Title: The Weird World of Quantum Physics - Part 5

Date: Jul 26, 2006 01:00 PM

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Abstract:

List of mentors and topics

Black Hole Thermodynamics, Rowan Thomson.

Quantum Memory, Carlos Mochon.

String theory: The ADS-CFT correspondence and black holes: Sean Gryb

Boson, fermions and the harmonic oscillator: Nemani Nemani Suryanarayana.

Mathematical Physics and Quantum Gravity, Jon Hackett.

The foundations of quantum theory and the pilot-wave interpretation, Ward Stryve

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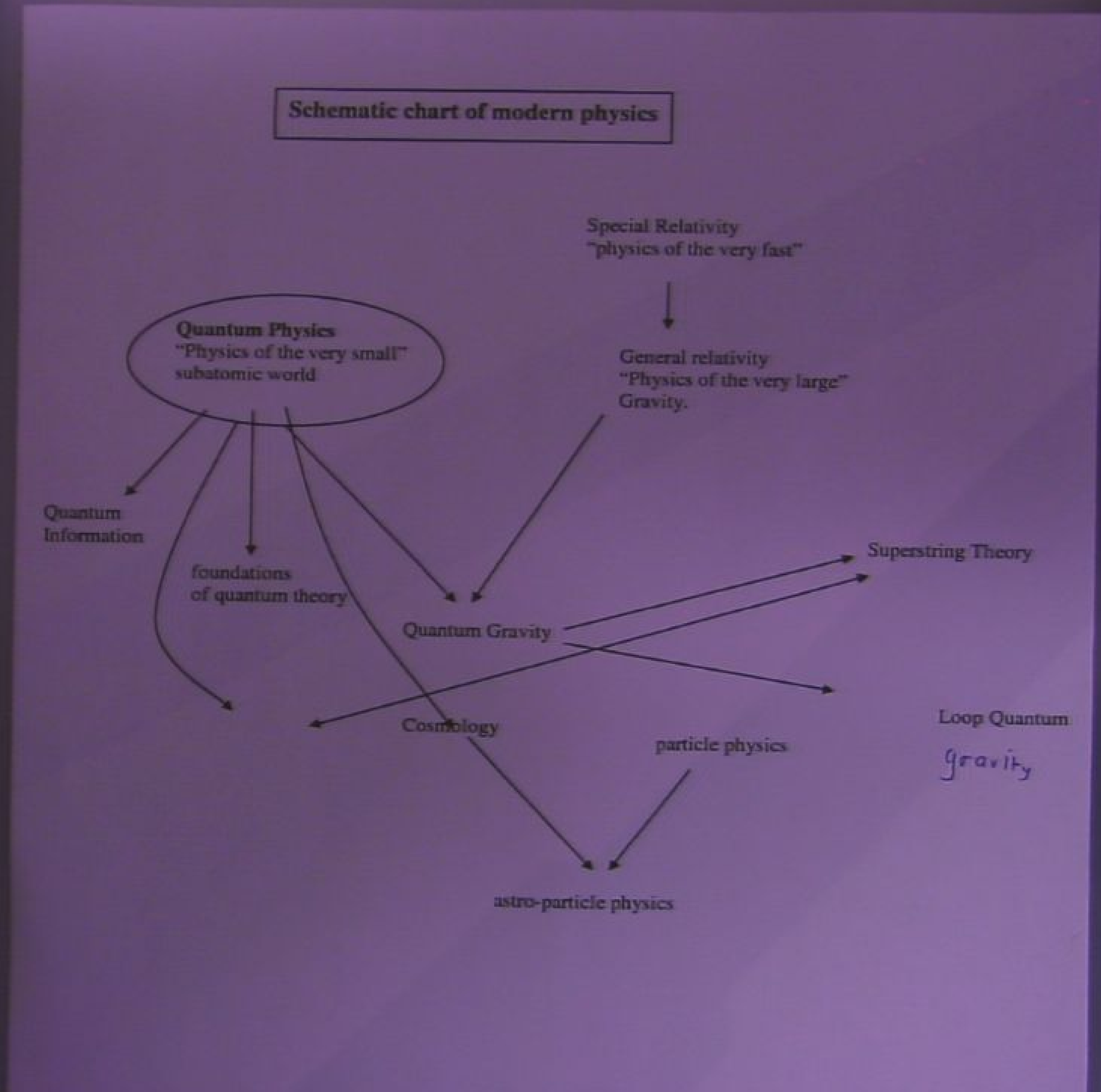
Schematic chart of modern physics
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Quantum Physics
"Physics of the very small"
subatomic world
General relativity
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Gravity.
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foundations
of quantum theory
Superstring Theory
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Loop Quantum
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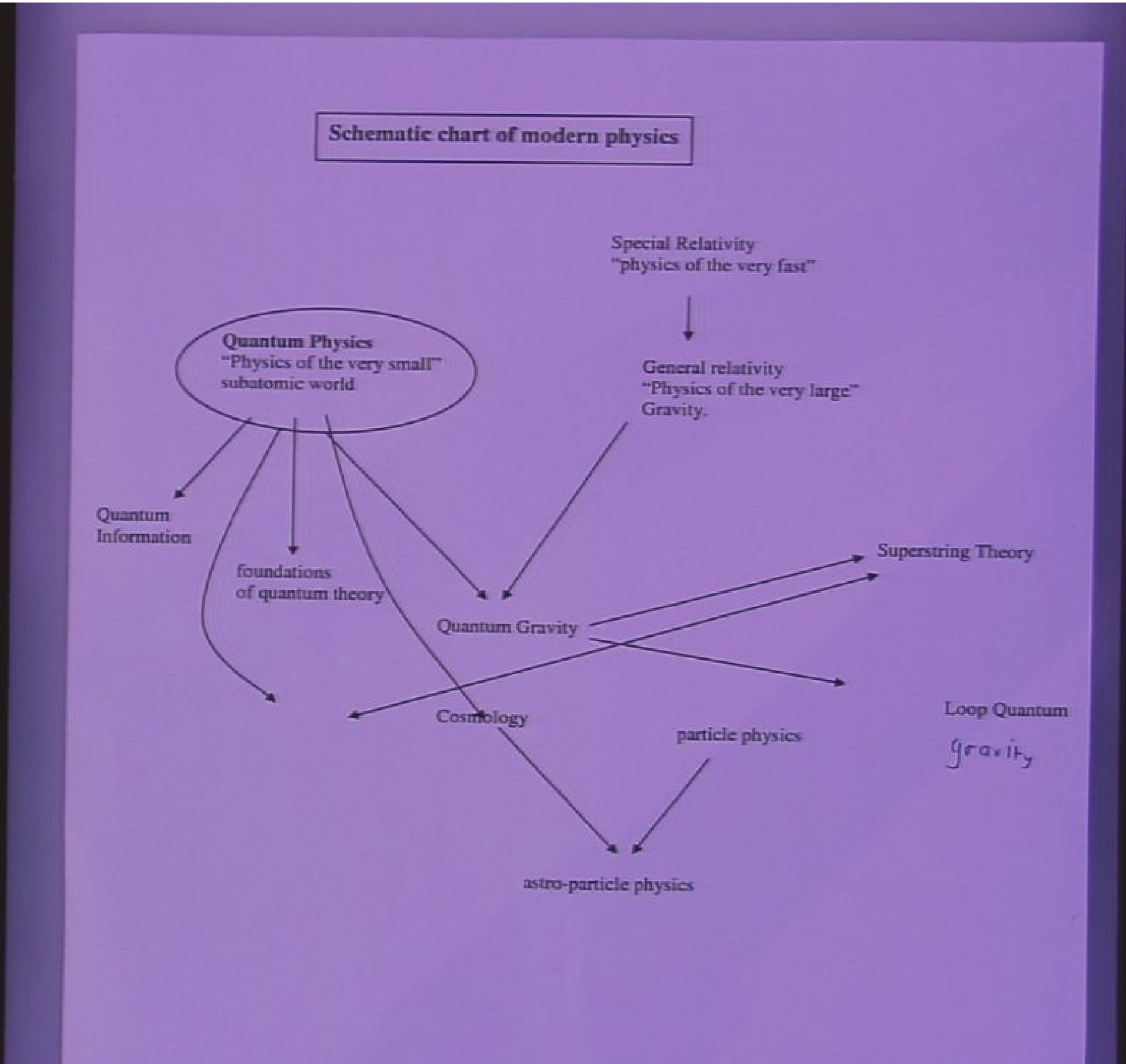
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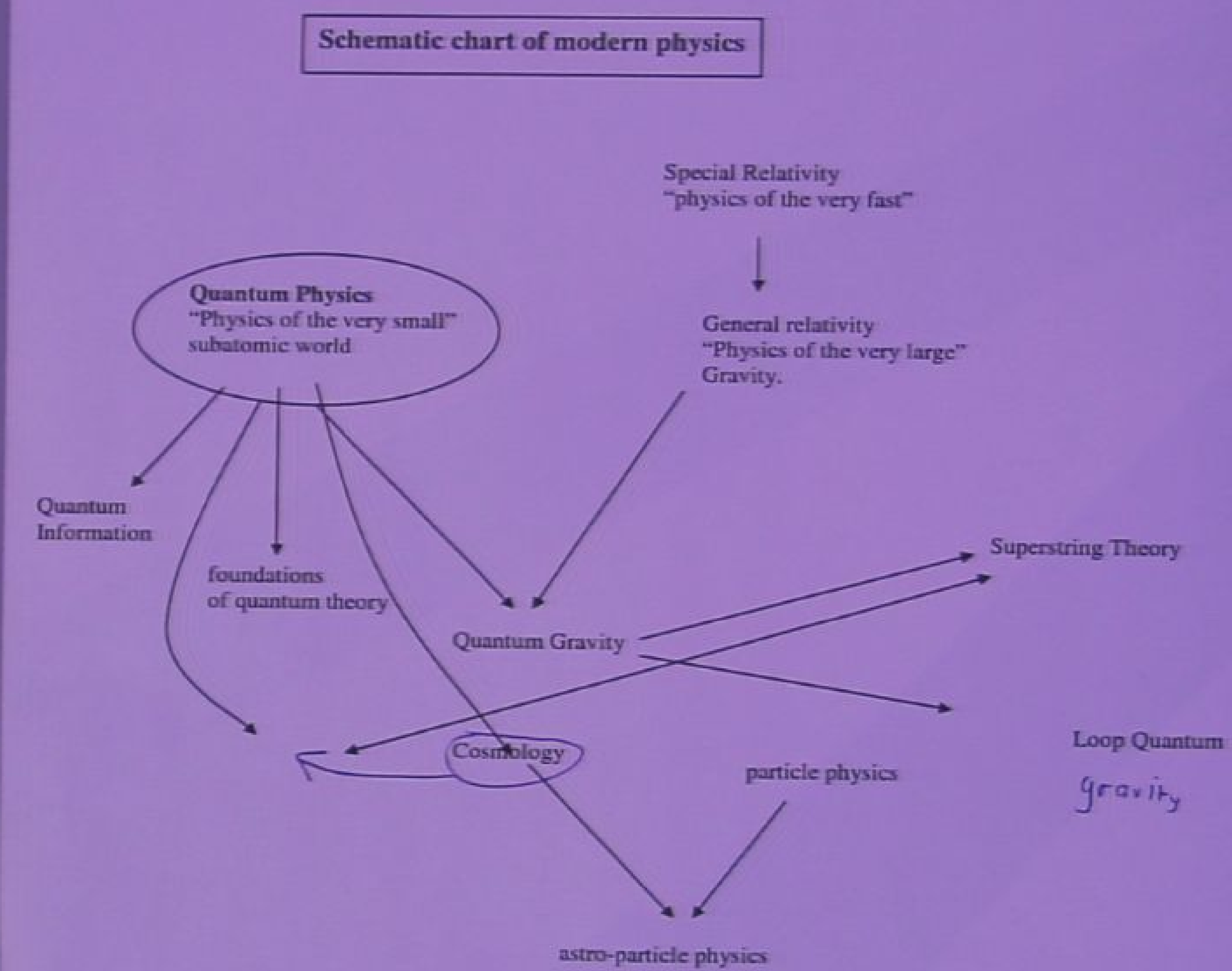
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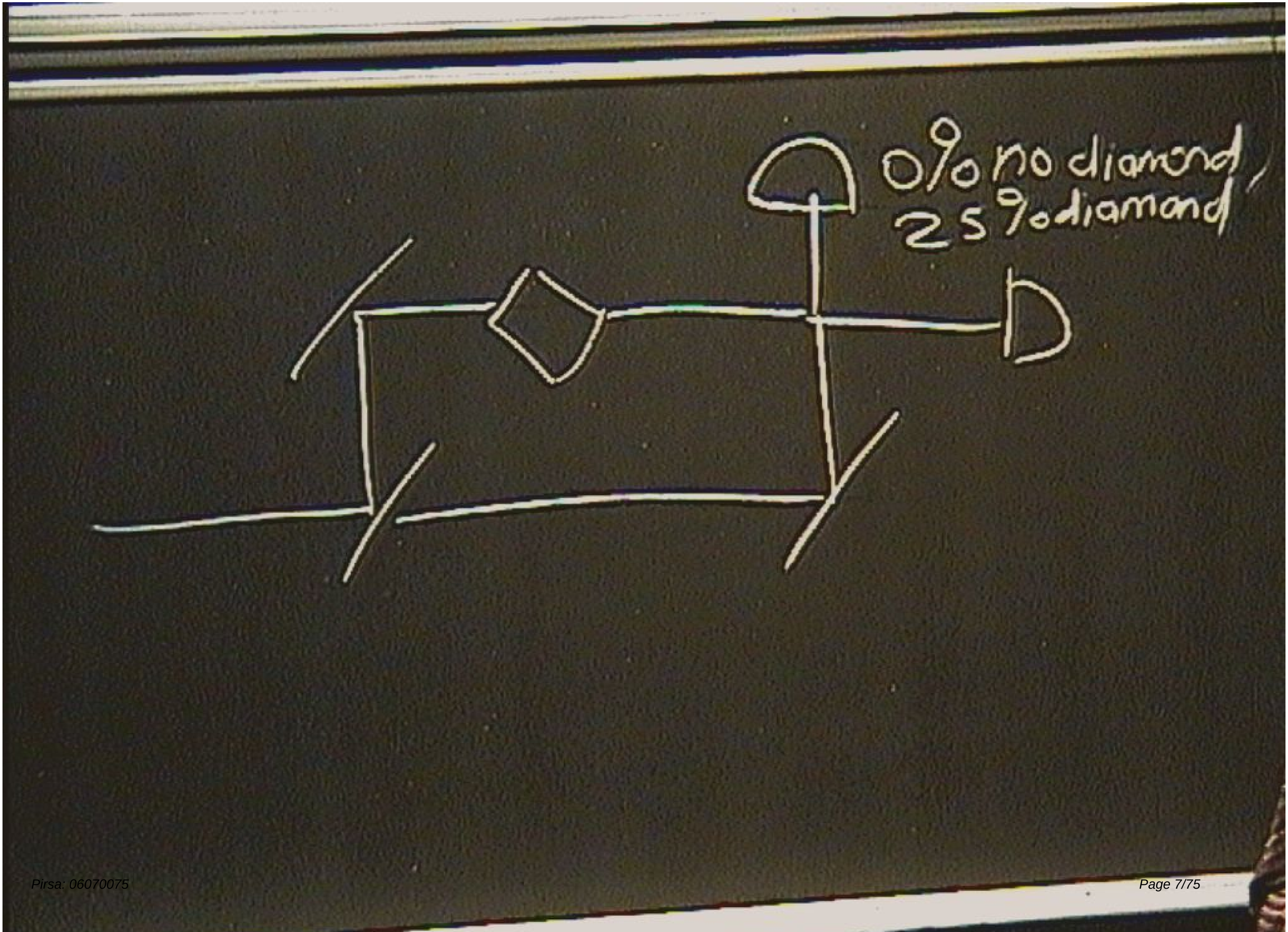
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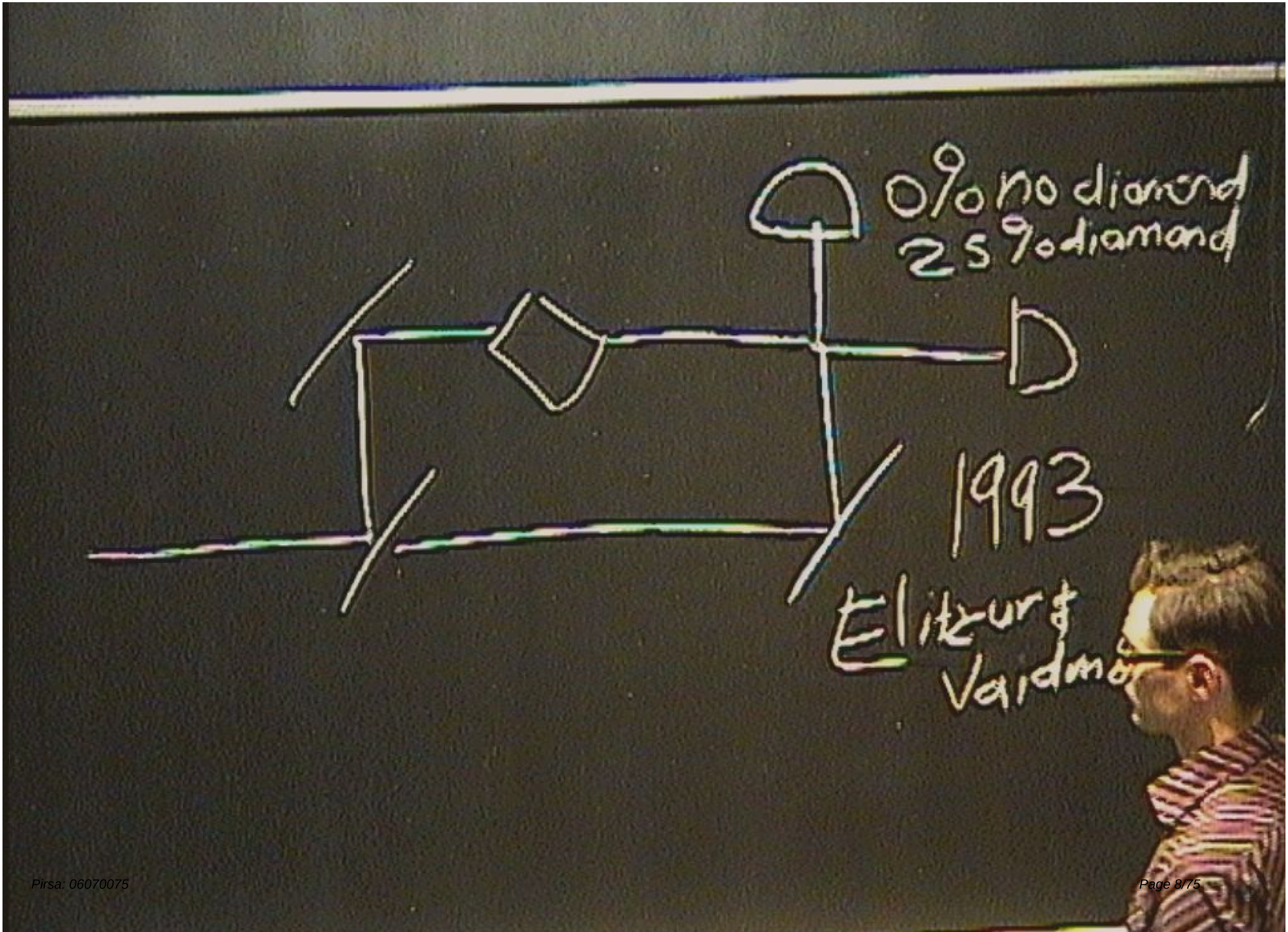
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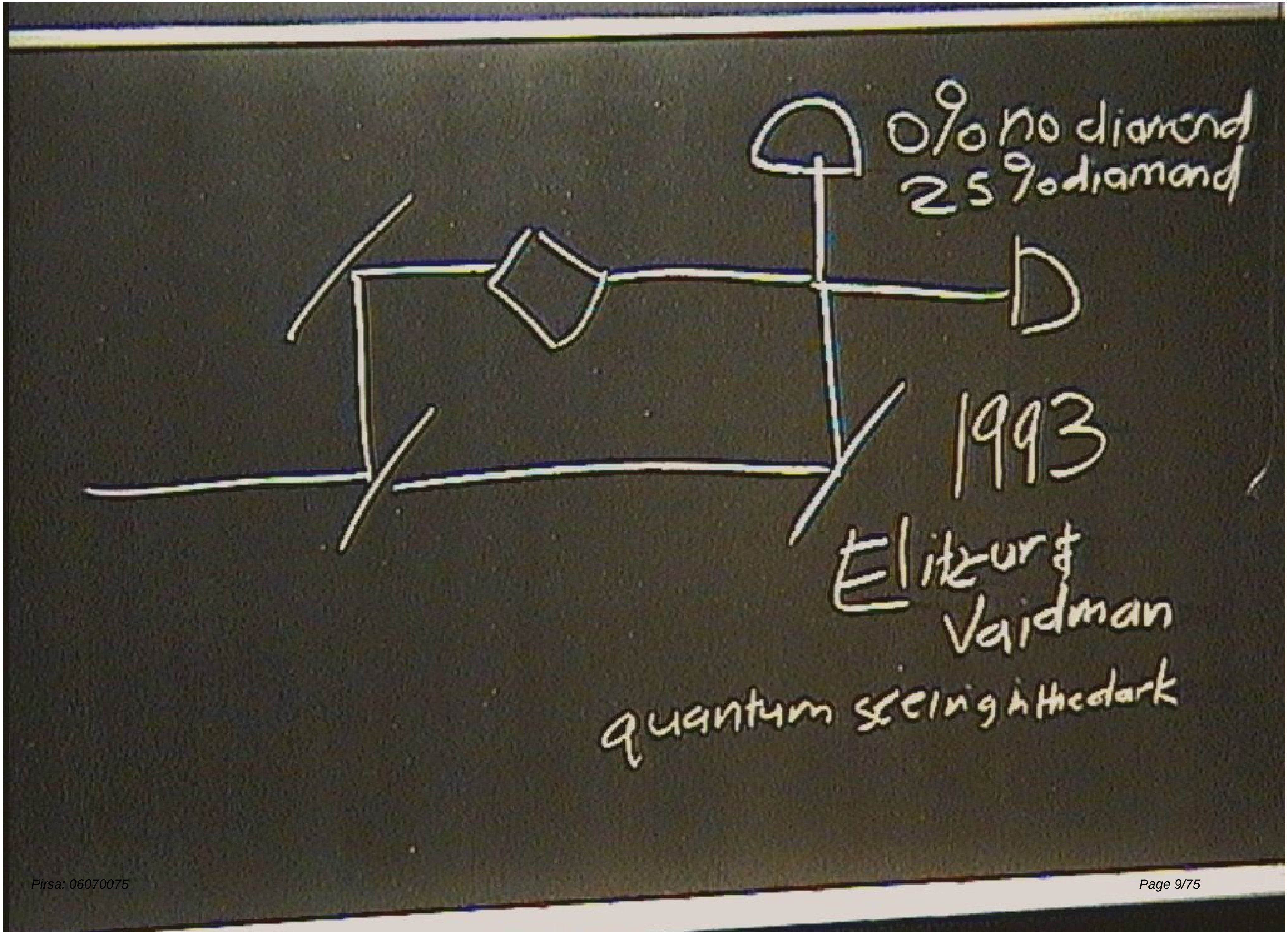
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quantum seeing in the dark

High-efficiency quantum interrogation measurements via the quantum Zeno effect

P. G. Kwiat[1,*], A. G. White[1], J. R. Mitchell[1], O. Nairz[2,†], G. Weihs[2,†], H. Weinfurter[2,‡], and A. Zeilinger[2,†]
[1] Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
[2] Institute for Experimental Physics, University of Innsbruck, Innsbruck 6020, Austria
(to appear in Phys. Rev. Lett; submitted June 11, 1999)

The phenomenon of quantum interrogation allows one to optically detect the presence of an absorbing object, without the measuring light interacting with it. In an application of the quantum Zeno effect, the object inhibits the otherwise coherent evolution of the light, such that the probability that an interrogating photon is absorbed can in principle be arbitrarily small. We have implemented this technique, demonstrating efficiencies exceeding the 50% theoretical-maximum of the original "interaction-free" measurement proposal. We have also predicted and experimentally verified a previously unsuspected dependence on loss; efficiencies of up to 73% were observed and the feasibility of efficiencies up to 85% was demonstrated.

PACS numbers: 03.65.Bz,03.65.-a,42.50.-p,42.25.Hz

"Negative result" measurements were discussed by Renninger [1] and later by Dicke [2], who analyzed the change in an atom's wavefunction by the *nonscattering* of a photon from it. In 1993 Elitzur and Vaidman (EV) showed that the wave-particle duality of light could allow "interaction-free" quantum interrogation of classical objects, in which the presence of a non-transmitting object is ascertained seemingly without interacting with it [3], i.e., with no photon absorbed or scattered by the object. In the basic EV technique, an interferometer is aligned to give complete destructive interference in one output port – the "dark" output – in the absence of an object. The presence of an opaque object in one arm of the interferometer eliminates the possibility of interference so that a photon may now be detected in this output. If the object is completely non-transmitting, any photon detected in the dark output port must have come from the path *not* containing the object. Hence, the measurements were deemed "interaction-free", though we stress that this term is sensible only for objects that completely block the beam. For measurements on partially-transmitting (and quantum) objects, we suggest the more general terminology "quantum interrogation". In any event there is necessarily a coupling between light and object (formally describable by some interaction Hamiltonian) – somewhat paradoxically, in the high-efficiency schemes discussed below, it is crucial that the *possibility* of an interaction exist, in order to reduce the probability that such an interaction actually occurs.

The EV gedanken experiment has been realized using

even been employed to investigate the possibility of performing "absorption-free" imaging [7]. The EV technique suffers two serious drawbacks, however. First, the measurement result is ambiguous at least half of the time – a photon may be detected in the non-dark output port whether or not there is an object. Second, at most half of the measurements are interaction-free [4,7]. Following Elitzur and Vaidman [3], we define a figure of merit $\eta = P(QI)/[P(QI) + P(abs)]$ to characterize the "efficiency" of a given scheme, where P(QI) is the probability that the photon is detected in the otherwise dark port, and P(abs) is the probability that the object absorbs or scatters the photon. Physically, η is the *fraction* of measurements that are "interaction-free". The maximum achievable efficiency, obtained by adjusting the reflectivities of the EV interferometer beamsplitters, is $\eta = 50\%$ [3,4,7].

