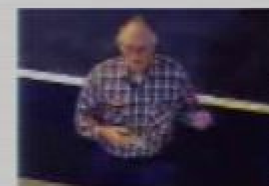

Assigned Reading for Week 9

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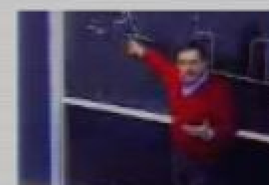

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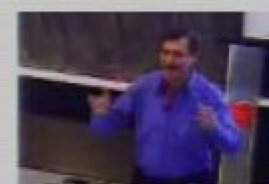
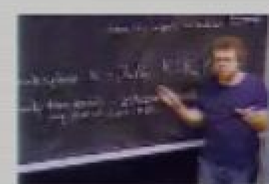
17 March - Lecture 20: Entanglement & Superluminal Signaling



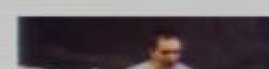
Assigned Reading for Week 10

WEEK 11: Axioms and Logic **Lucien Hardy / Matthew Leifer**



22 March - Lecture 21: Physical Axioms for Quantum Theory

24 March - Lecture 22: Quantum Logic



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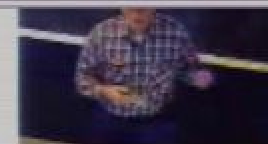
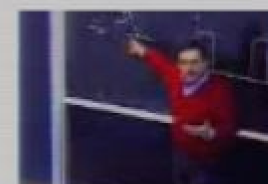


Assigned Reading for Week 9

WEEK 10: Experimental Interlude II **Alain Aspect**



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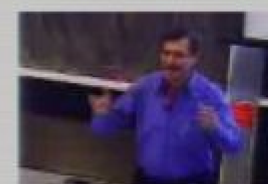
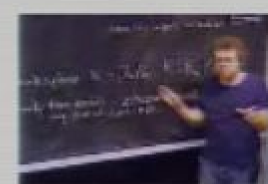


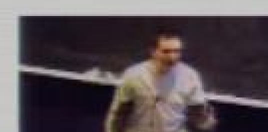
Assigned Reading for Week 10

WEEK 11: Axioms and Logic **Lucien Hardy / Matthew Leifer**



22 March - Lecture 21: Physical Axioms for Quantum Theory

24 March - Lecture 22: Quantum Logic



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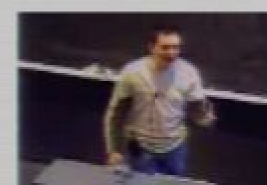
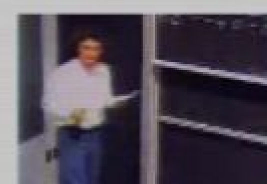


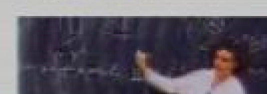
Assigned Reading for Week 11

WEEK 12: Advanced Topics in Hidden Variables **Antony Valentini**



29 March - Lecture 23: Quantum Non-Equilibrium Systems I

31 March - Lecture 24: Quantum Non-Equilibrium Systems II



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17 March - Lecture 20: Entanglement & Superluminal Signaling

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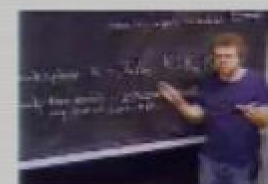

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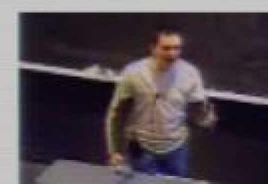
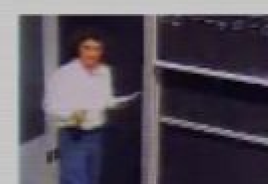


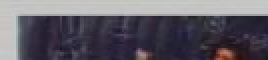
Assigned Reading for Week 11

WEEK 12: Advanced Topics in Hidden Variables **Antony Valentini**



29 March - Lecture 23: Quantum Non-Equilibrium Systems I

31 March - Lecture 24: Quantum Non-Equilibrium Systems II



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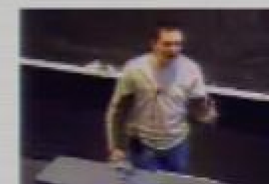
24 March - Lecture 22: Quantum Logic