It was proposed that one could circumvent these limitations by using a hybrid scheme [4], combining the interferometric ideas of EV and incorporating an optical version of the *quantum Zeno effect* [8], in which a weak, repeated measurement inhibits the otherwise coherent evolution of the interrogating photon. Our specific embodiment of the Zeno effect is based on an inhibited polarization rotation [9], although the only generic requirement is a weakly-coupled multi-level system. A photon with

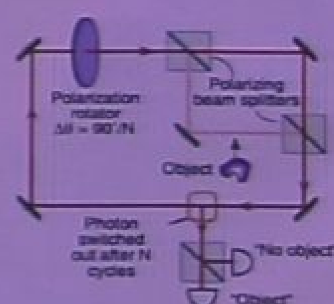
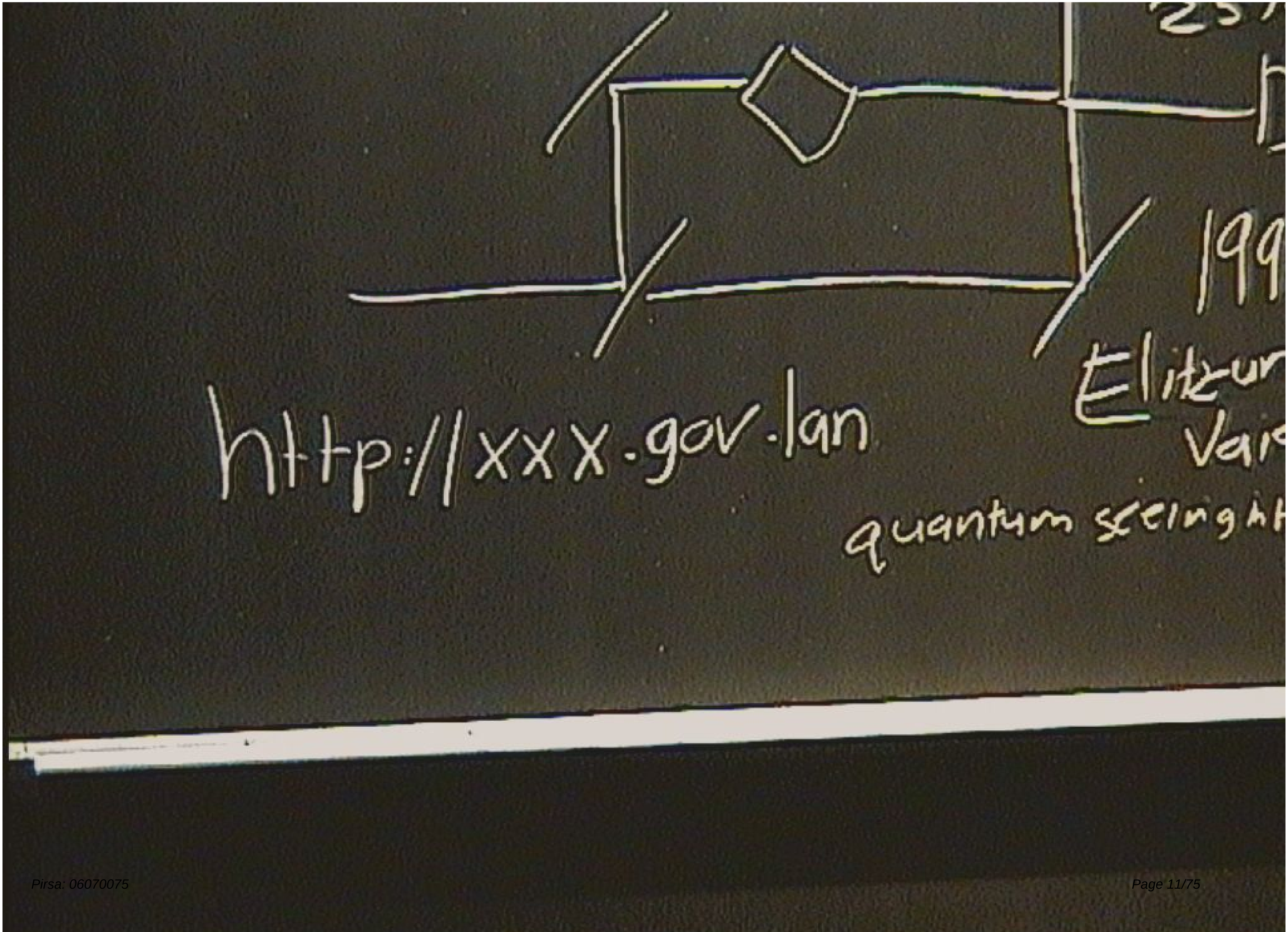


FIG. 1. Simple schematic of a hybrid scheme to allow high-efficiency quantum interrogation of the presence of an opaque object. With no object, the initial horizontal polarization of the interrogating photon is rotated stepwise to vertical. The presence of an object in the V-arm inhibits this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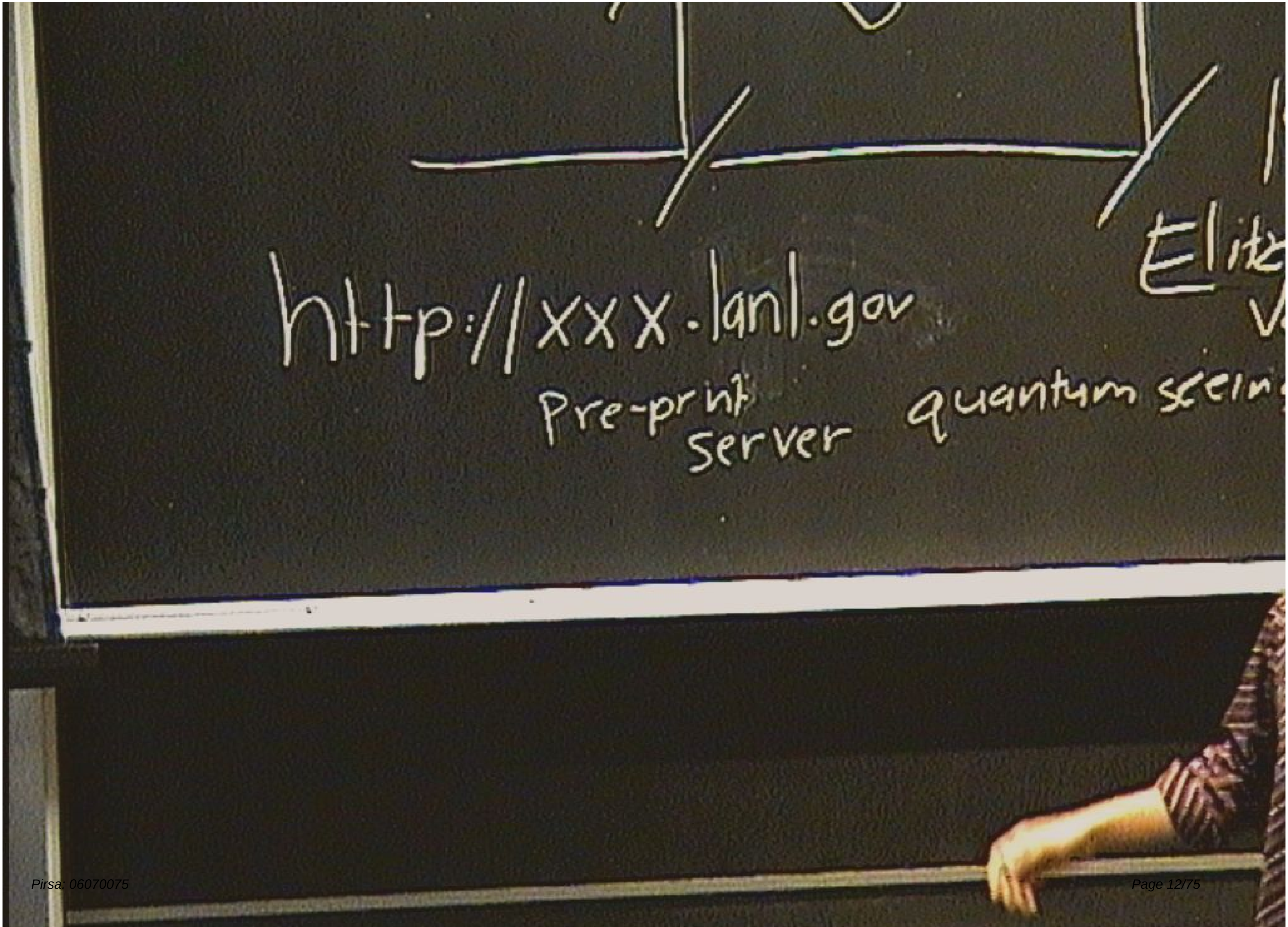
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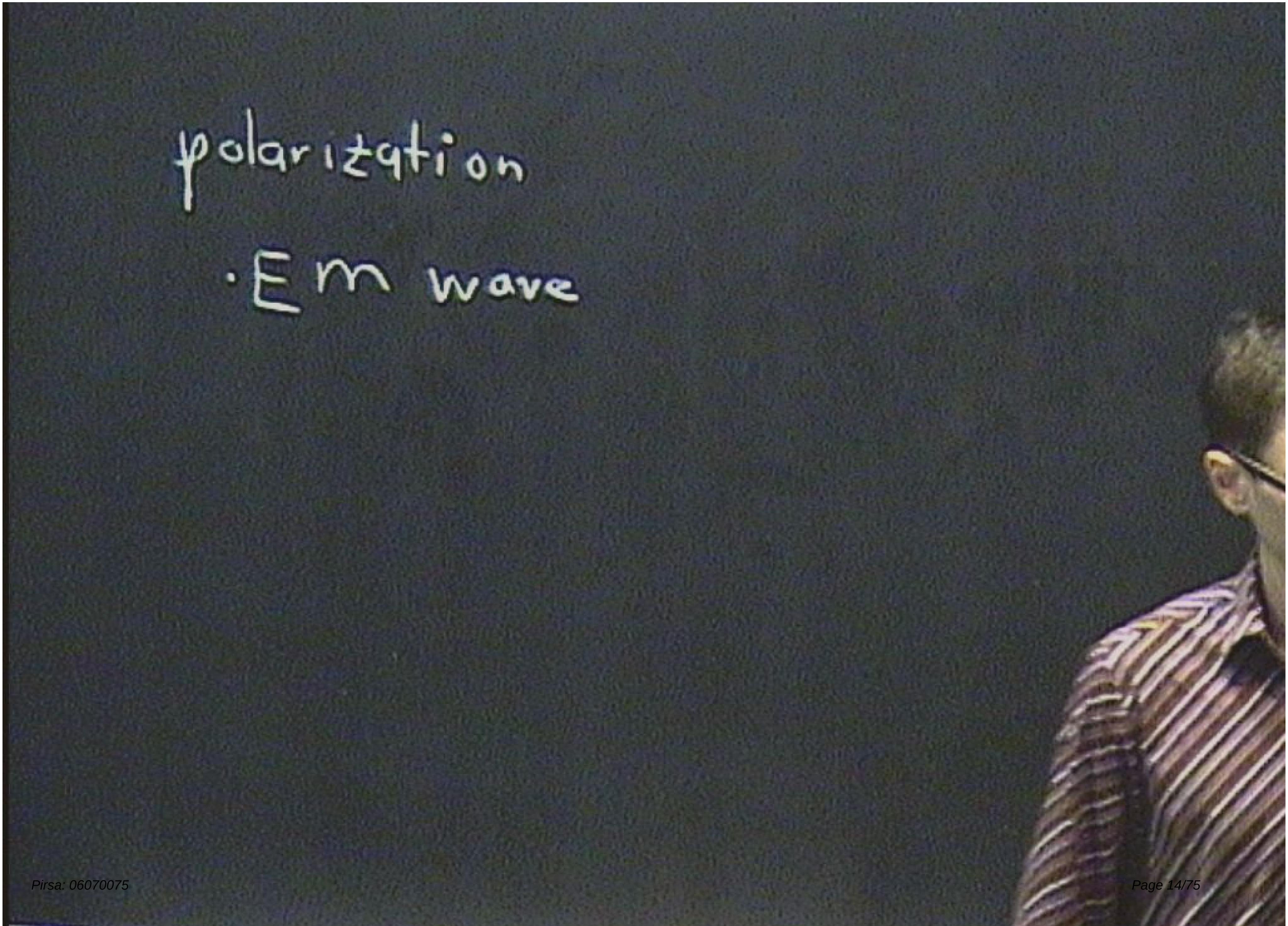
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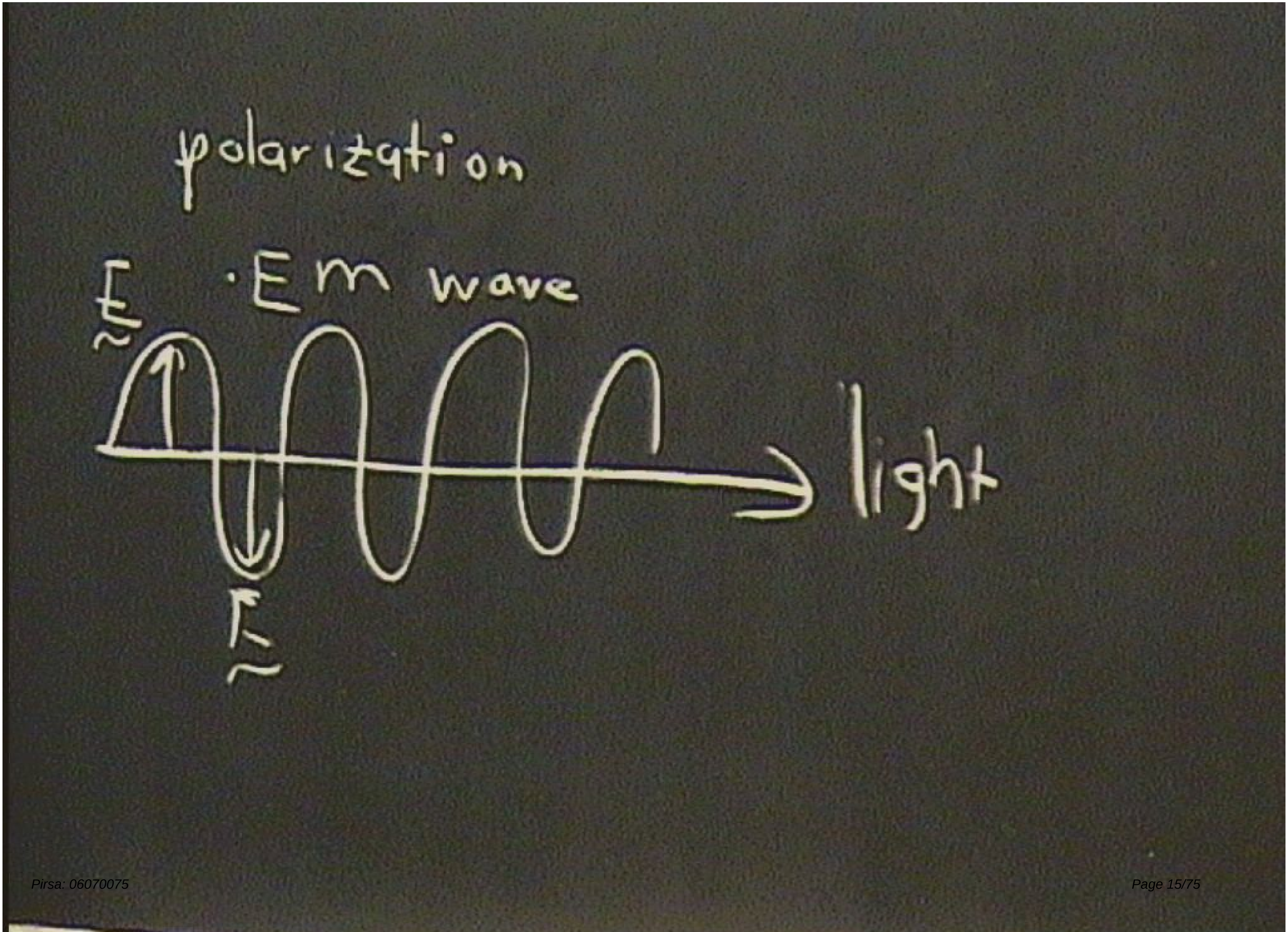
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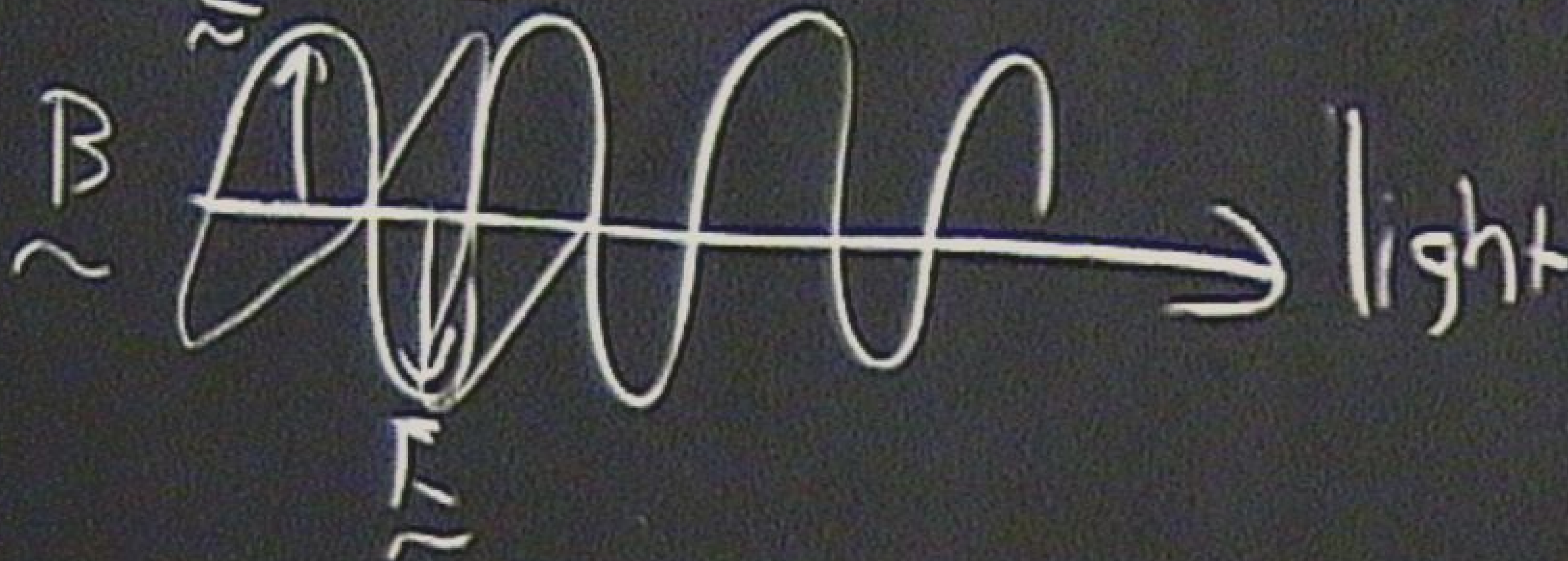

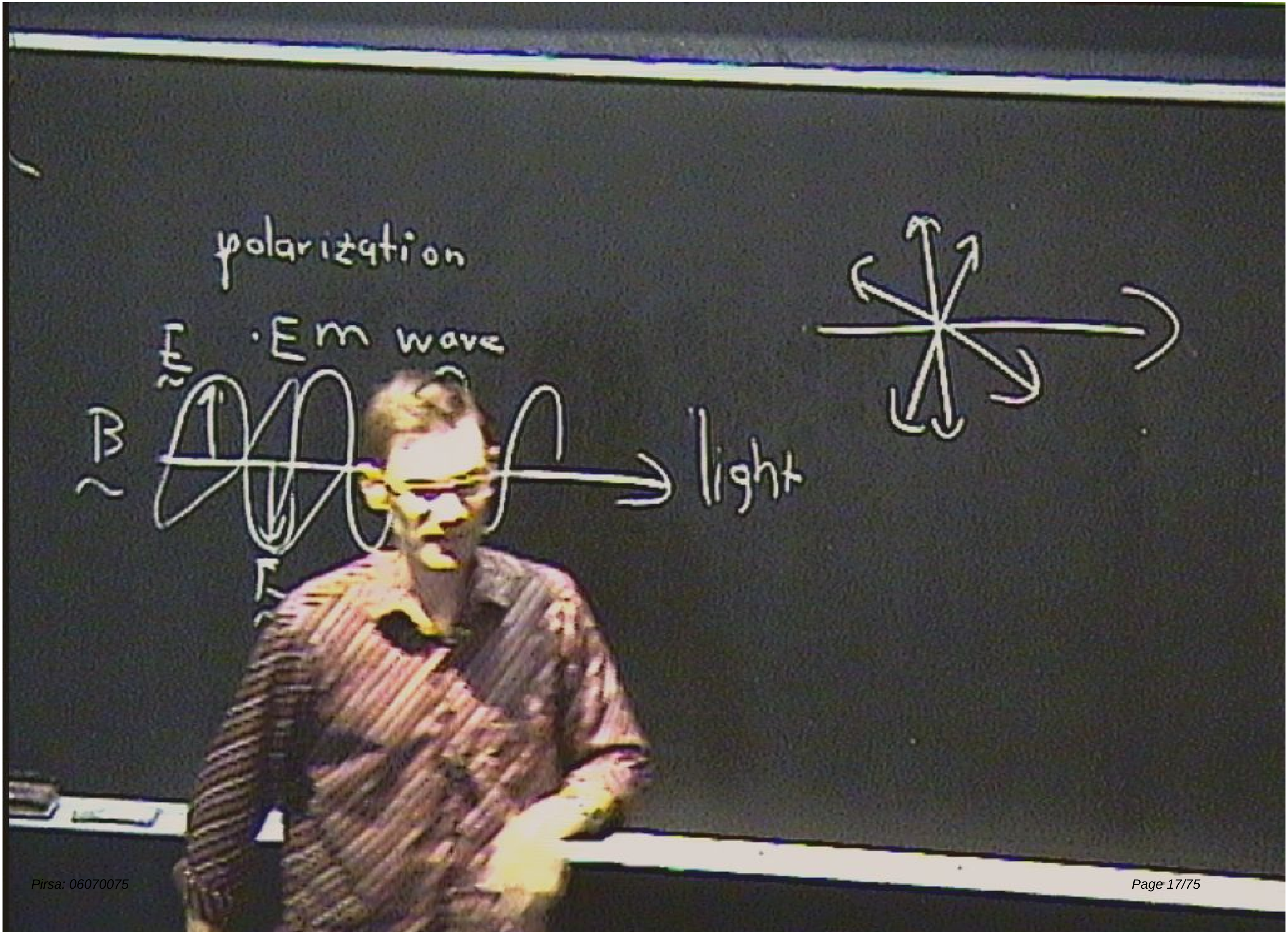
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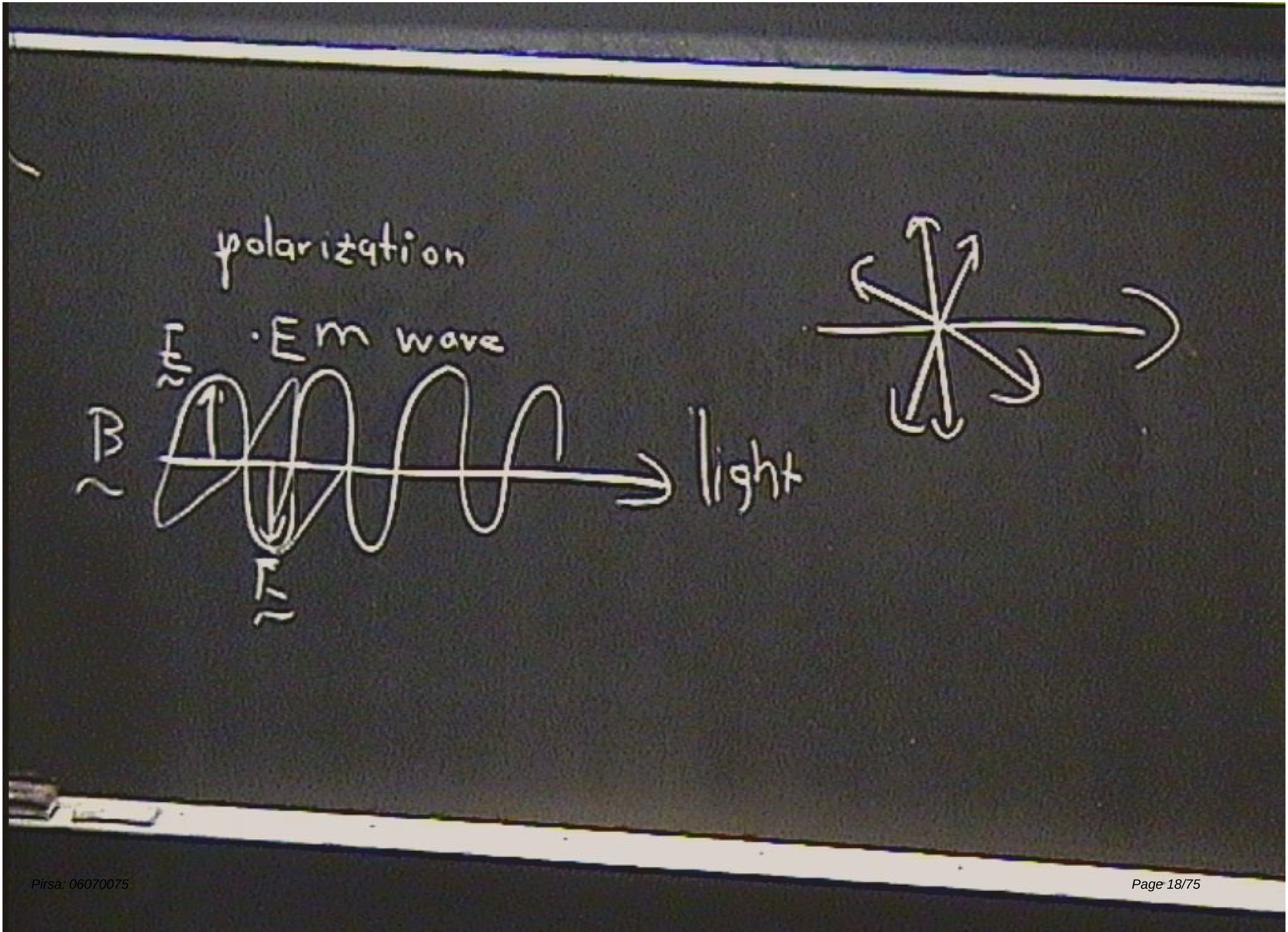
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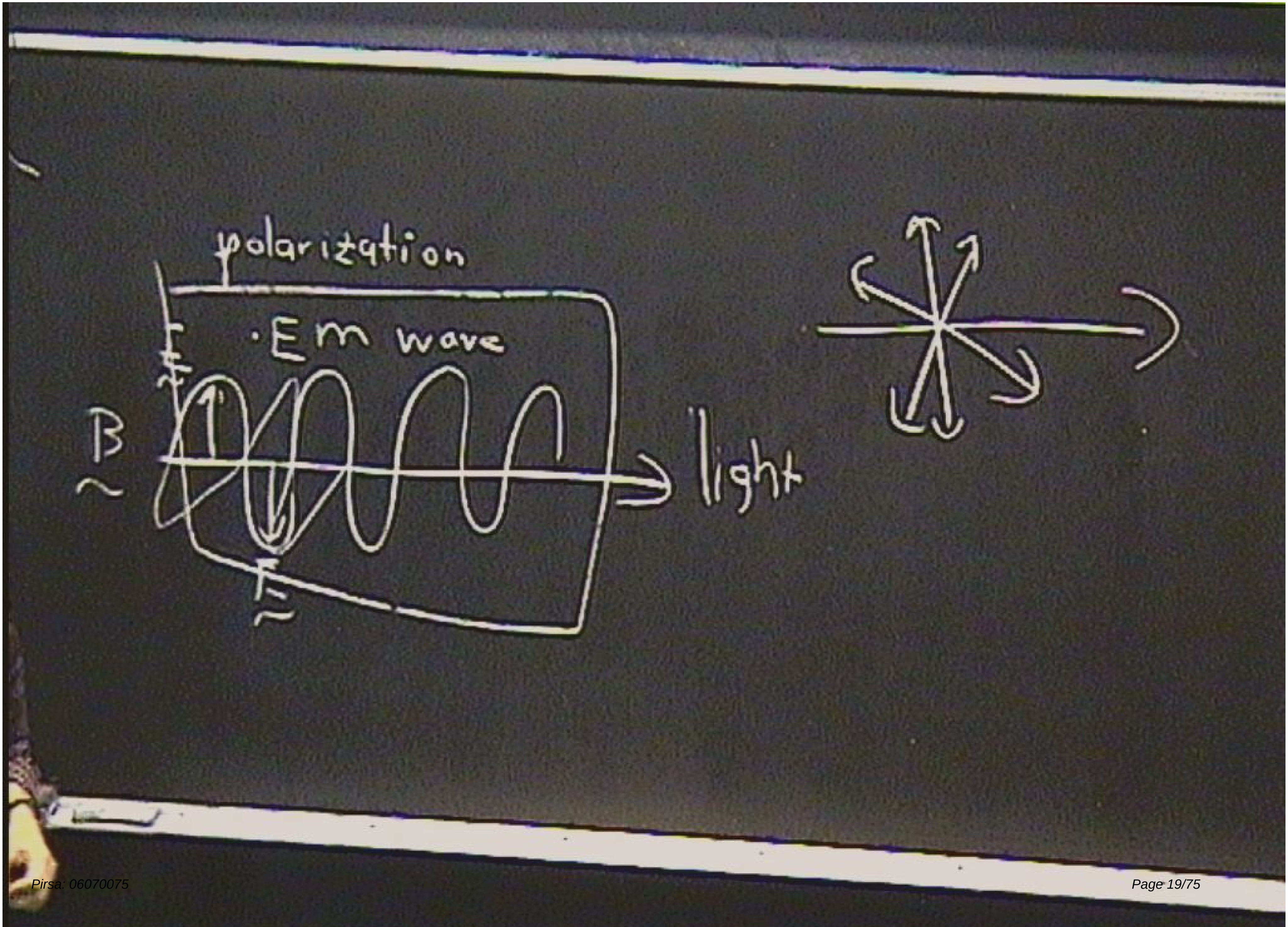

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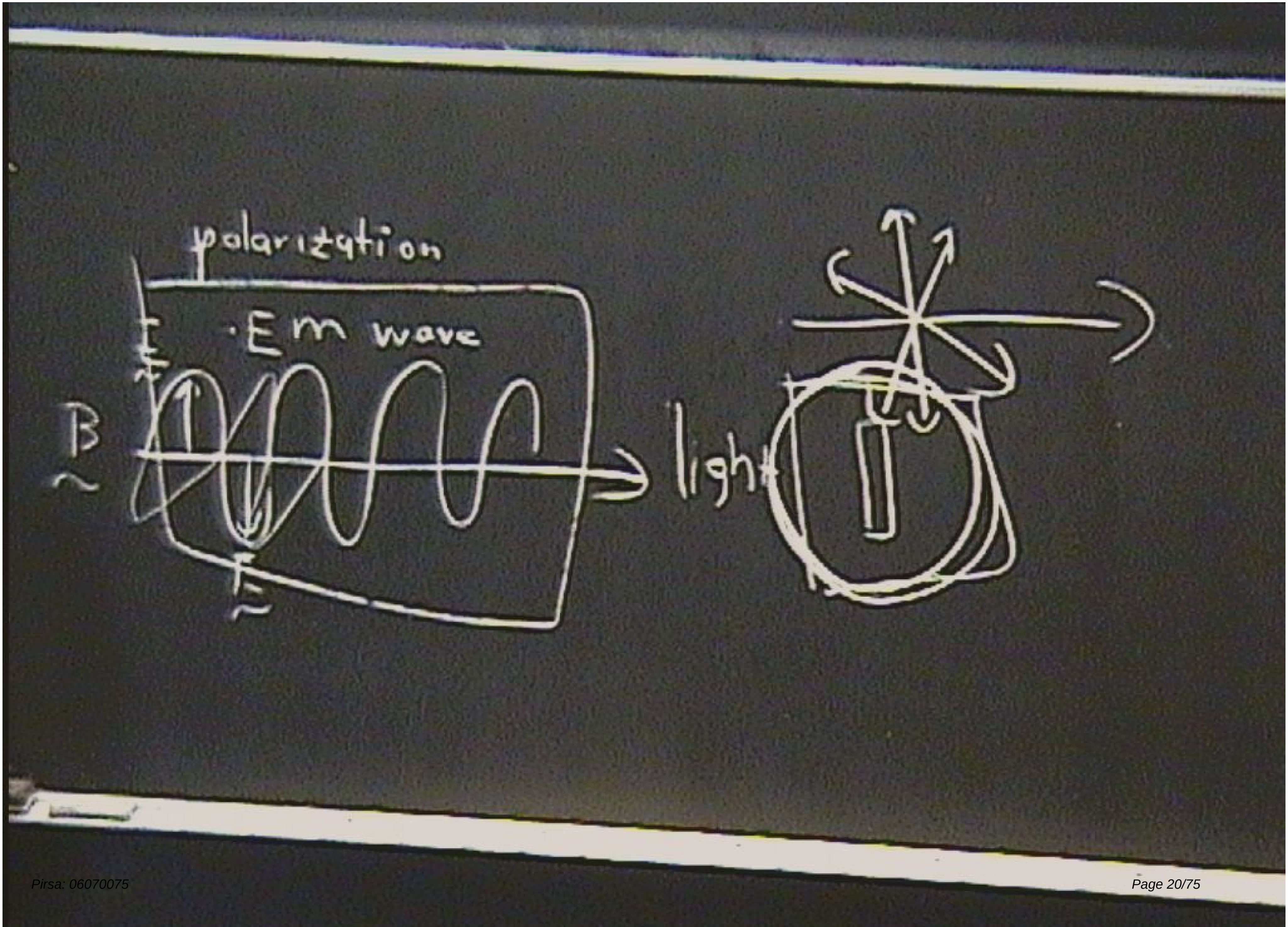
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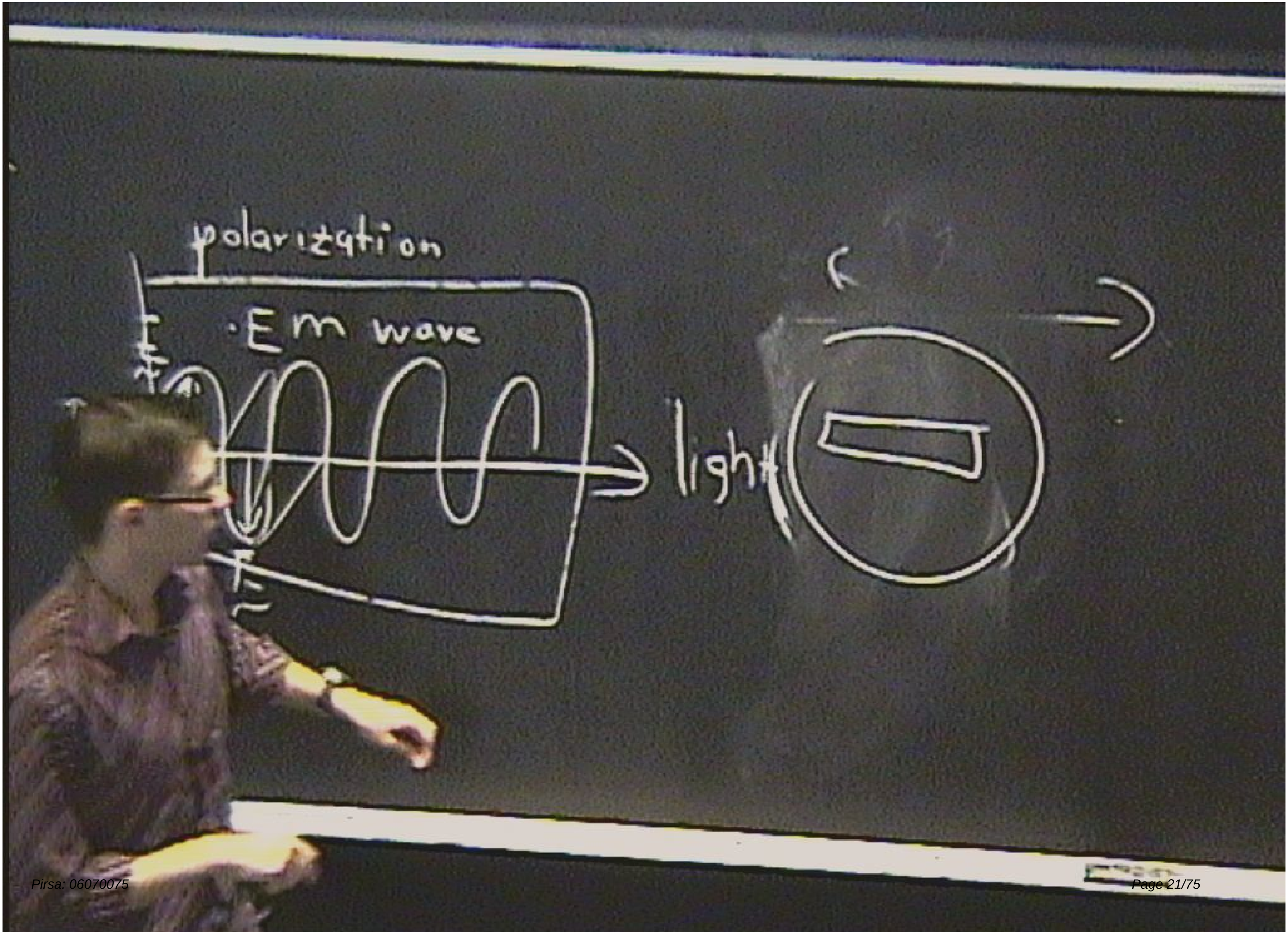

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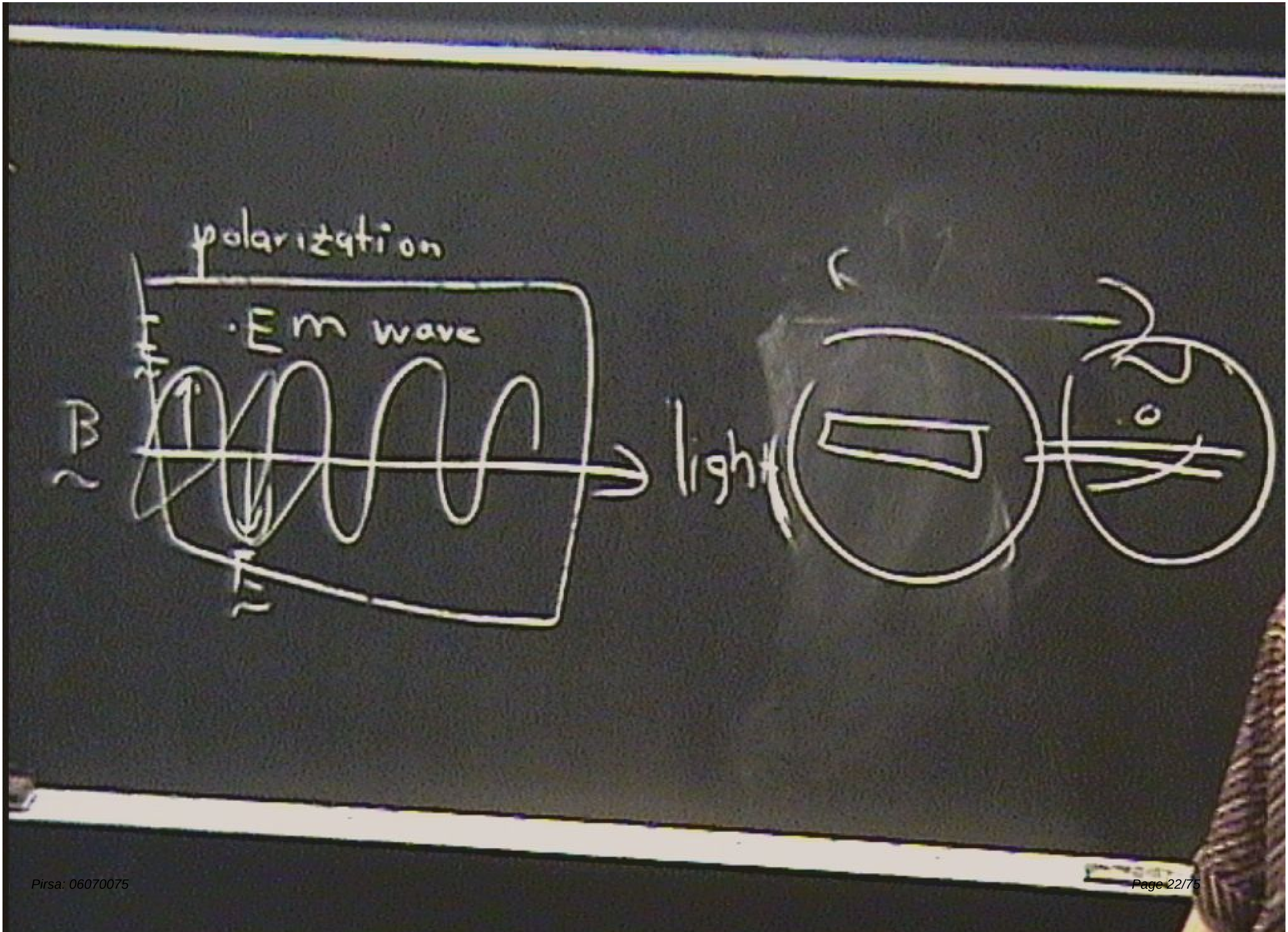
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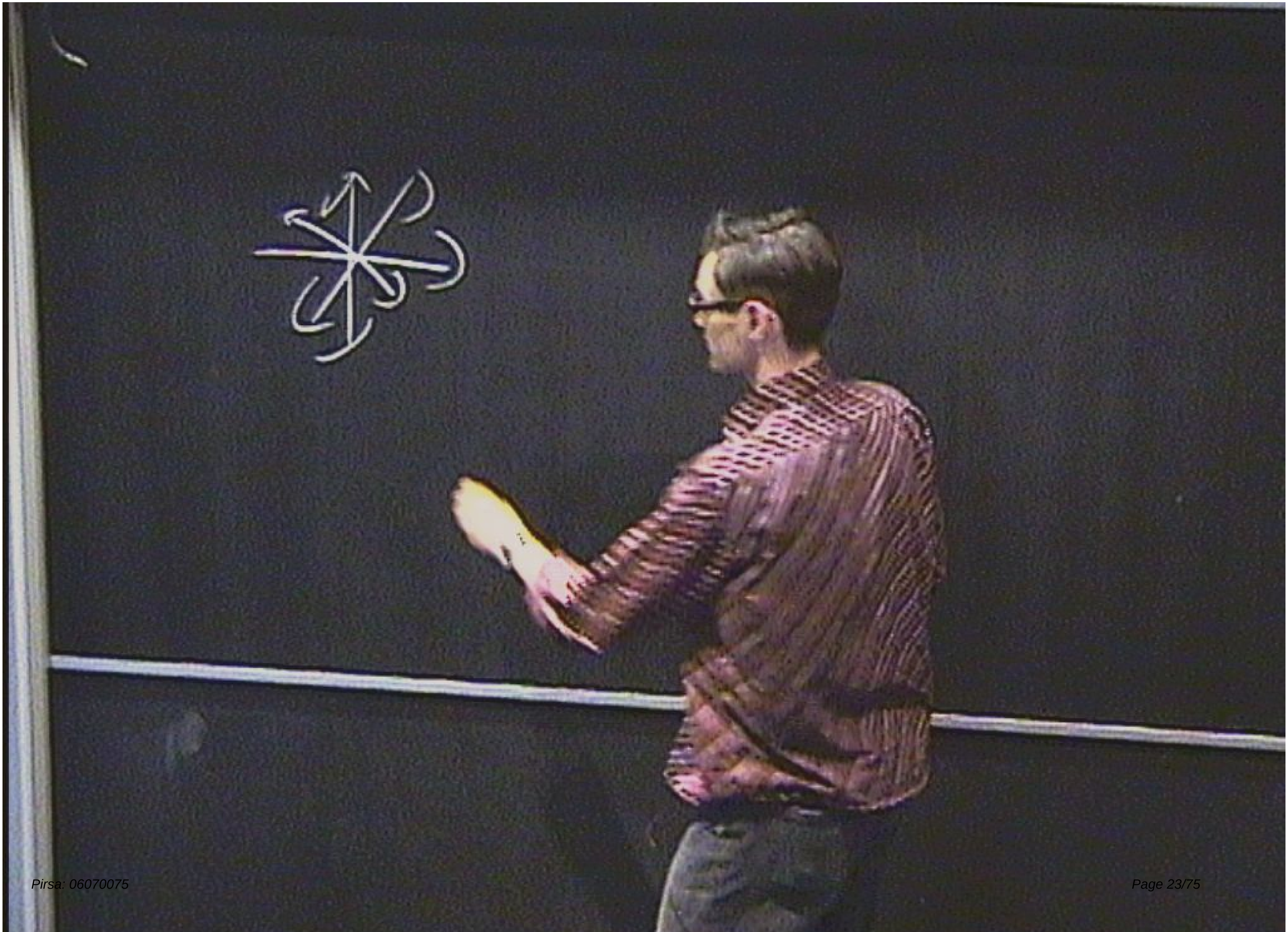