Assigned Reading for Week 11

WEEK 12: Advanced Topics in Hidden Variables **Antony Valentini**

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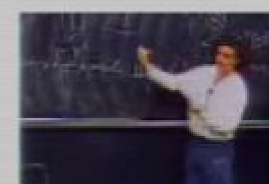
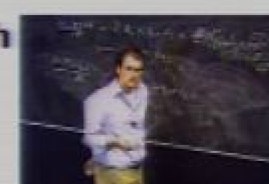
31 March - Lecture 24: Quantum Non-Equilibrium Systems II



Assigned Reading for Week 12

WEEK 13: Epistemic Features of the Quantum State **Joseph Emerson**



5 April - Lecture 25: Chaos and Quantum/Classical Correspondence

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WEEK 12: Advanced Topics in Hidden Variables **Antony Valentini**

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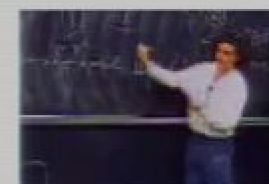

Assigned Reading for Week 12

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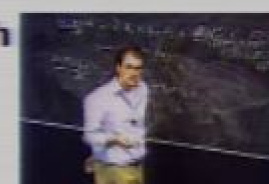

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course information | lectures | assignments | term project | additional materials

Course Information

Winter 2005 - PHYS 490 / PHYS 773

Winter 2005 - PHYS 490 / PHYS 773

Course Outline (in .doc format)

Instructors:

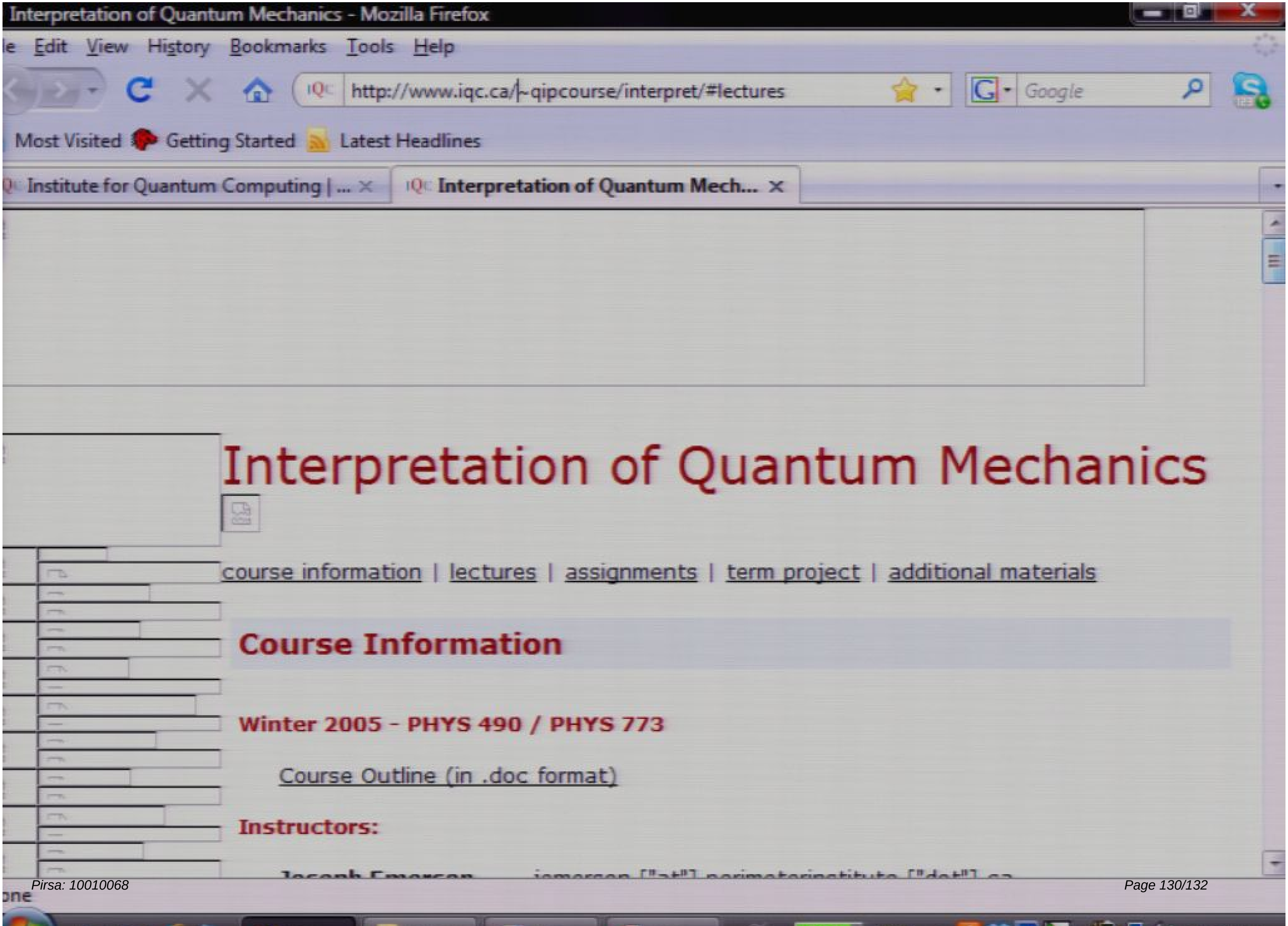
Joseph Emerson jemerson ["at"] perimeterinstitute ["dot"] ca
Raymond Laflamme laflamme ["at"] iqc ["dot"] ca