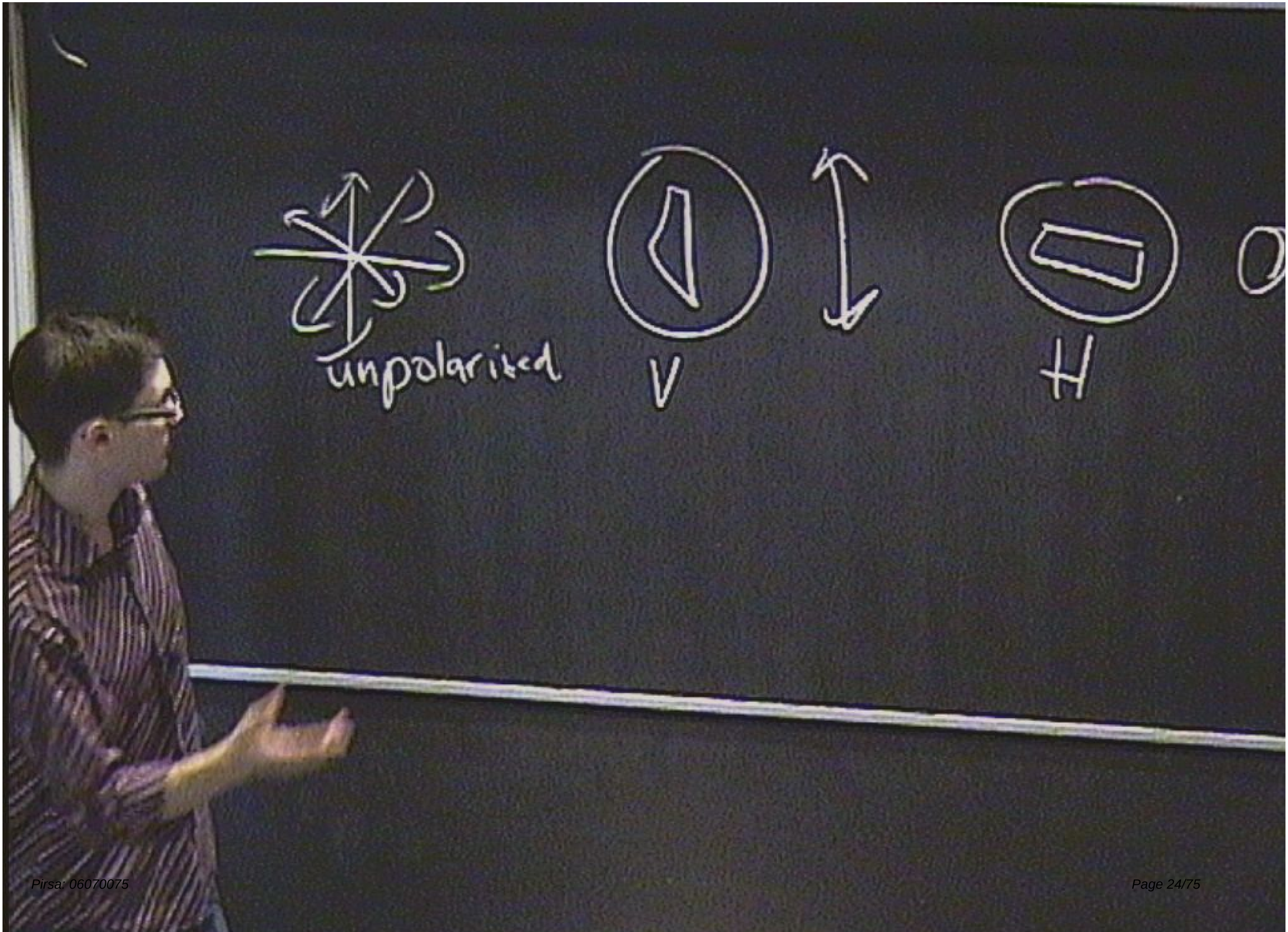
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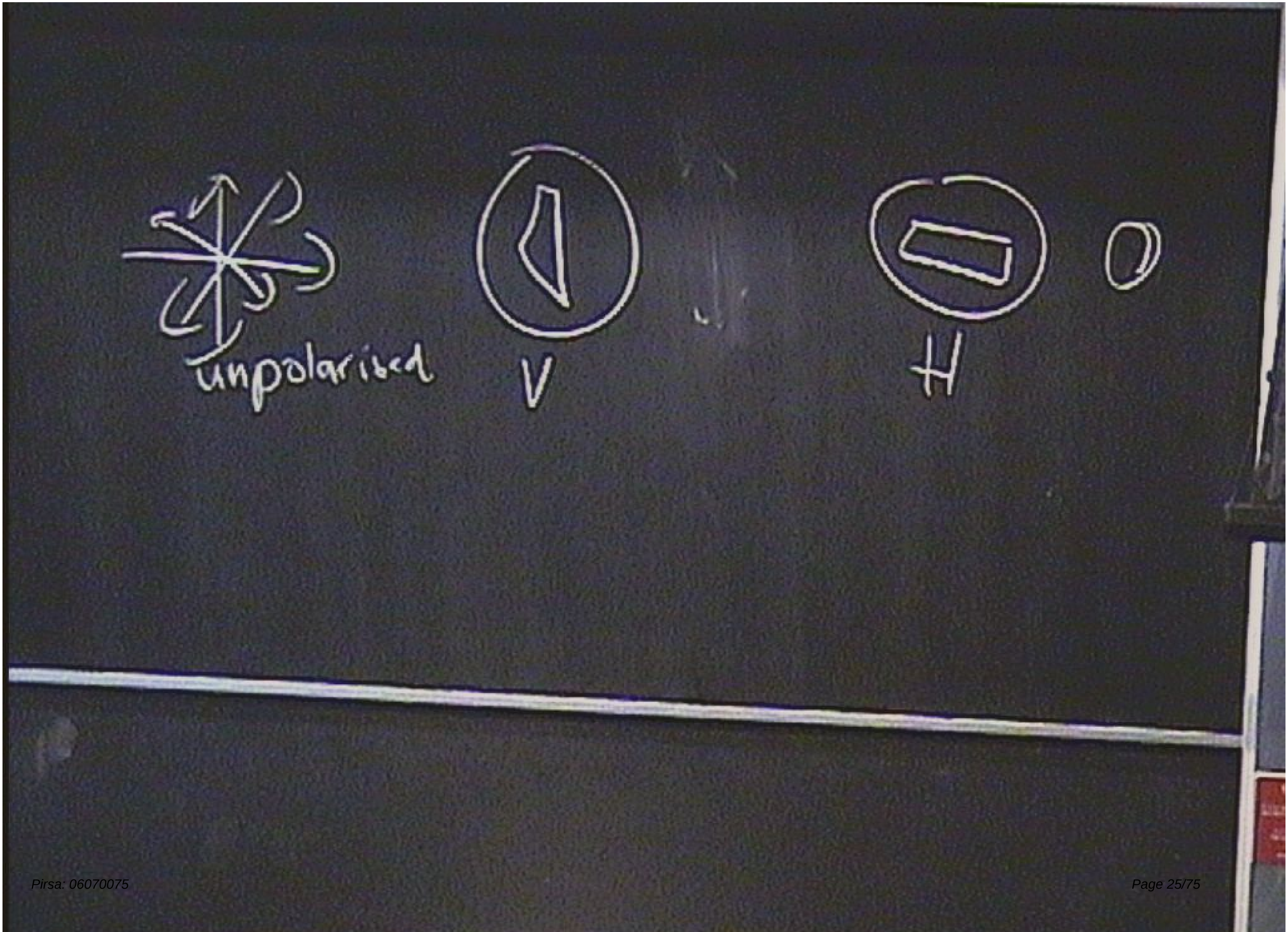
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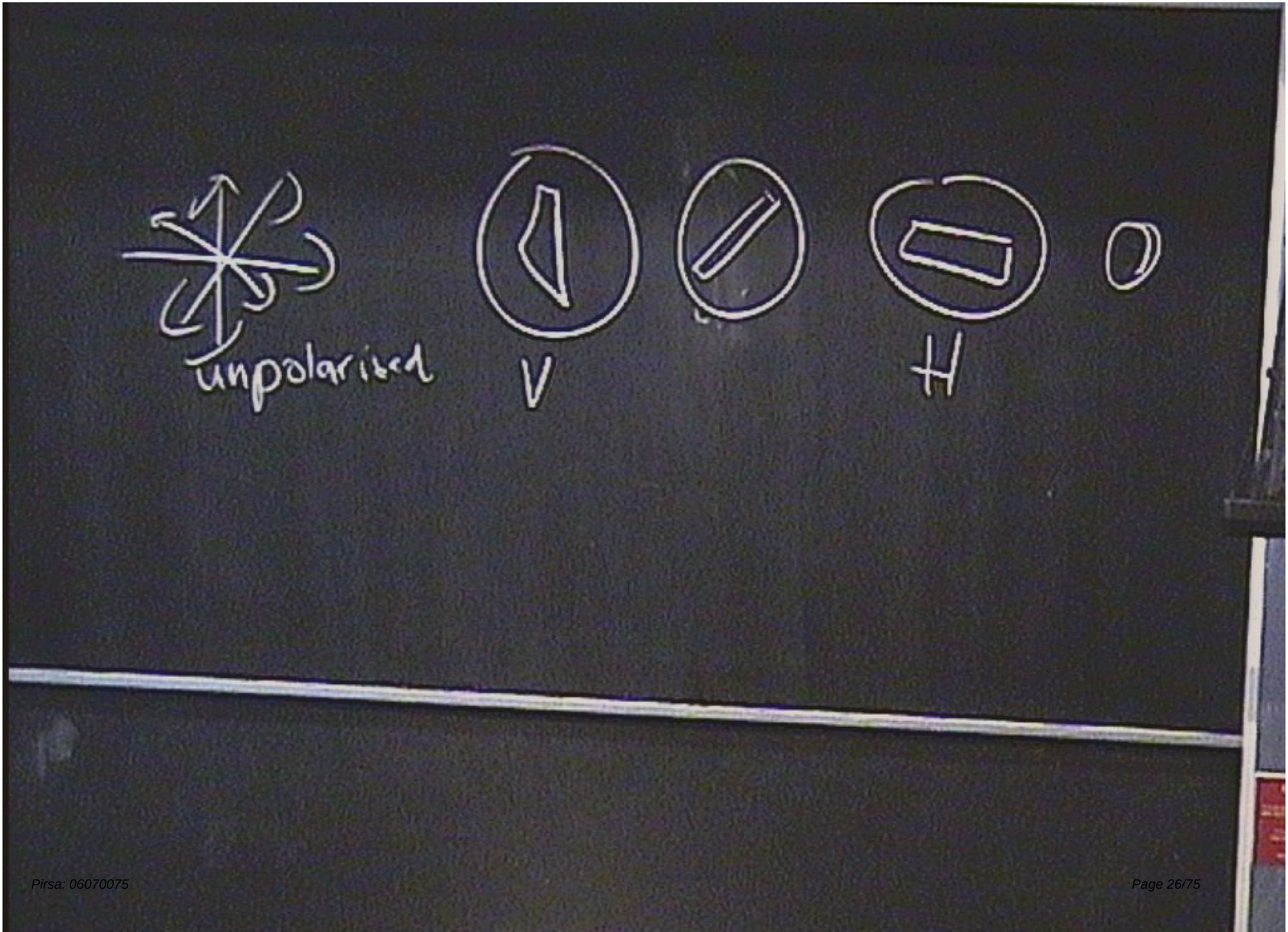
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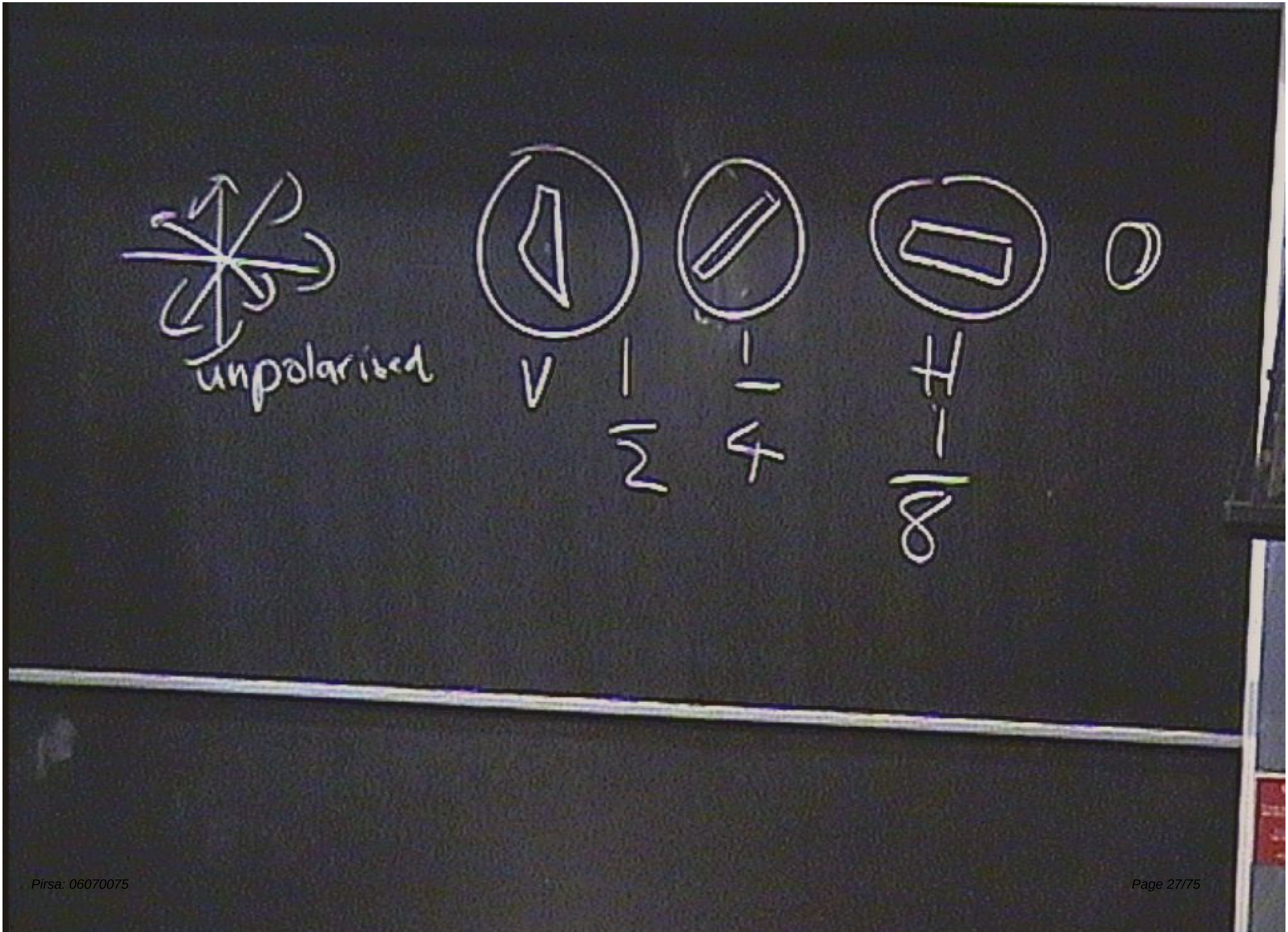
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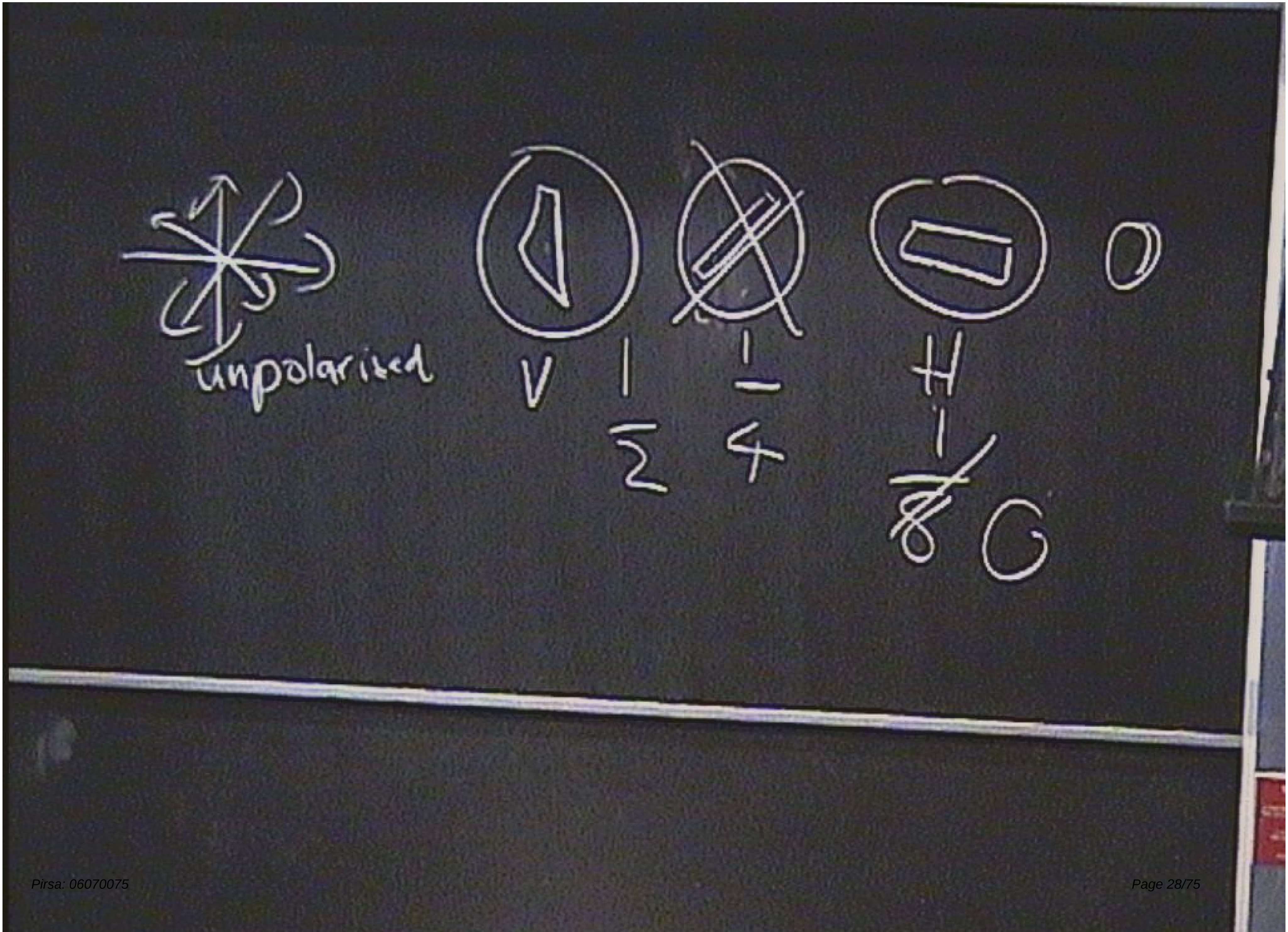
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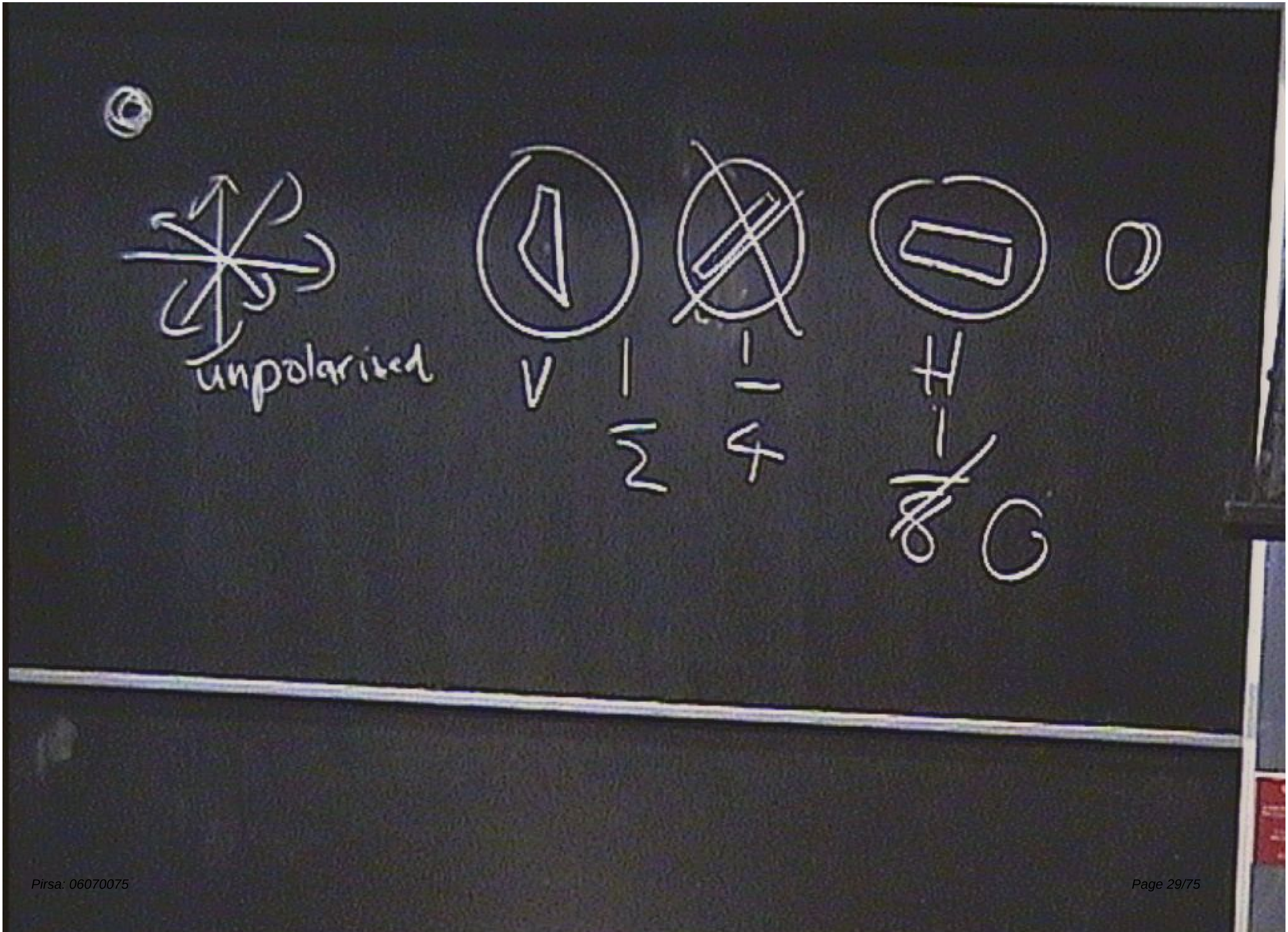
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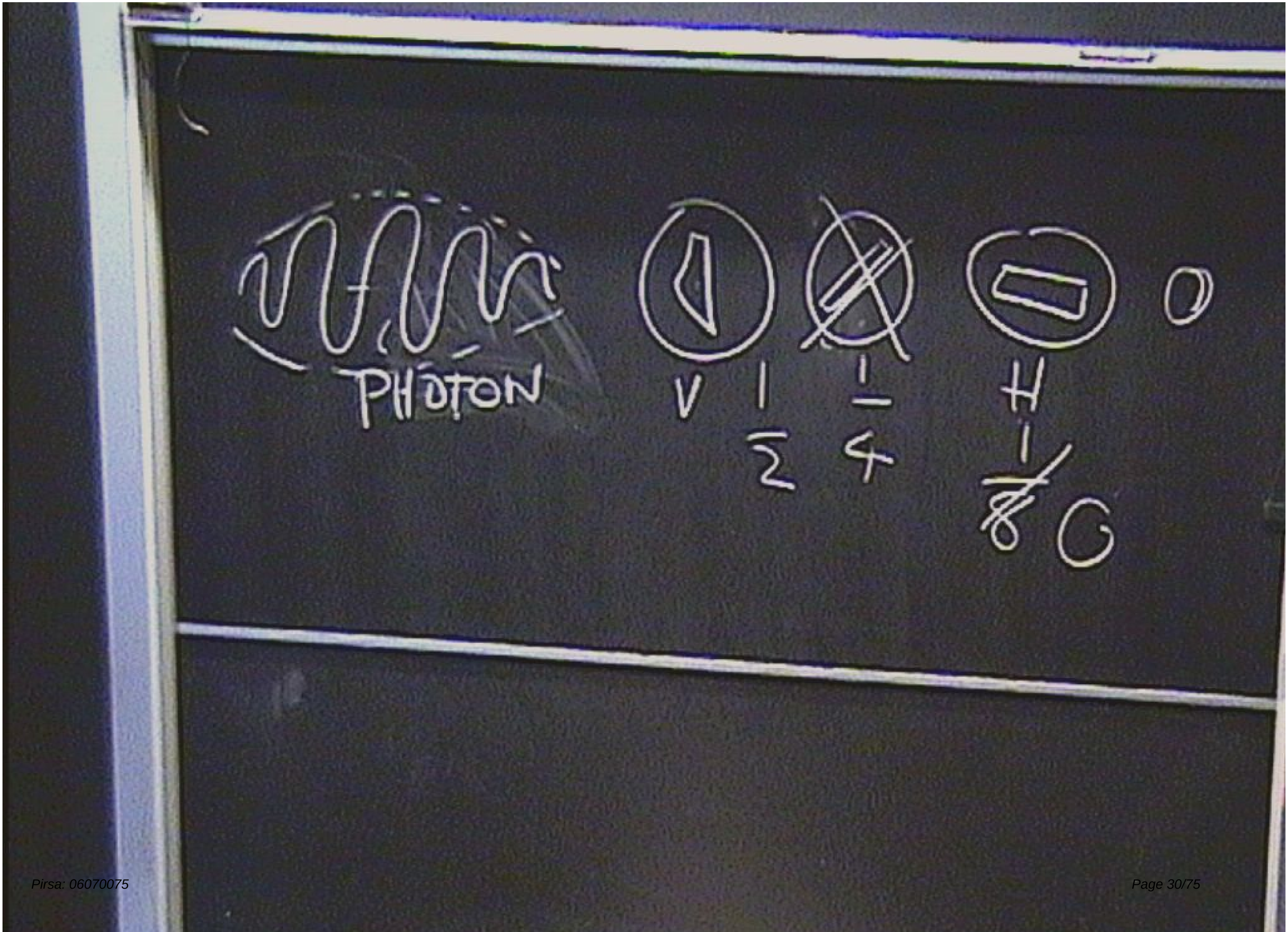
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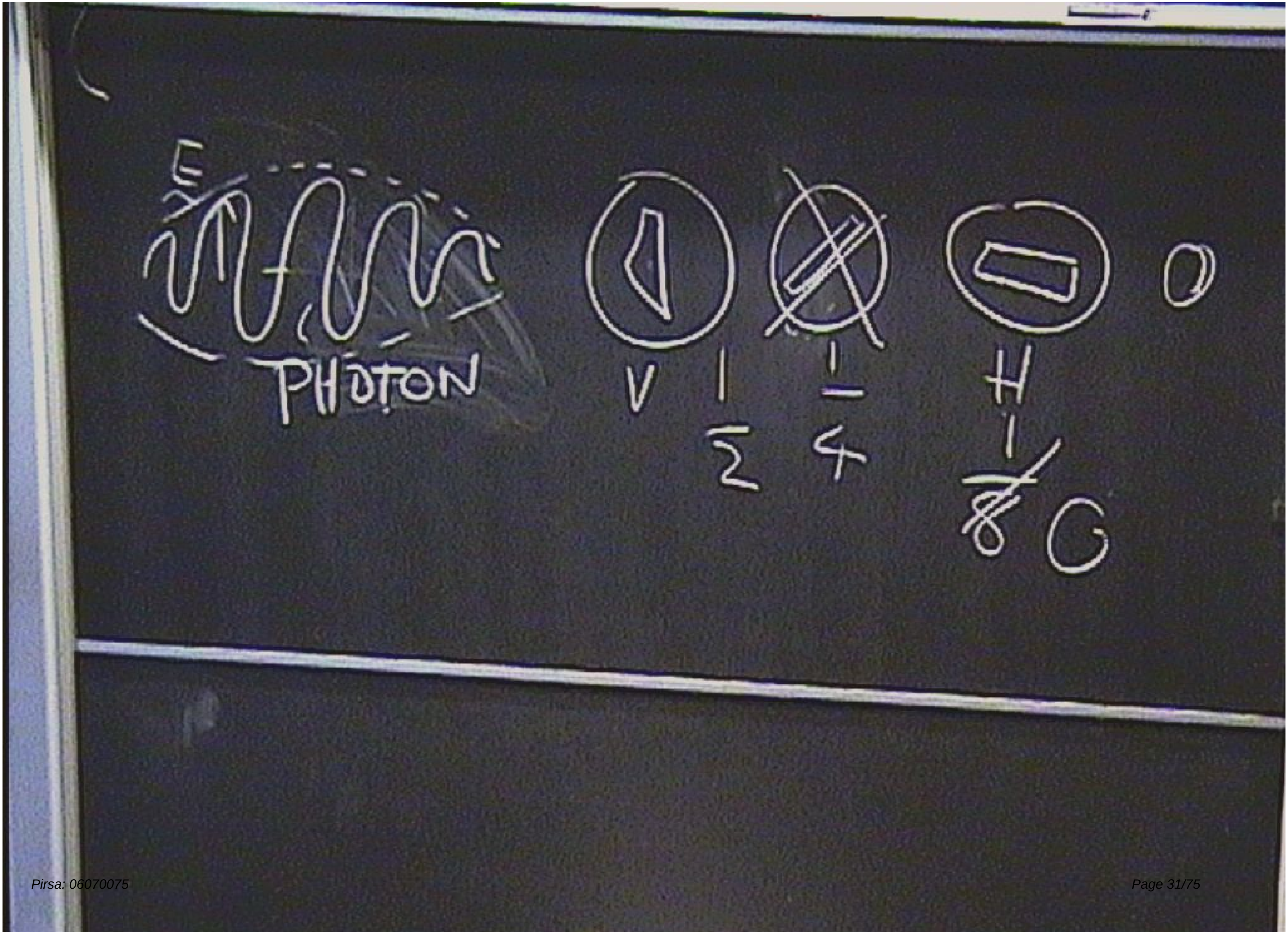
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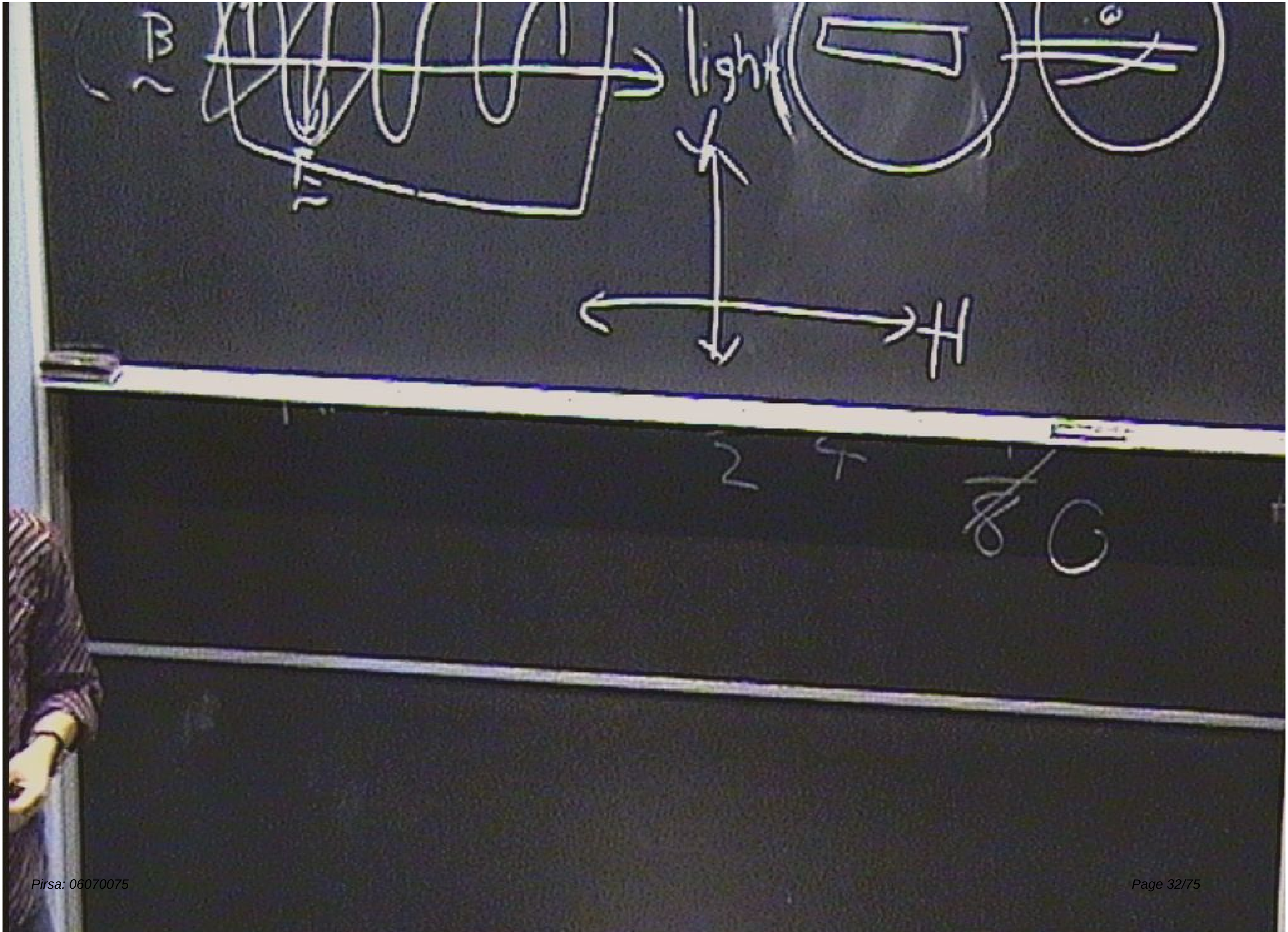
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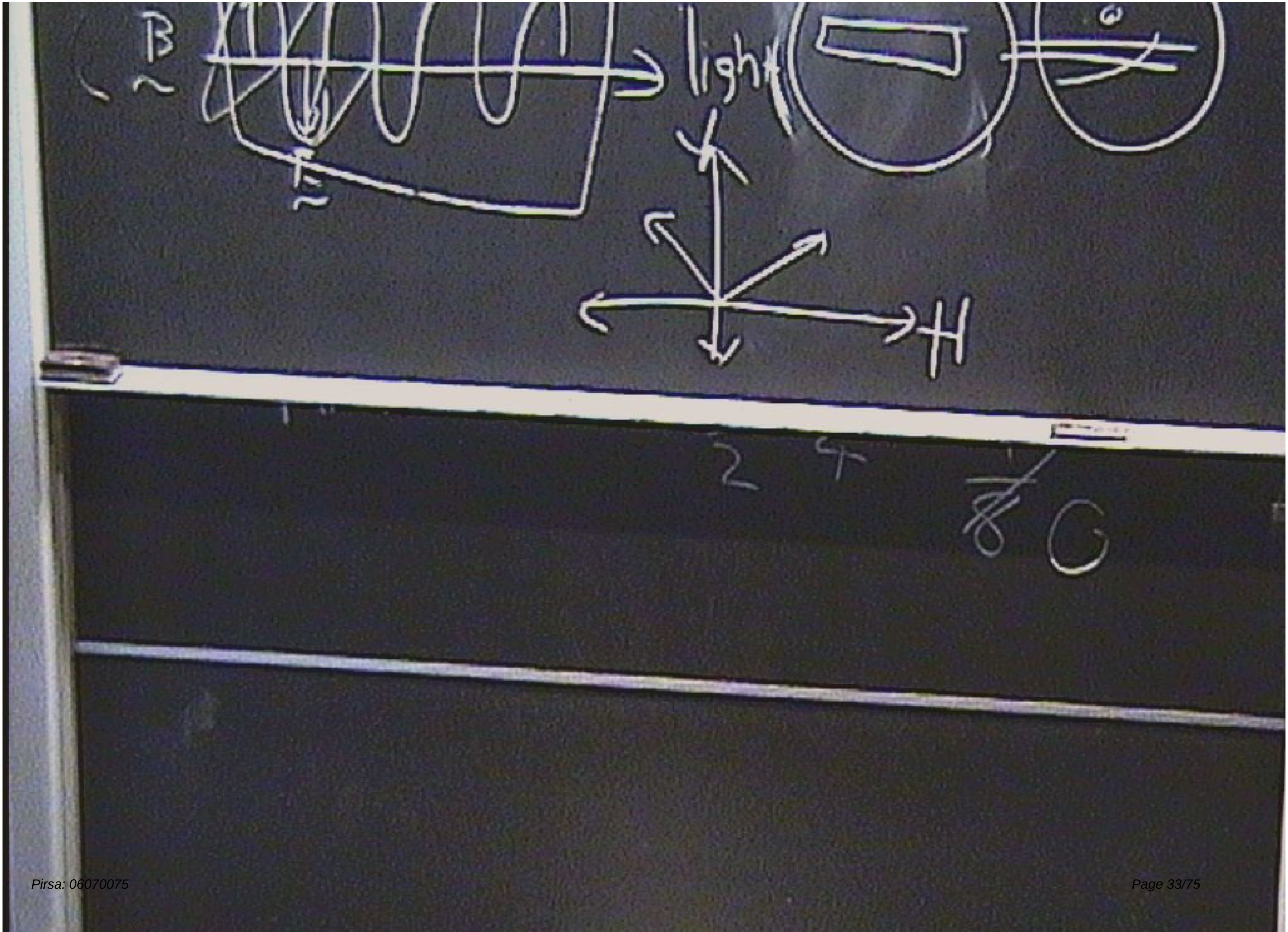
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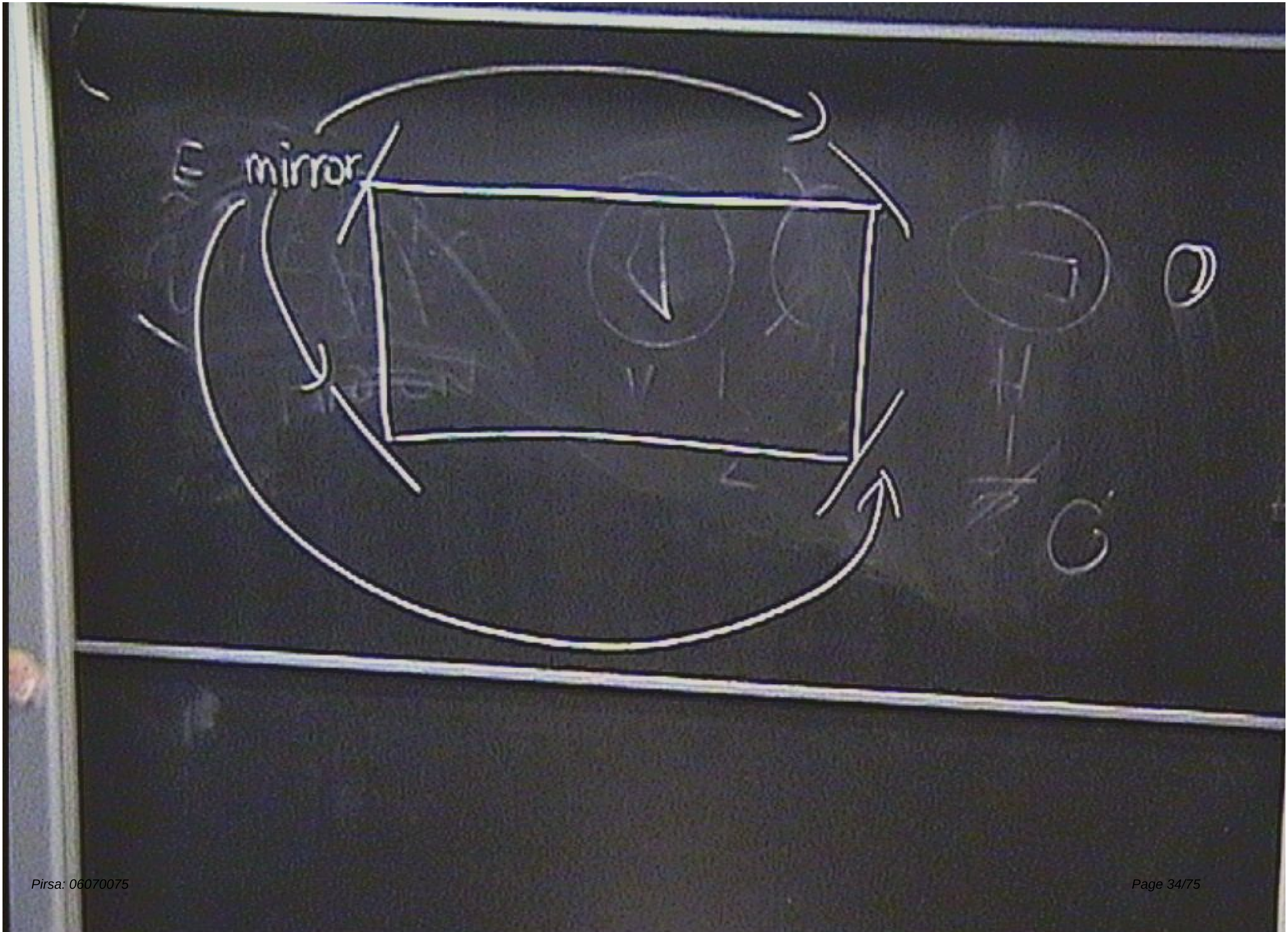
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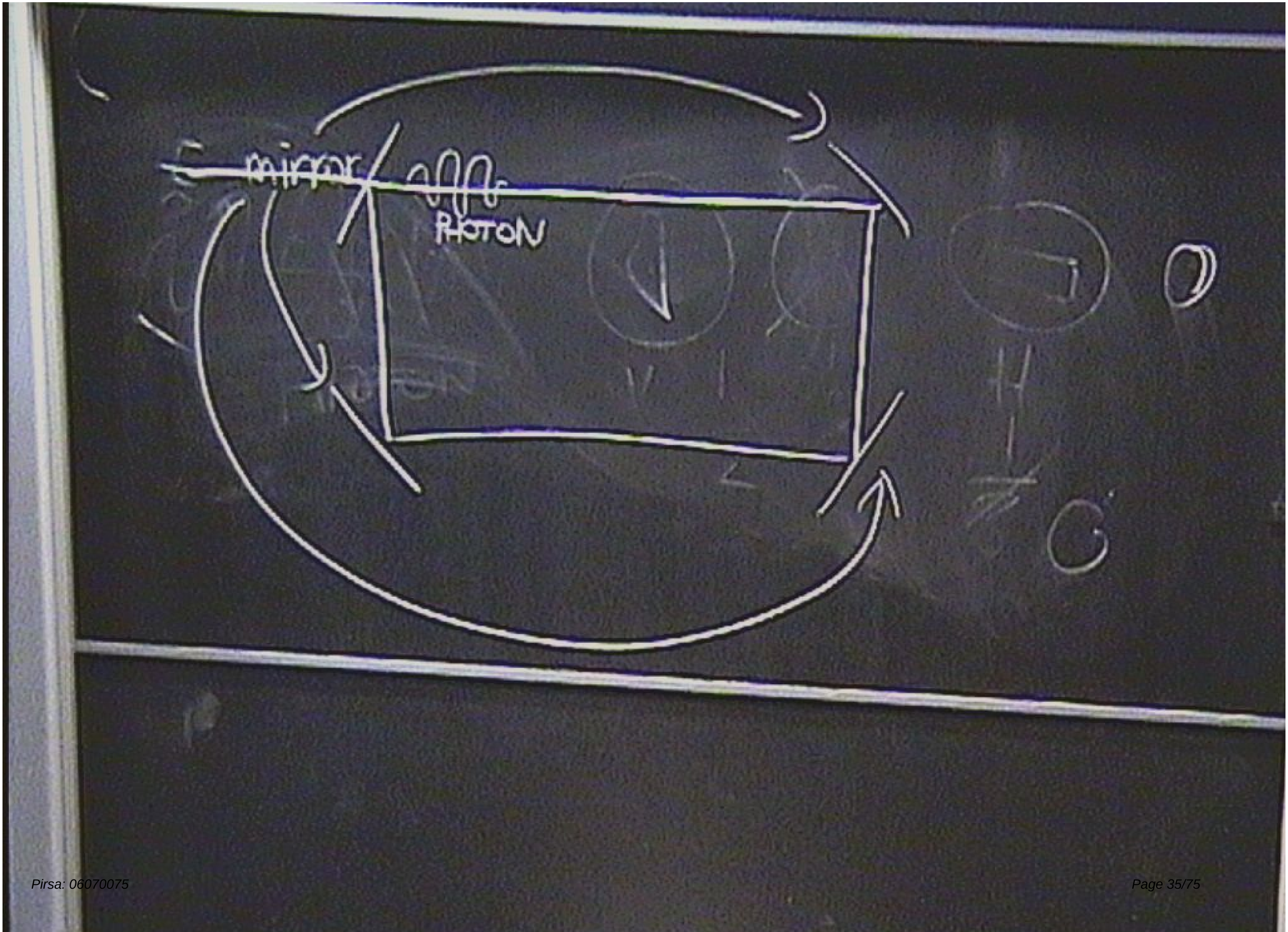
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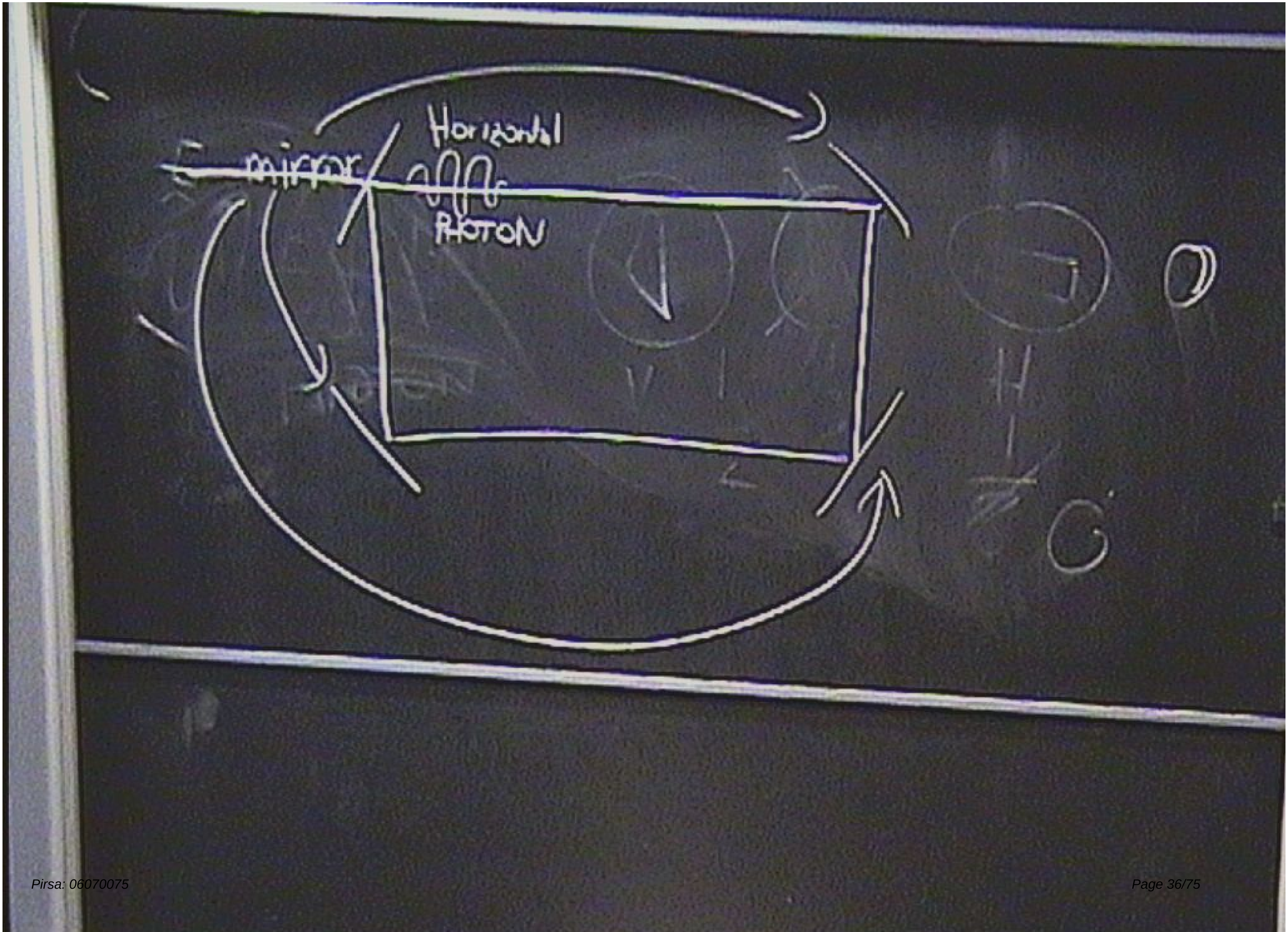
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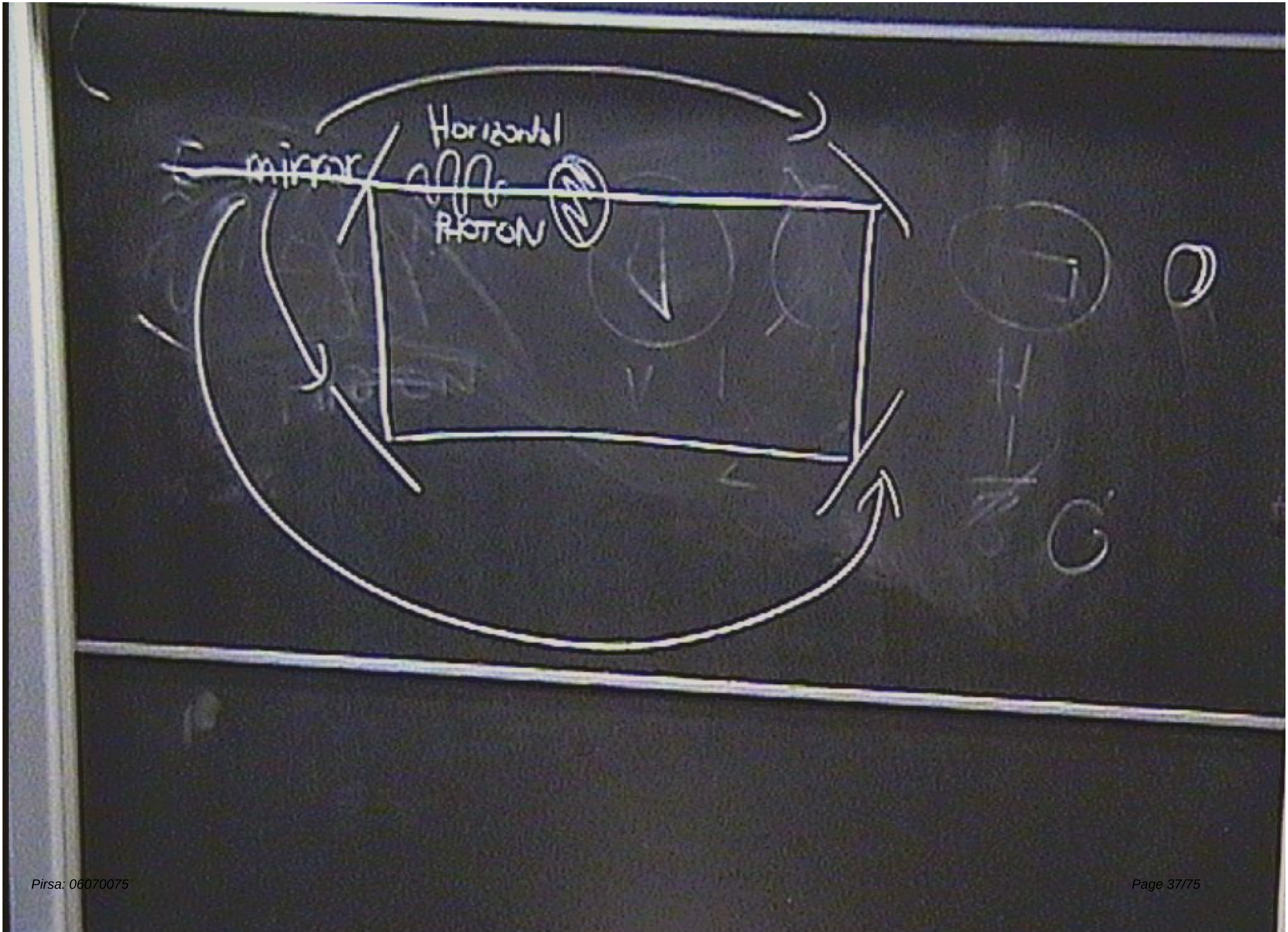
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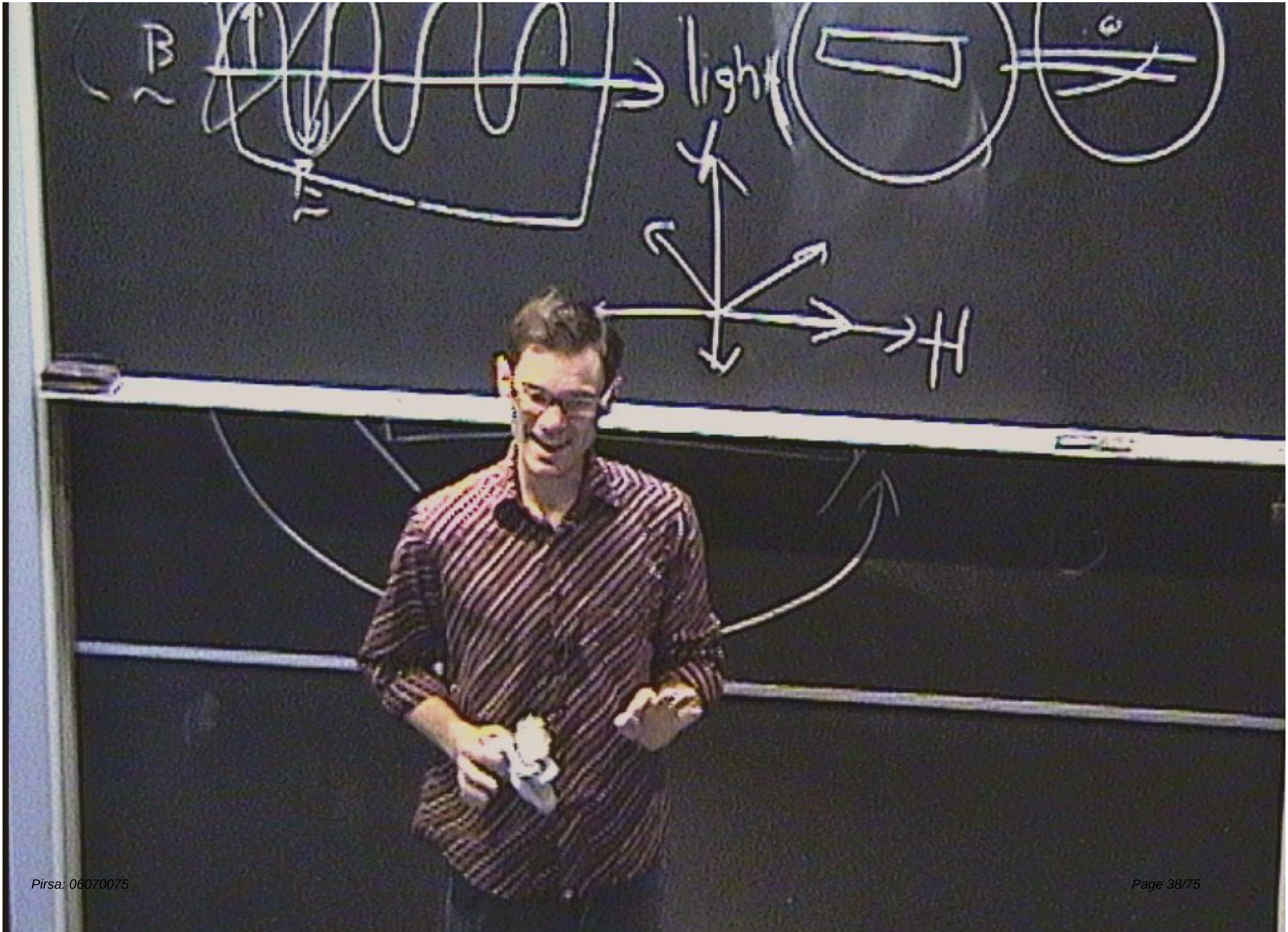
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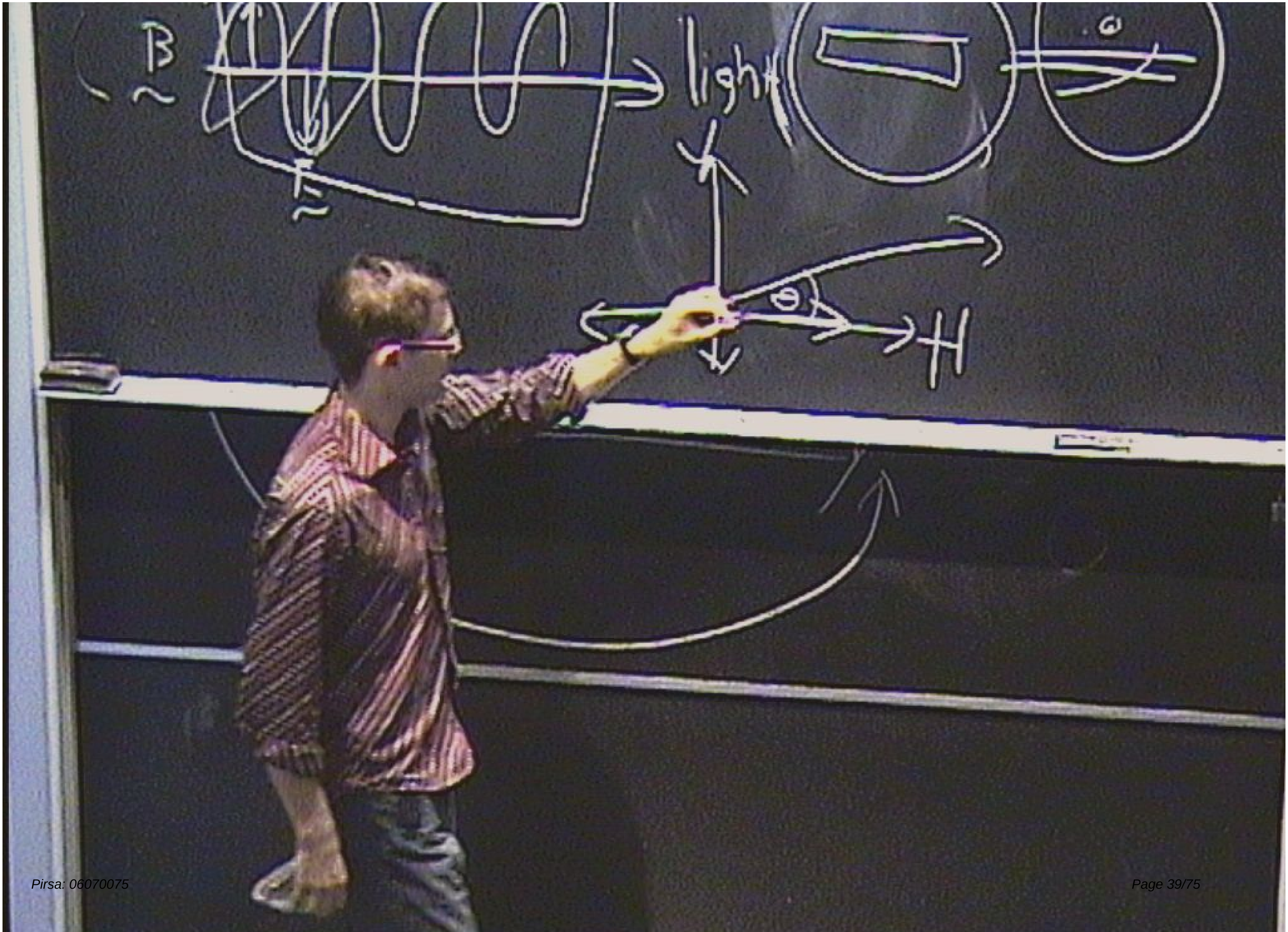
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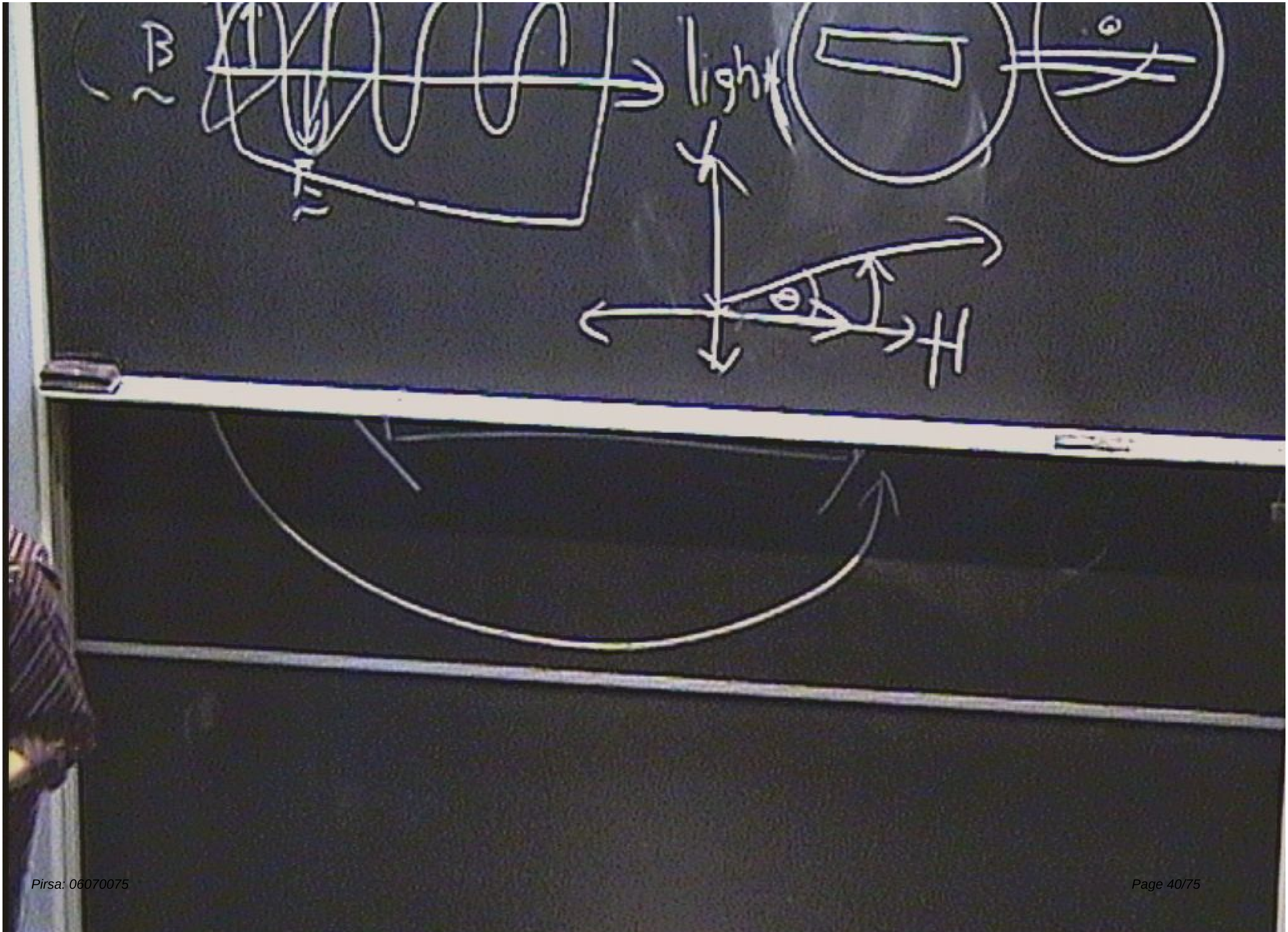
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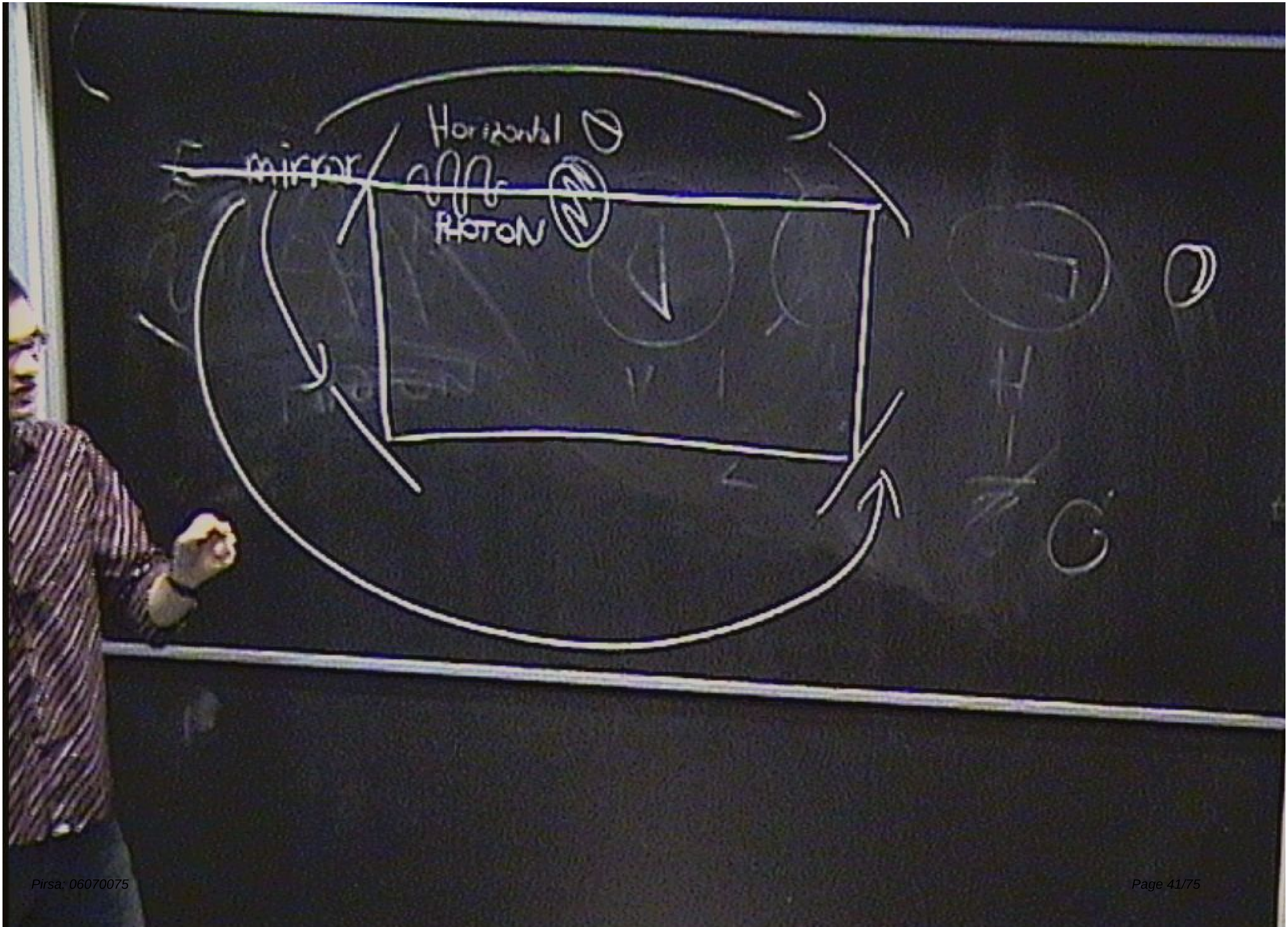
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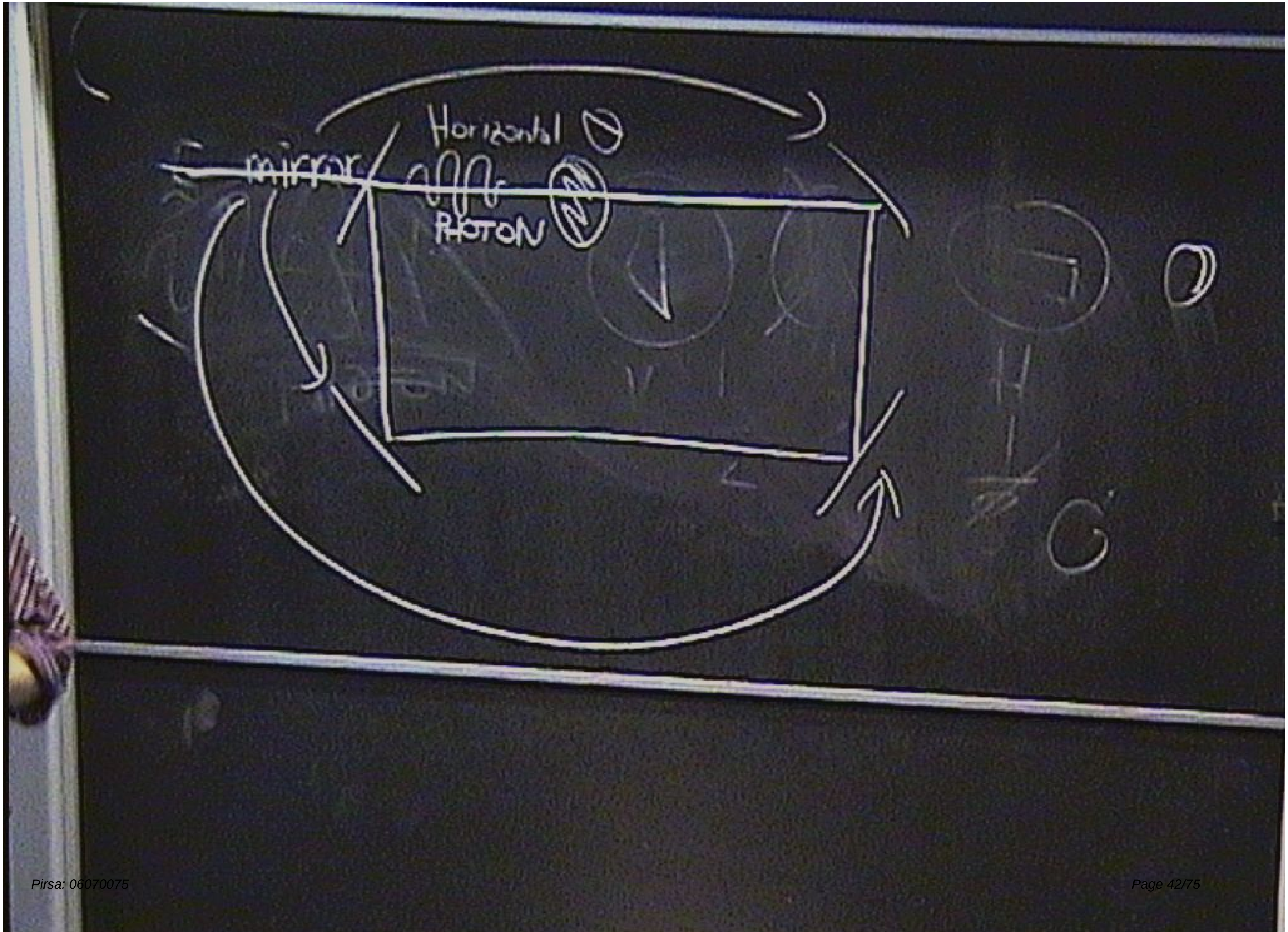
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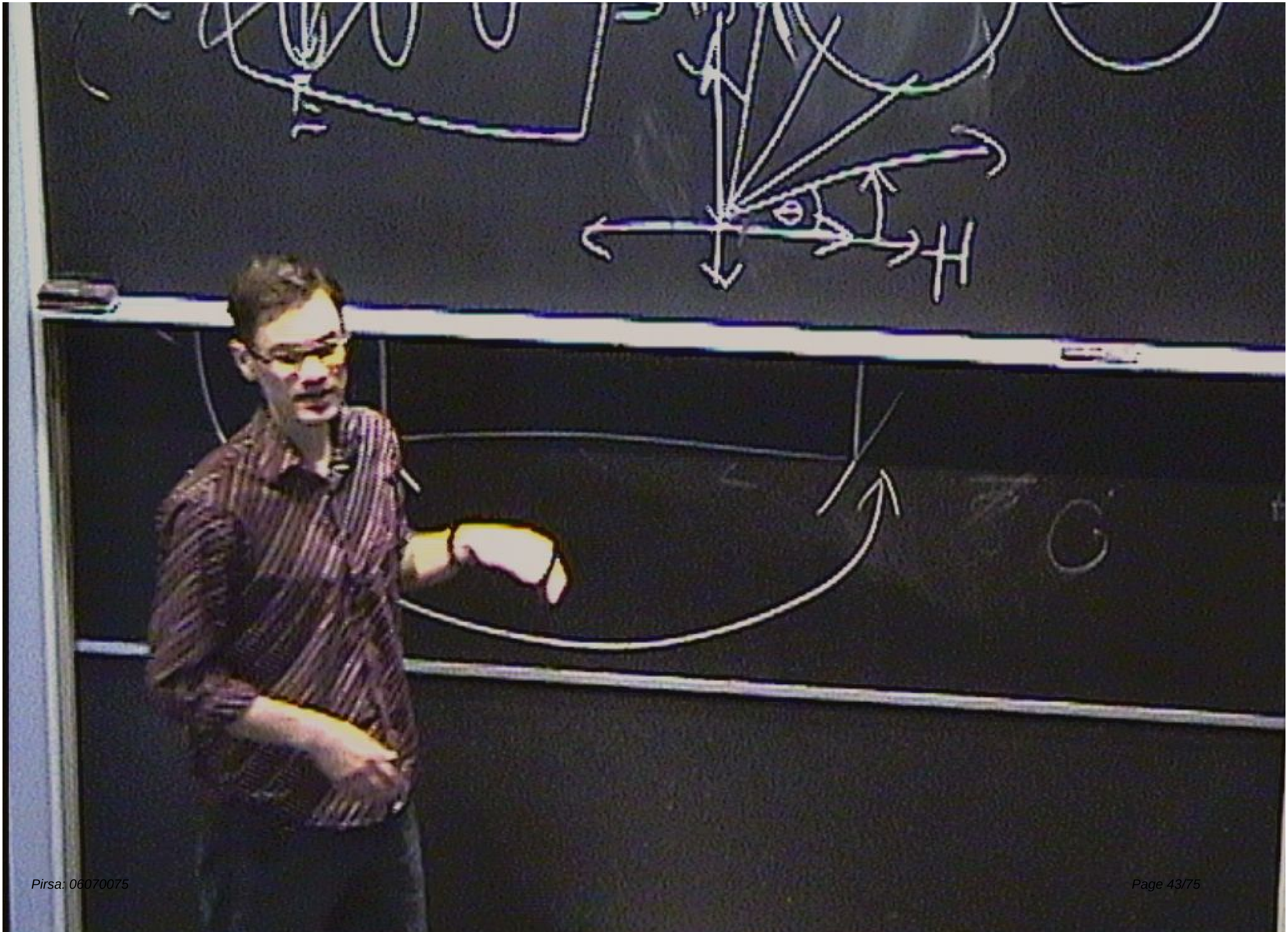