Dates & Times:

Tuesdays & Thursdays, 2:15pm - 3:45pm,
January through April, 2005 (Winter Term).

Location:

Perimeter Institute, Room 405.
(Note: Thursday, 3 March, the lecture will be at UW in BFG 2125 at the usual time.)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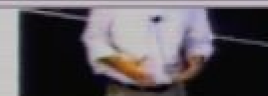
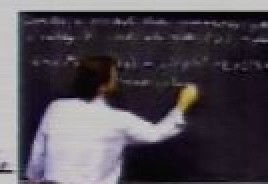


4 January - Lecture 1: Postulates of Quantum Theory I

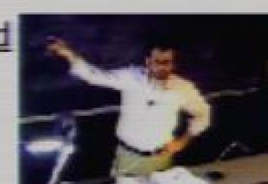
6 January - Lecture 2: Postulates of Quantum Theory II

Bibliography for Week 1



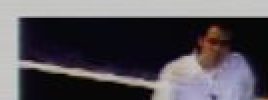
WEEK 2: Measurement & Interpretation **Joseph Emerson**

11 January - Lecture 3: Generalized States, Measurements, Transformations



13 January - Lecture 4: Interpretations of Bohr, von Neumann, and Dirac

Bibliography for Week 2



WEEK 3: State Collapse & Hidden Variables **Joseph Emerson**

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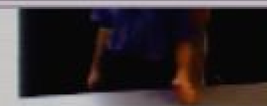
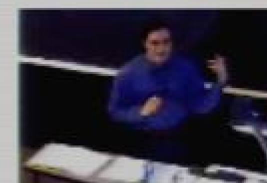


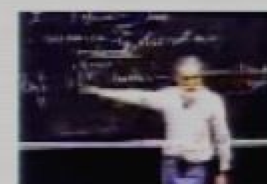
25 January - Lecture 7: Many Worlds I

27 January - Lecture 8: Many Worlds II



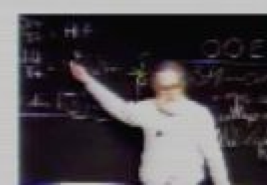
Assigned Reading for Week 4

WEEK 5: The de Broglie-Bohm Interpretation **Sheldon Goldstein**



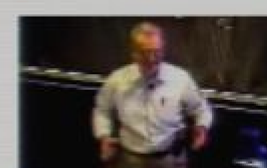
1 February - Lecture 9: de Broglie-Bohm I

3 February - Lecture 10: de Broglie-Bohm II



Assigned Reading for Week 5

WEEK 6: The Statistical Interpretation **Leslie Ballentine**



8 February - Lecture 11: Statistical I