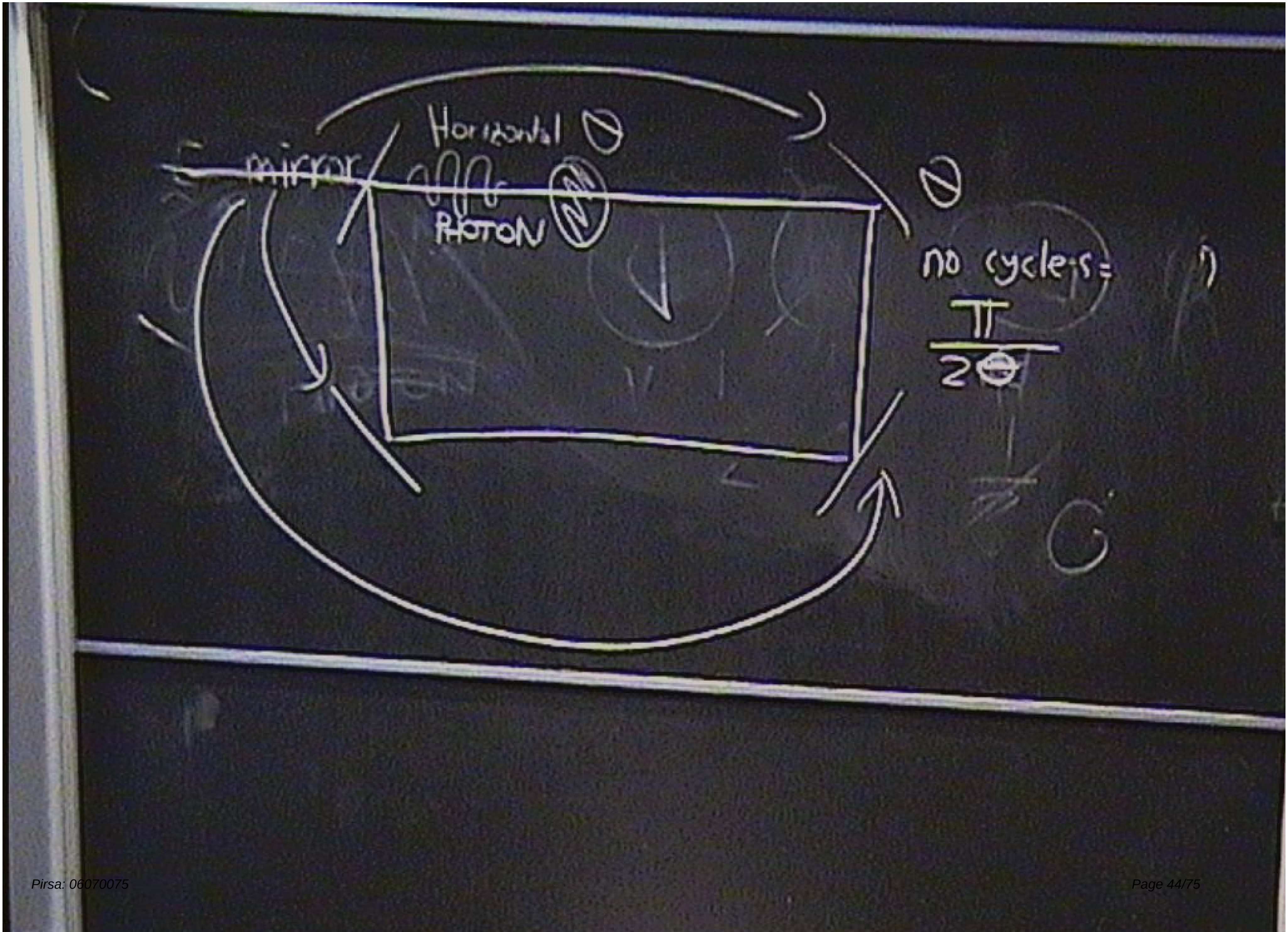
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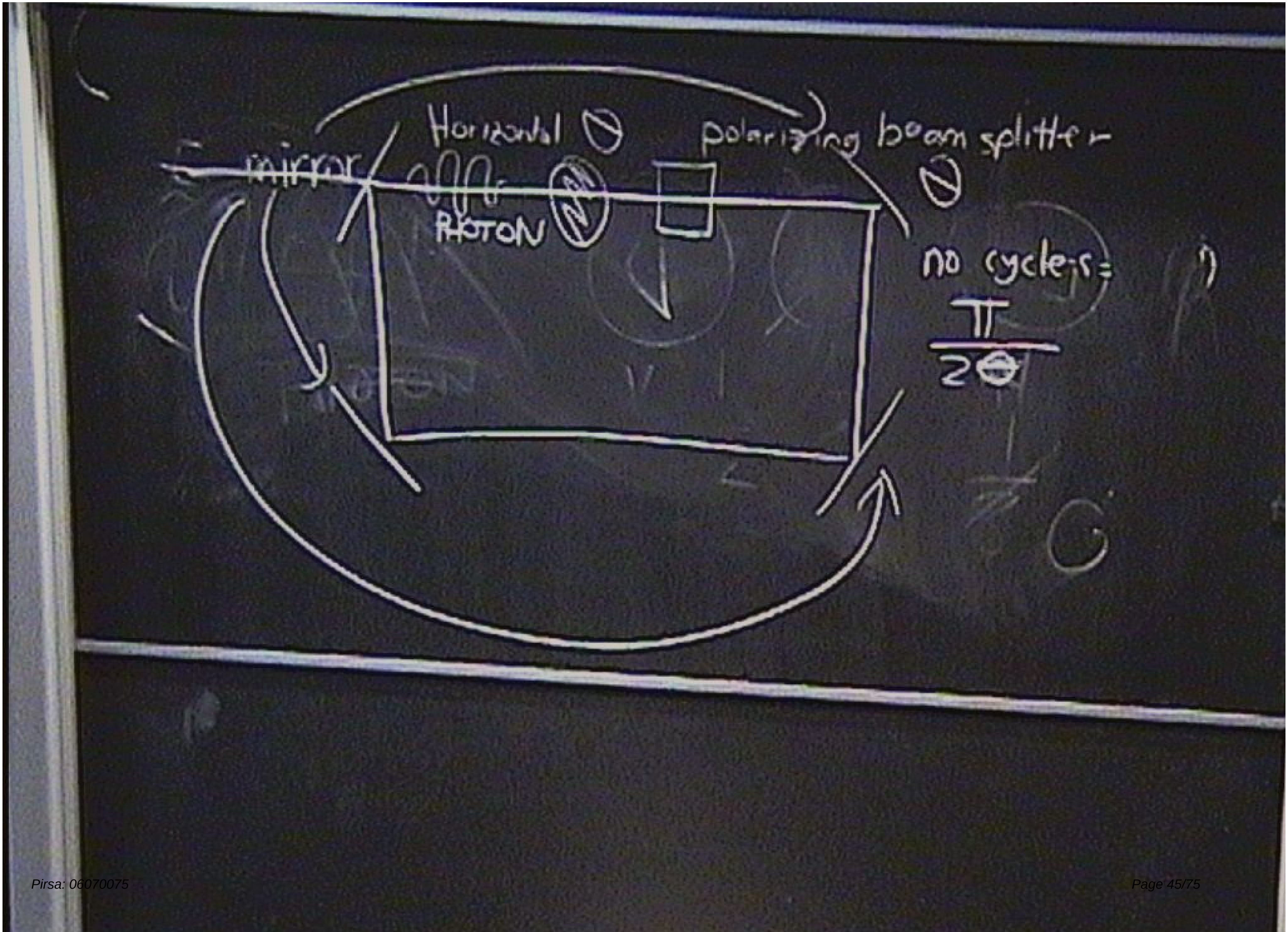
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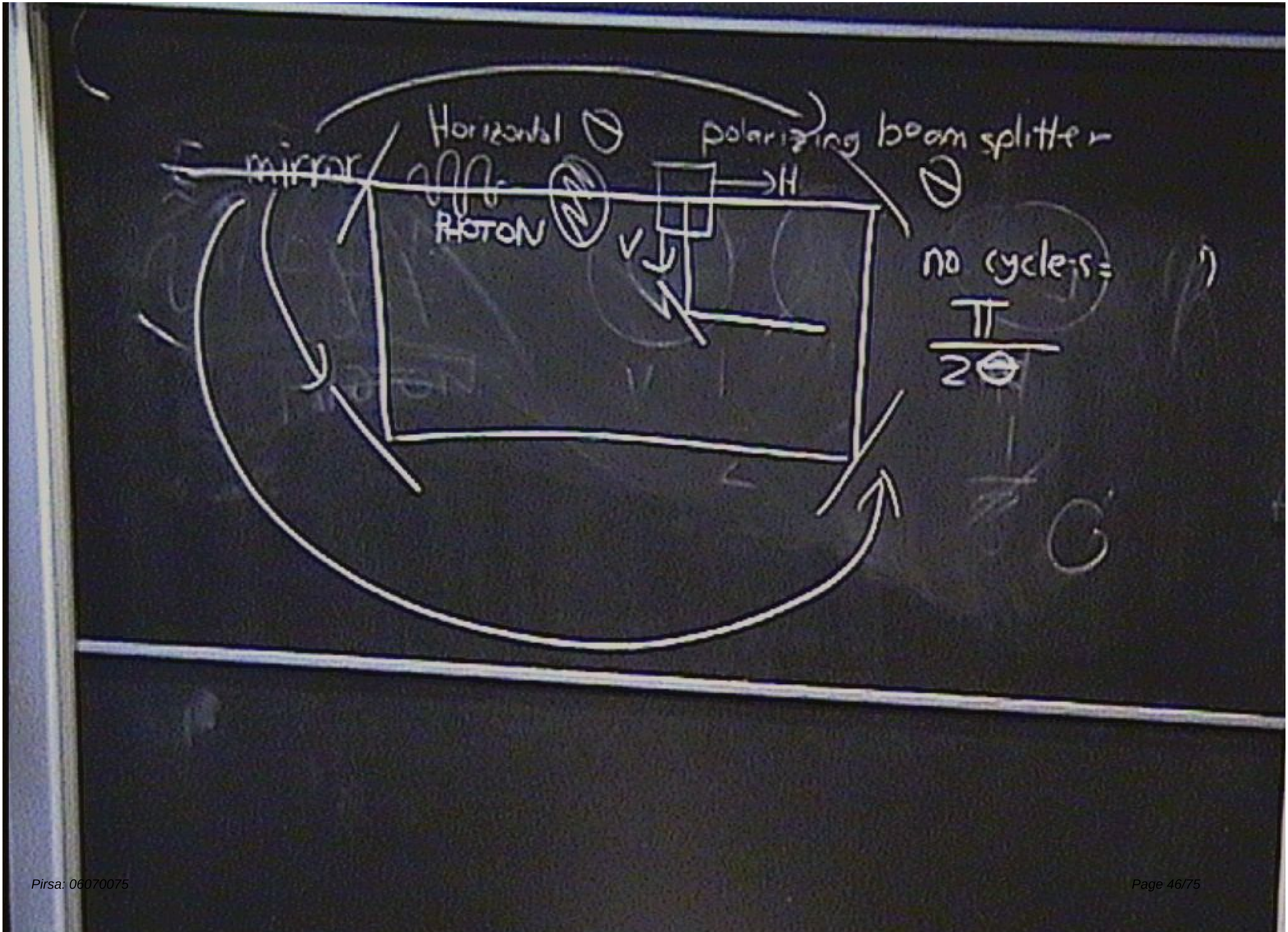
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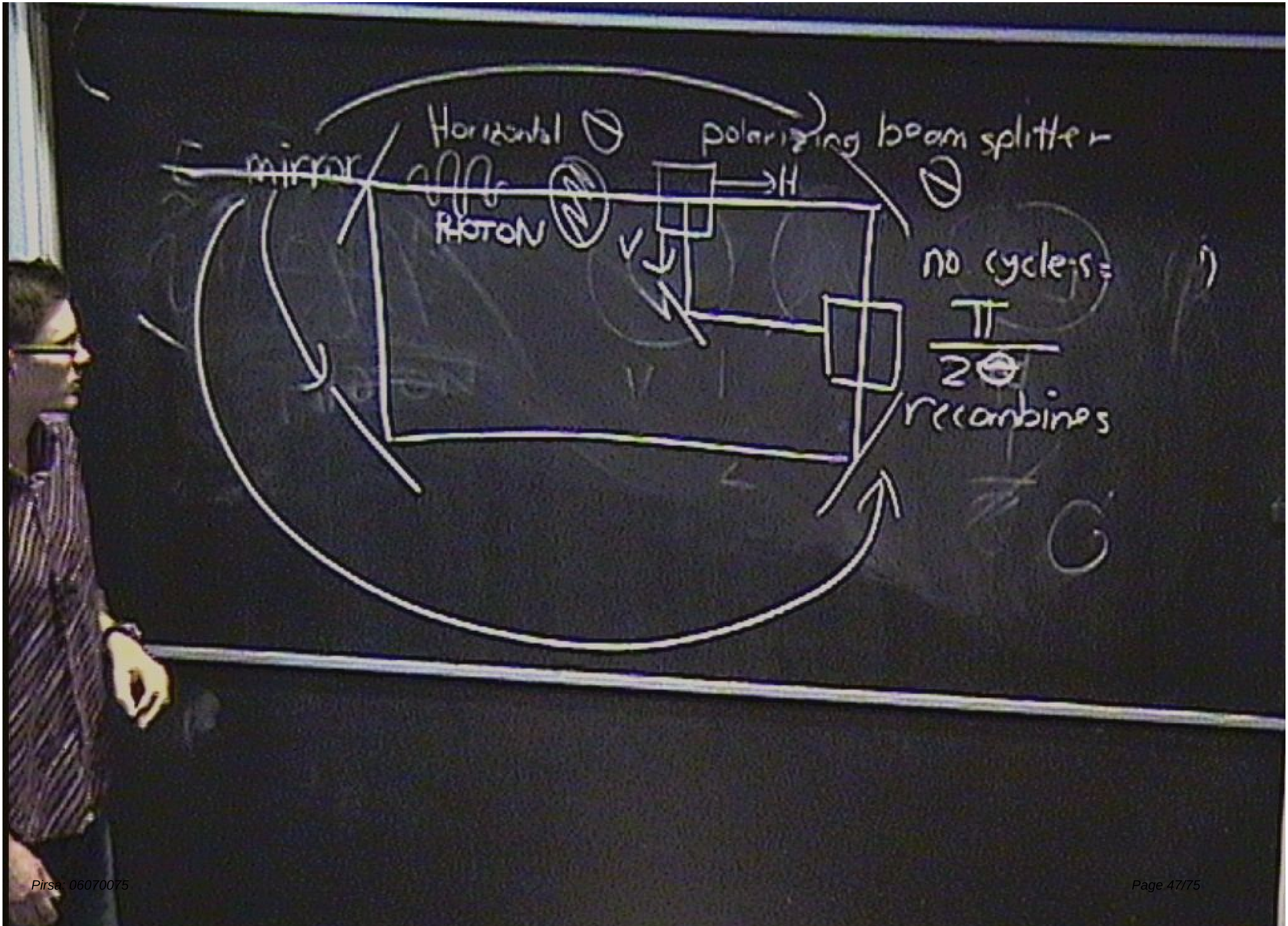
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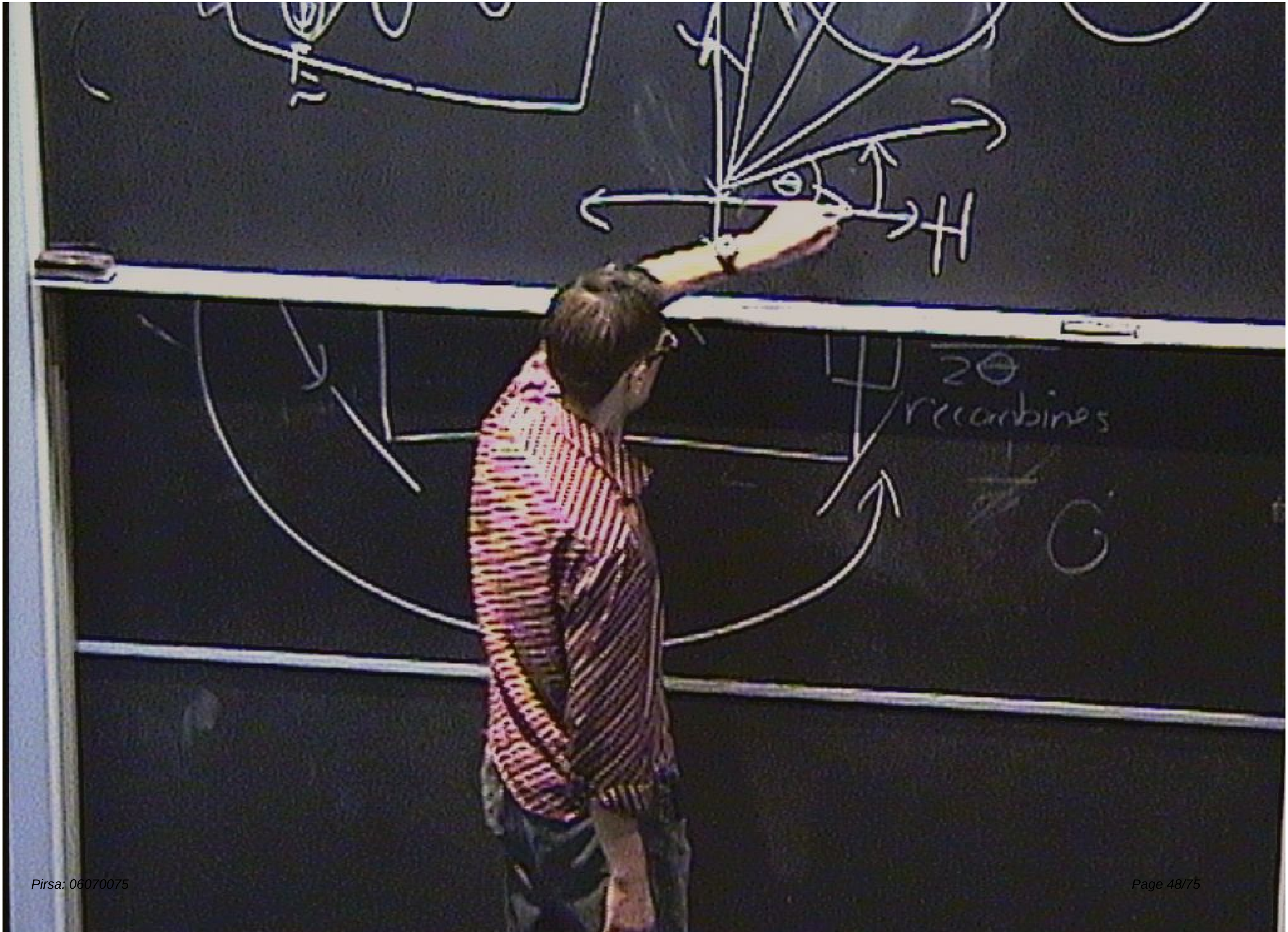
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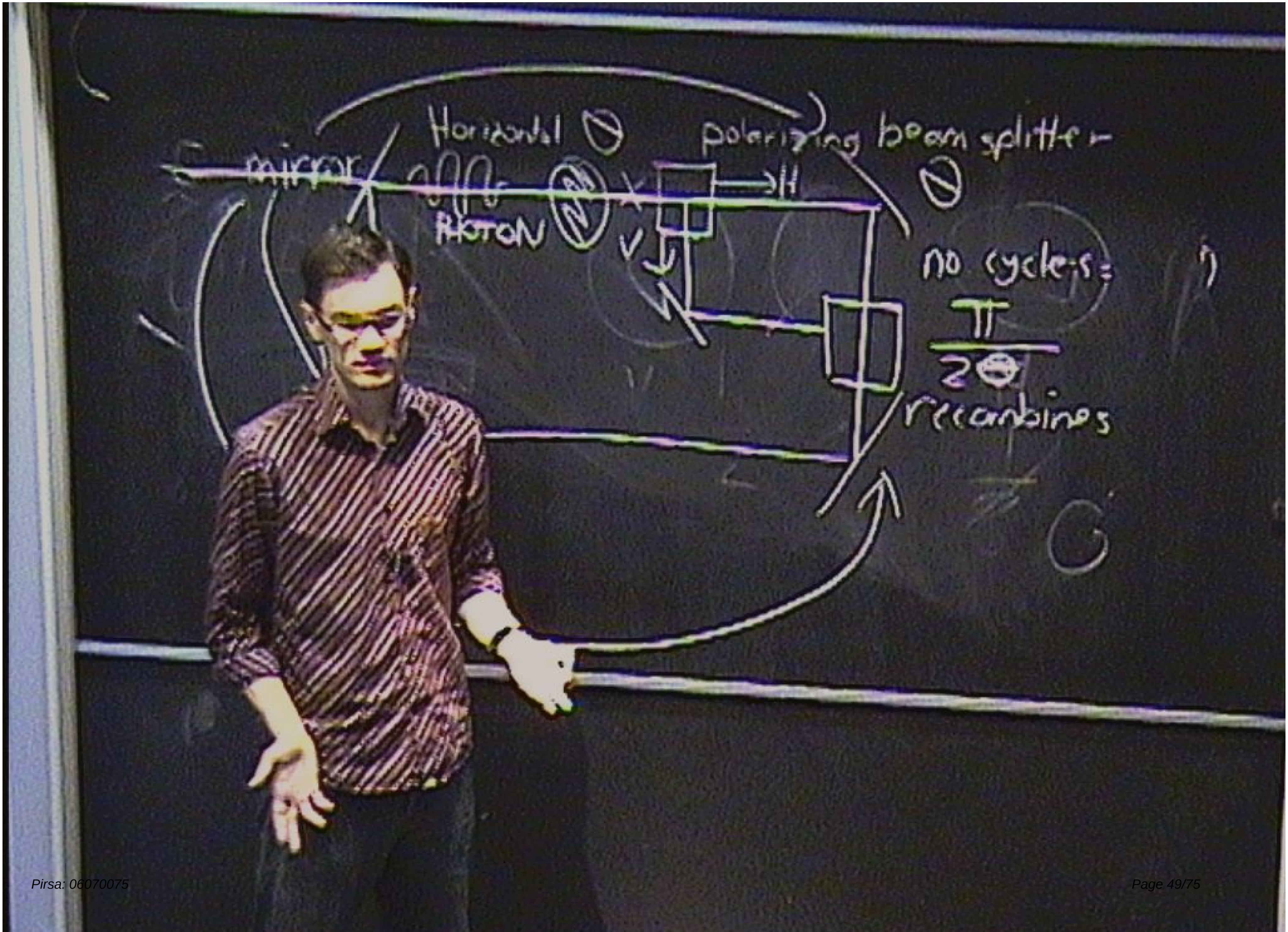
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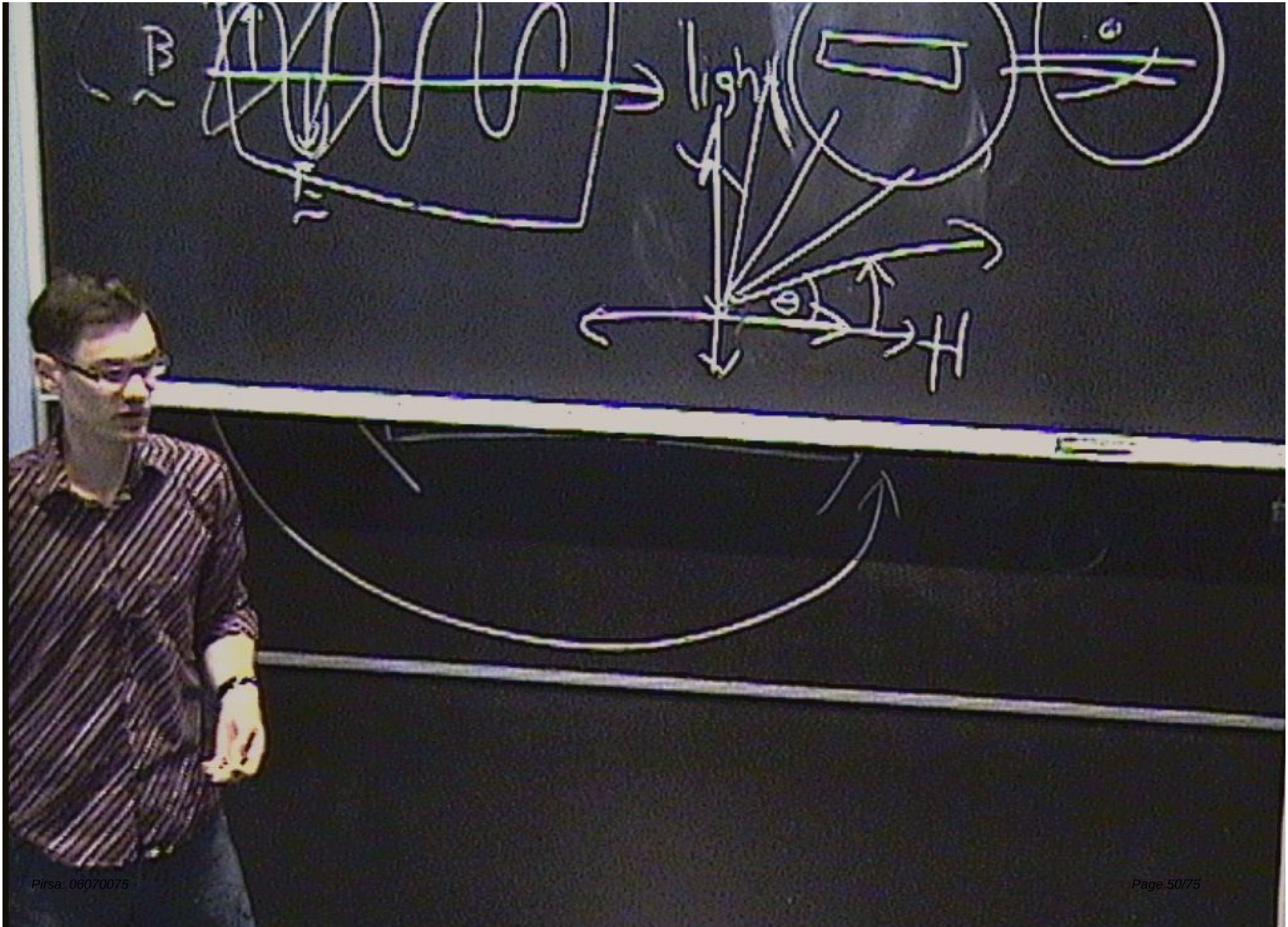
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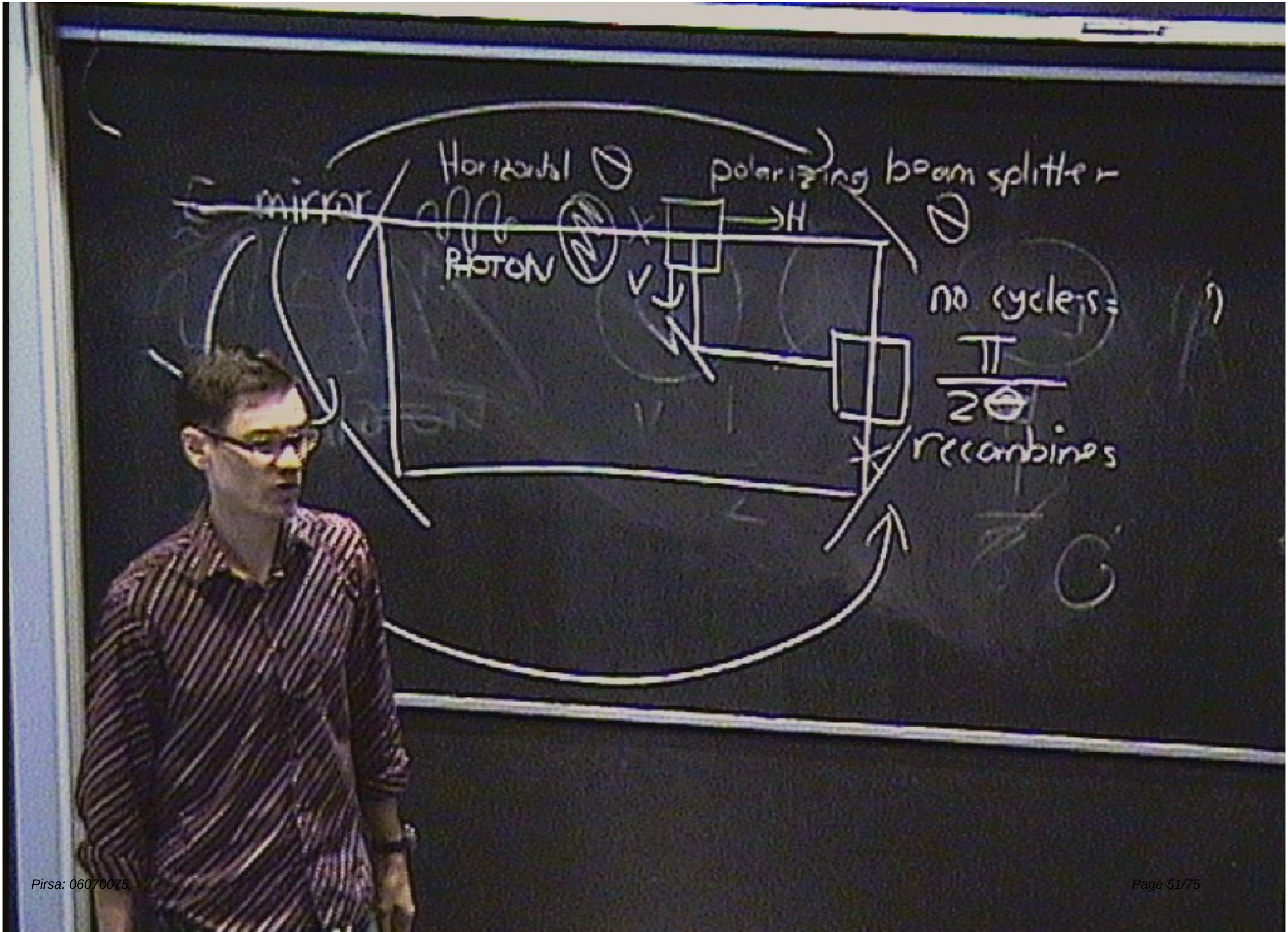
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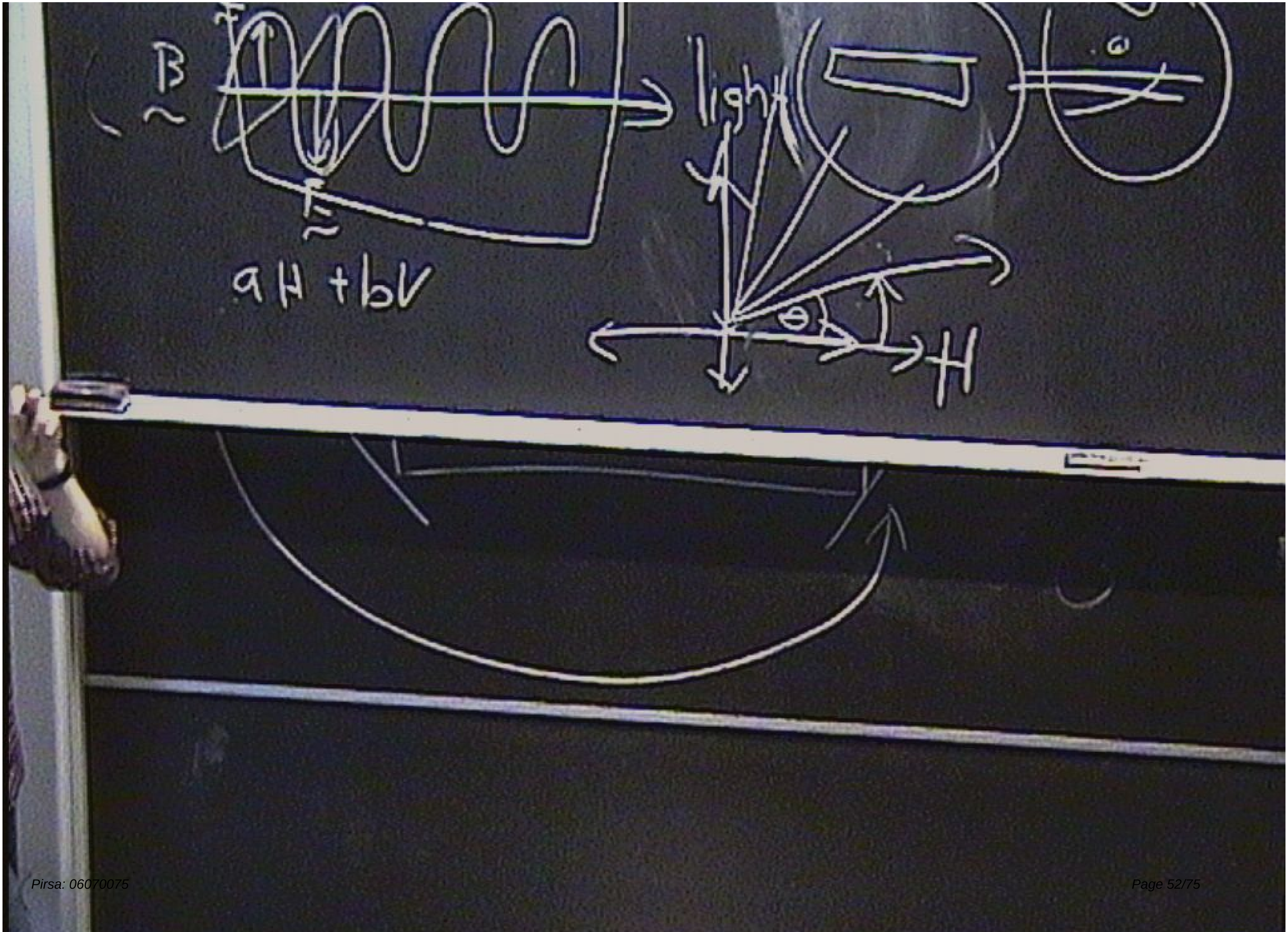
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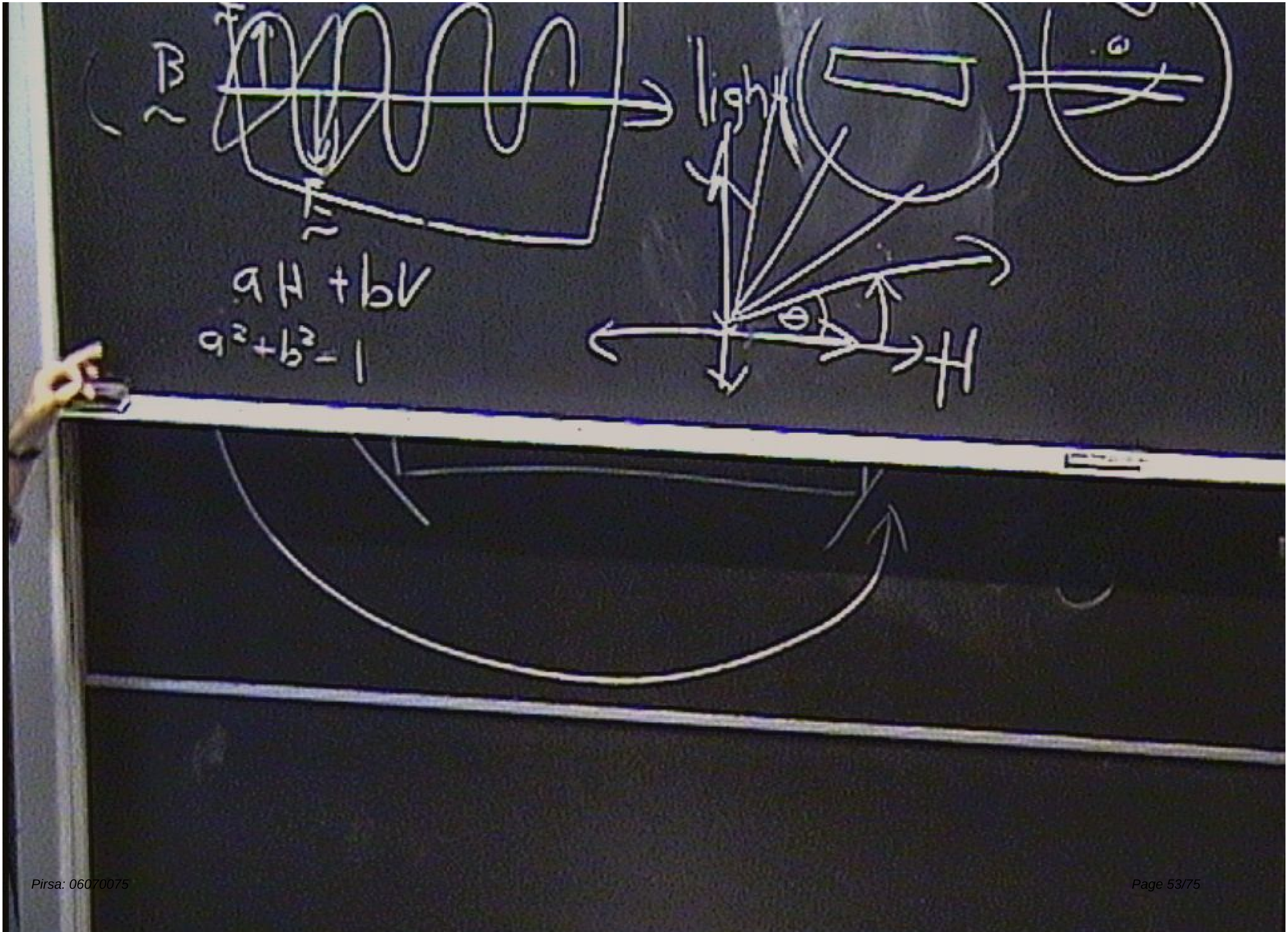
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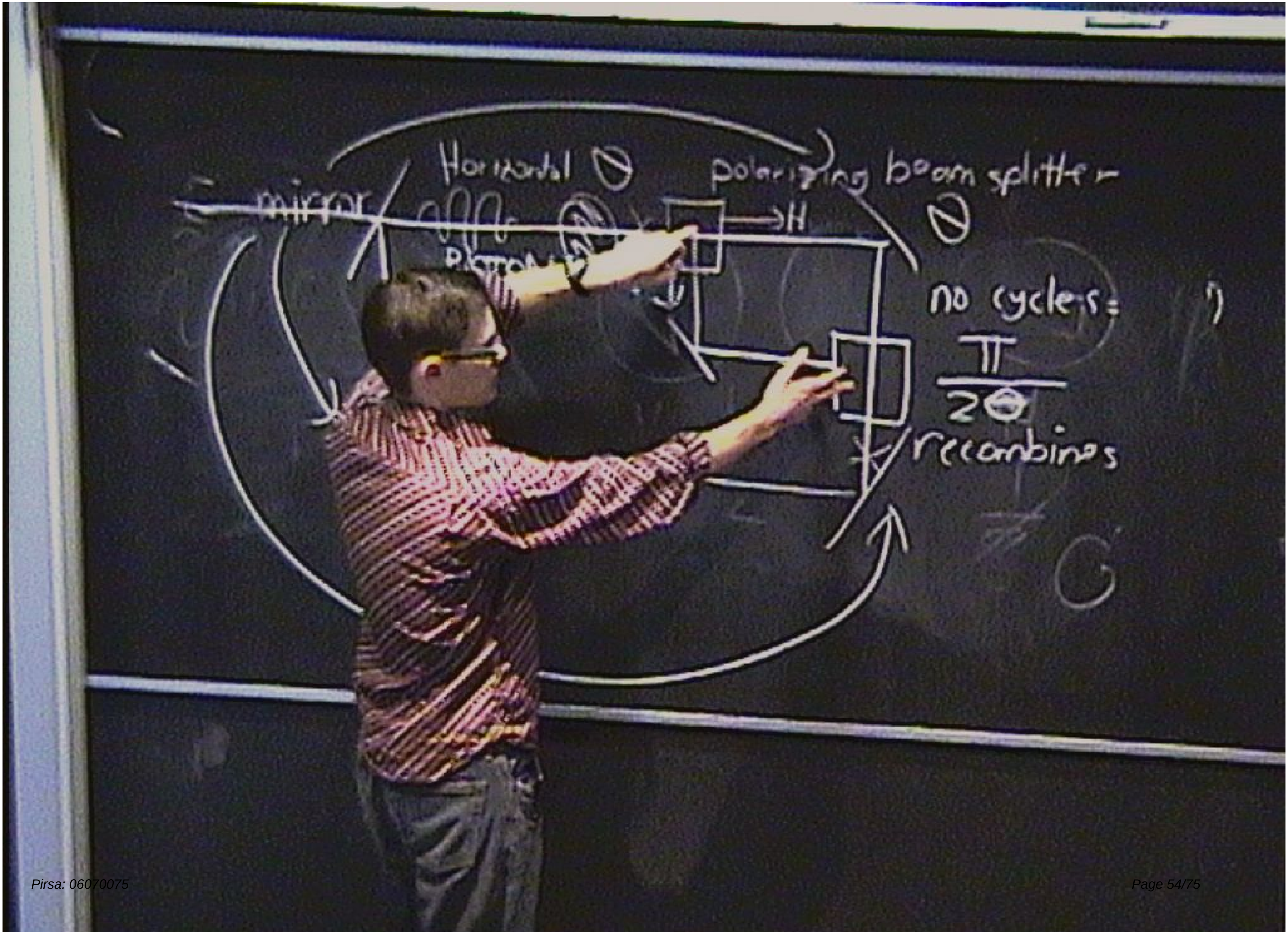
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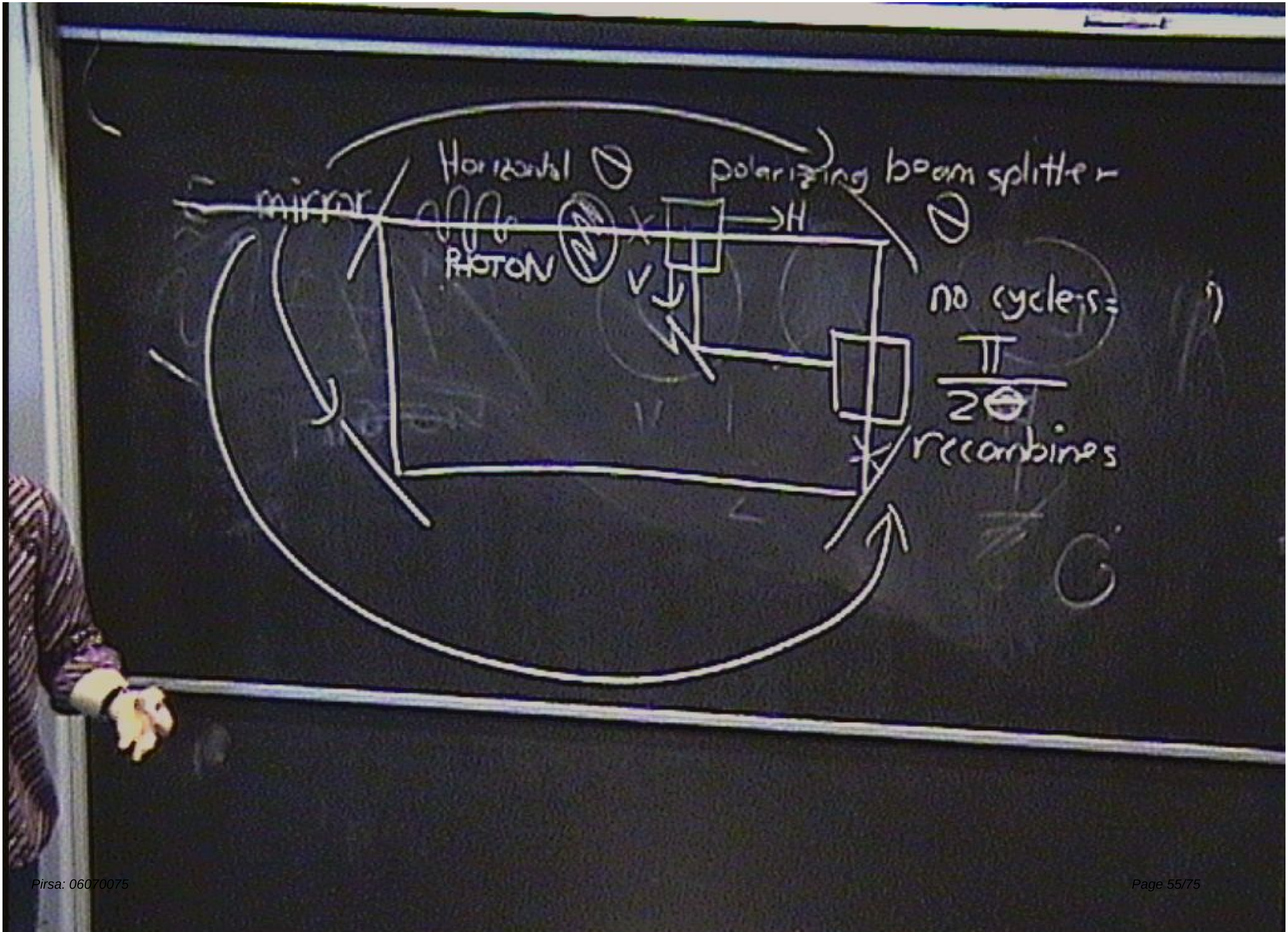
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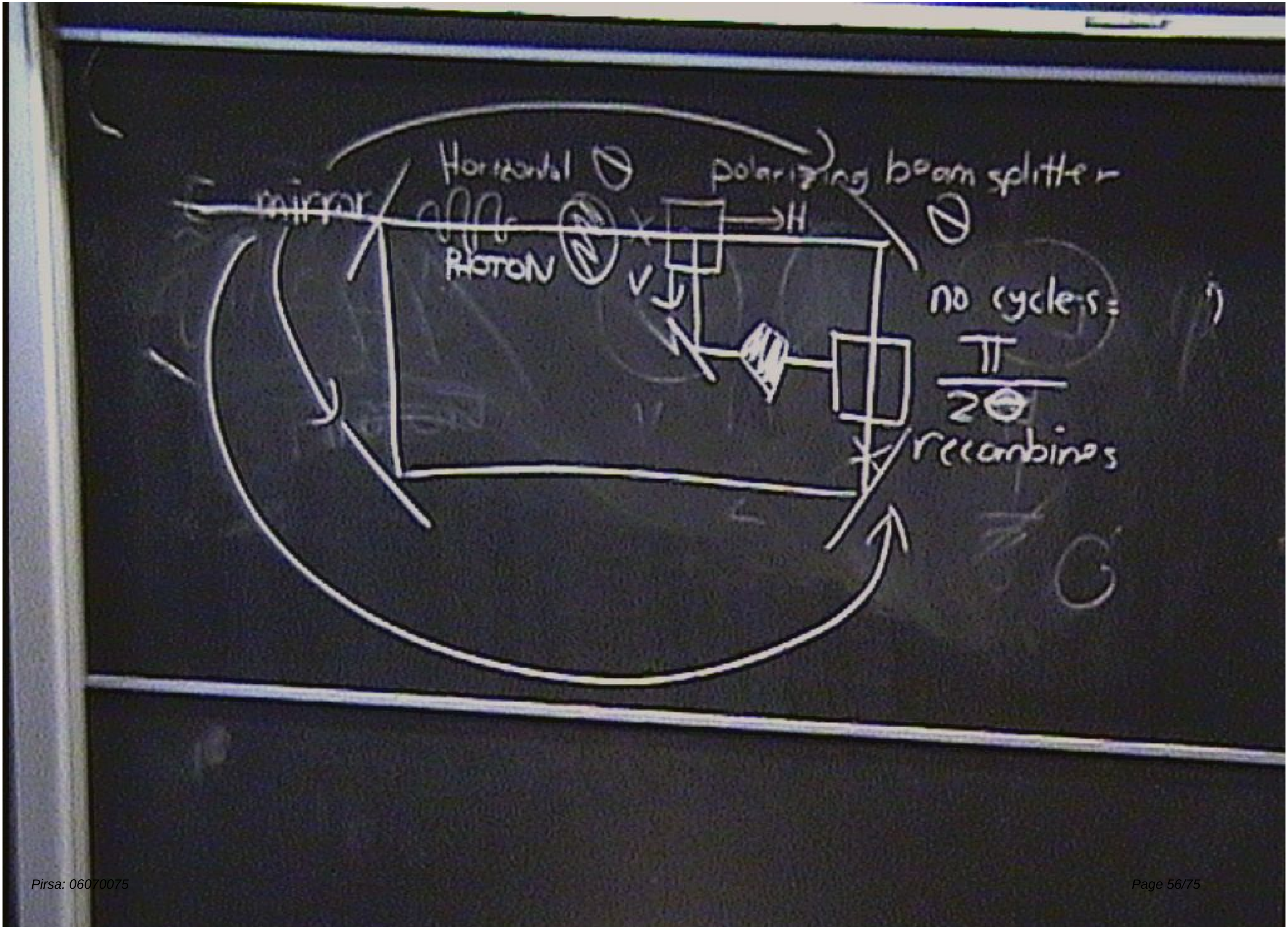
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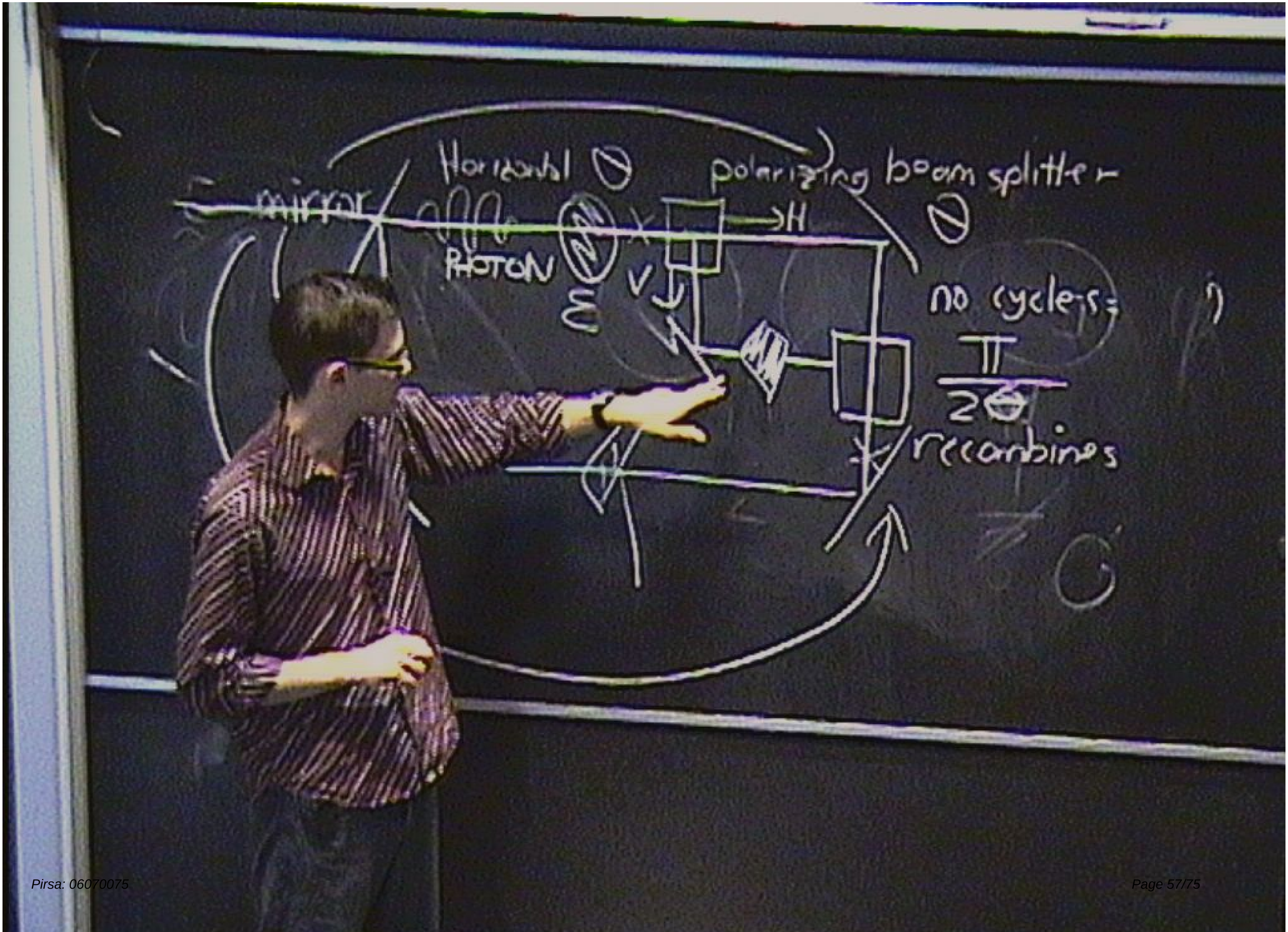
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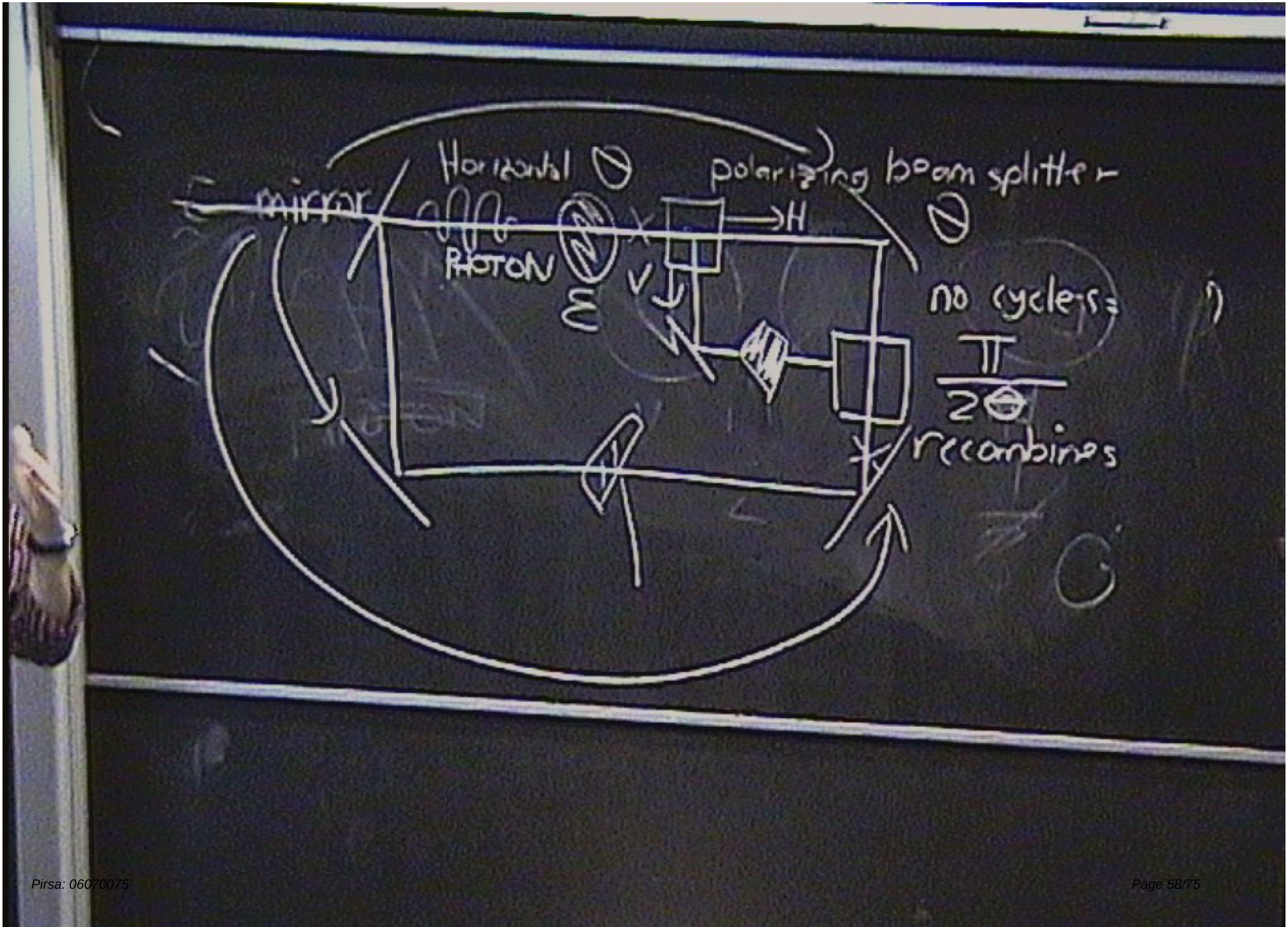
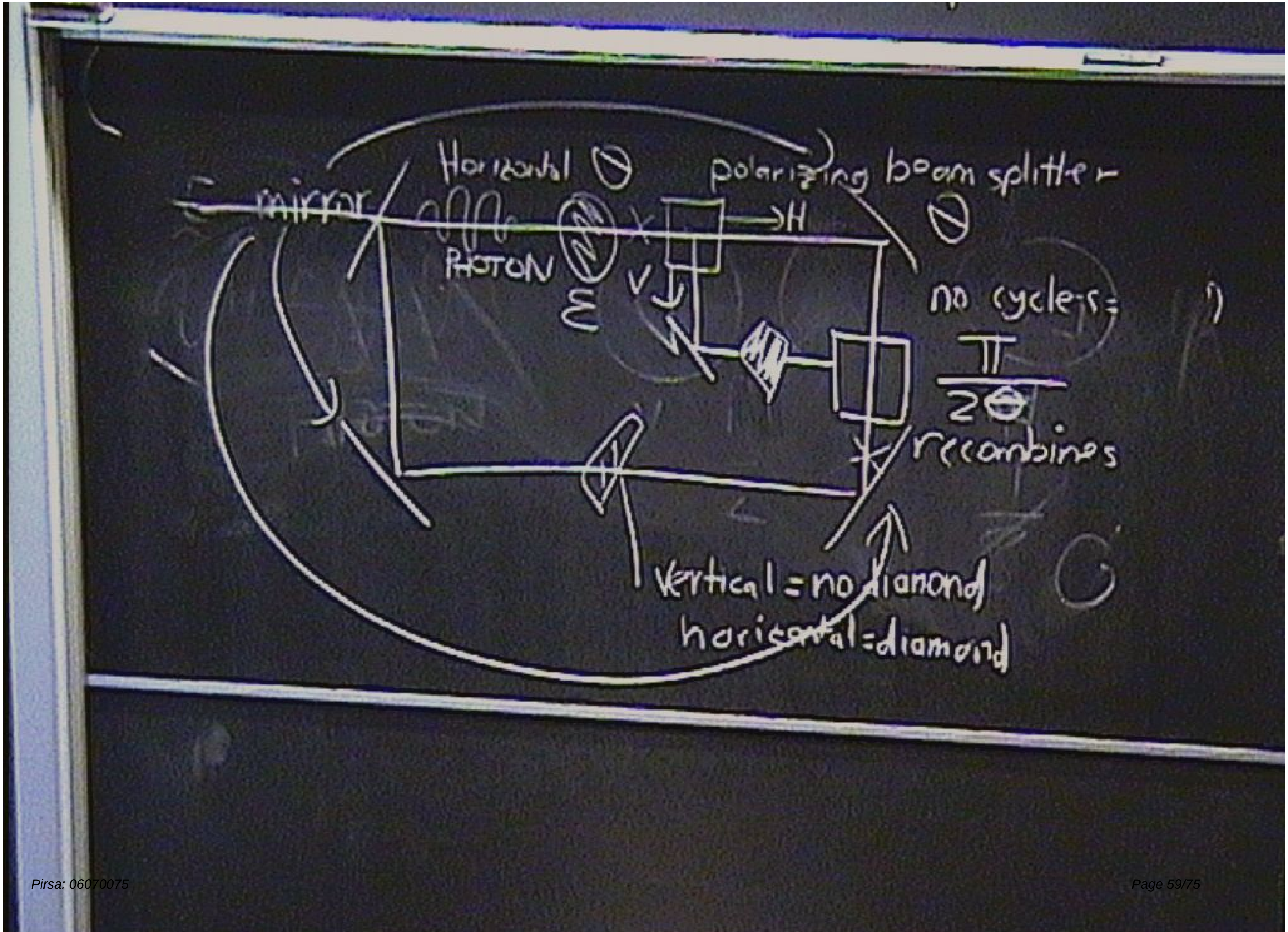
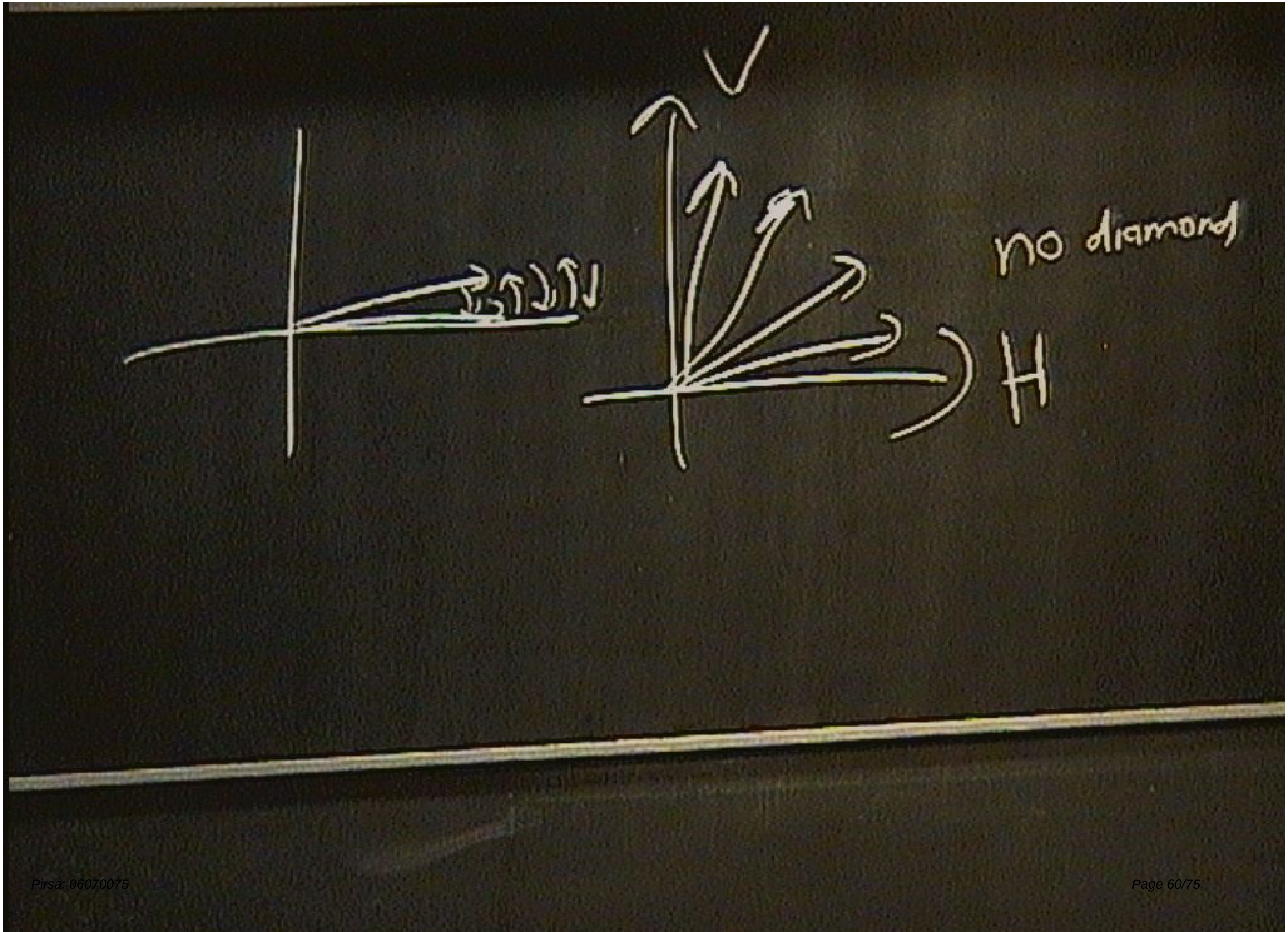
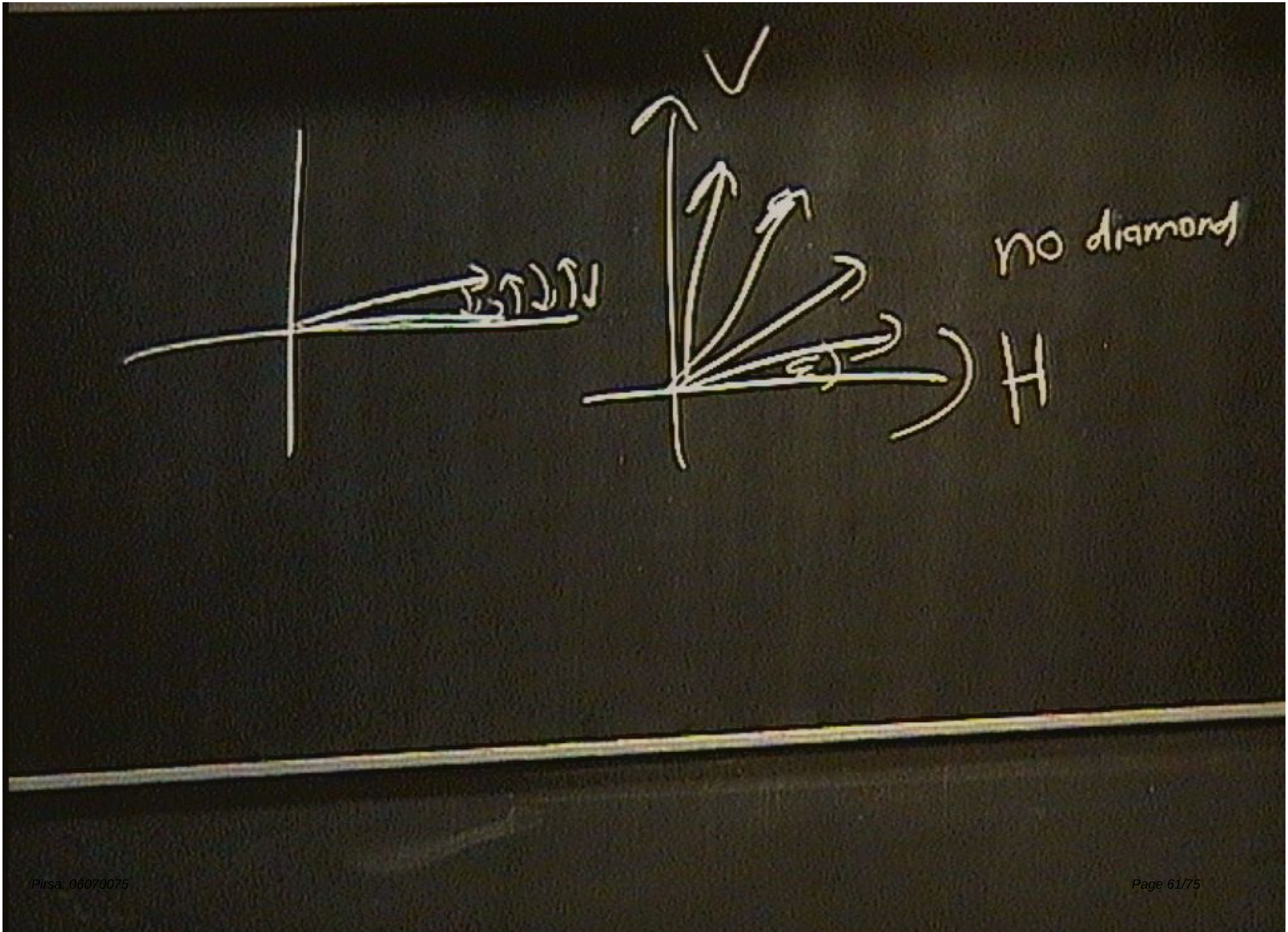
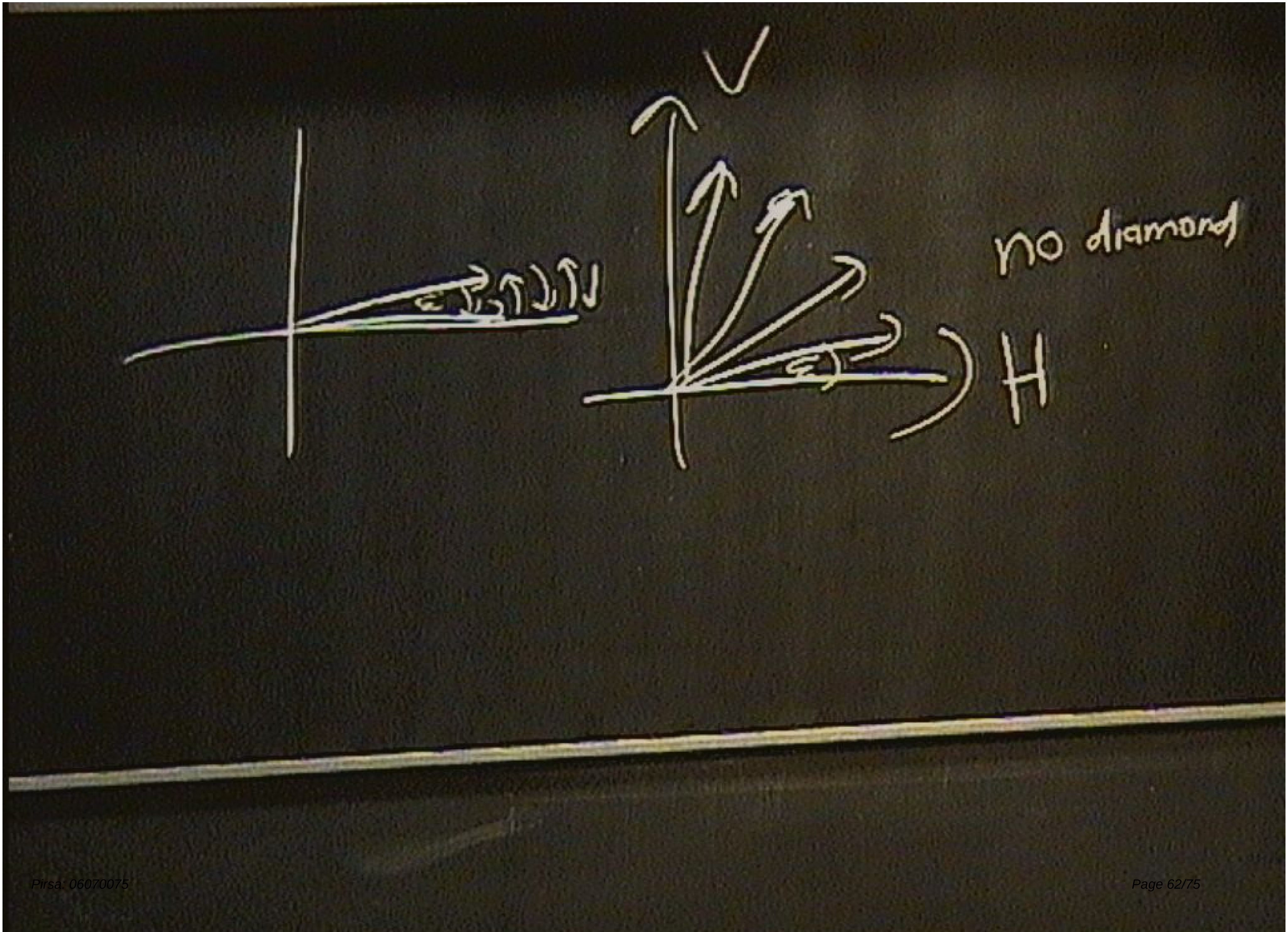

mirror
Horizontal
polarizing beam splitter
H
PHOTON
V
no cycles =
π
recombines

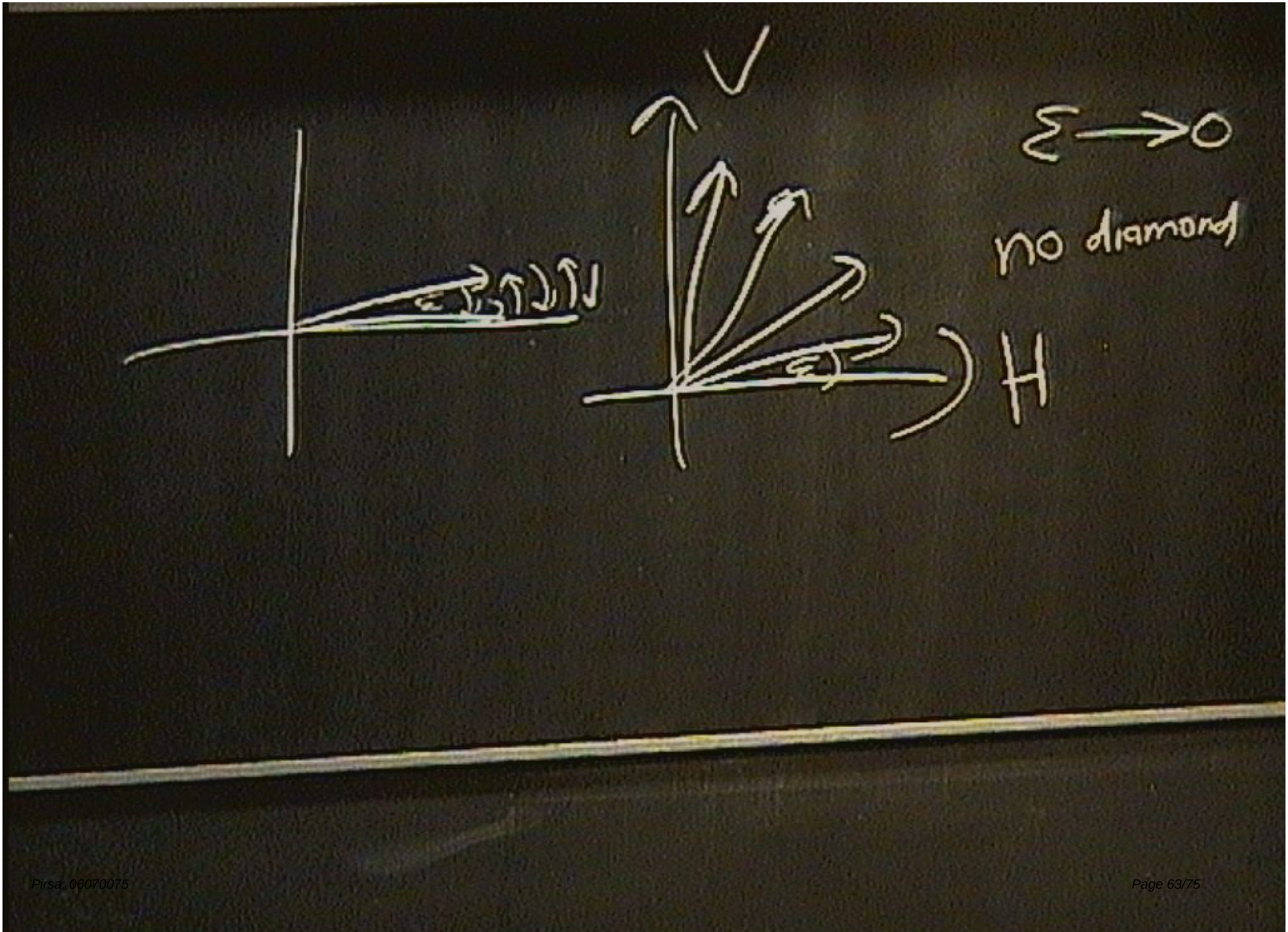


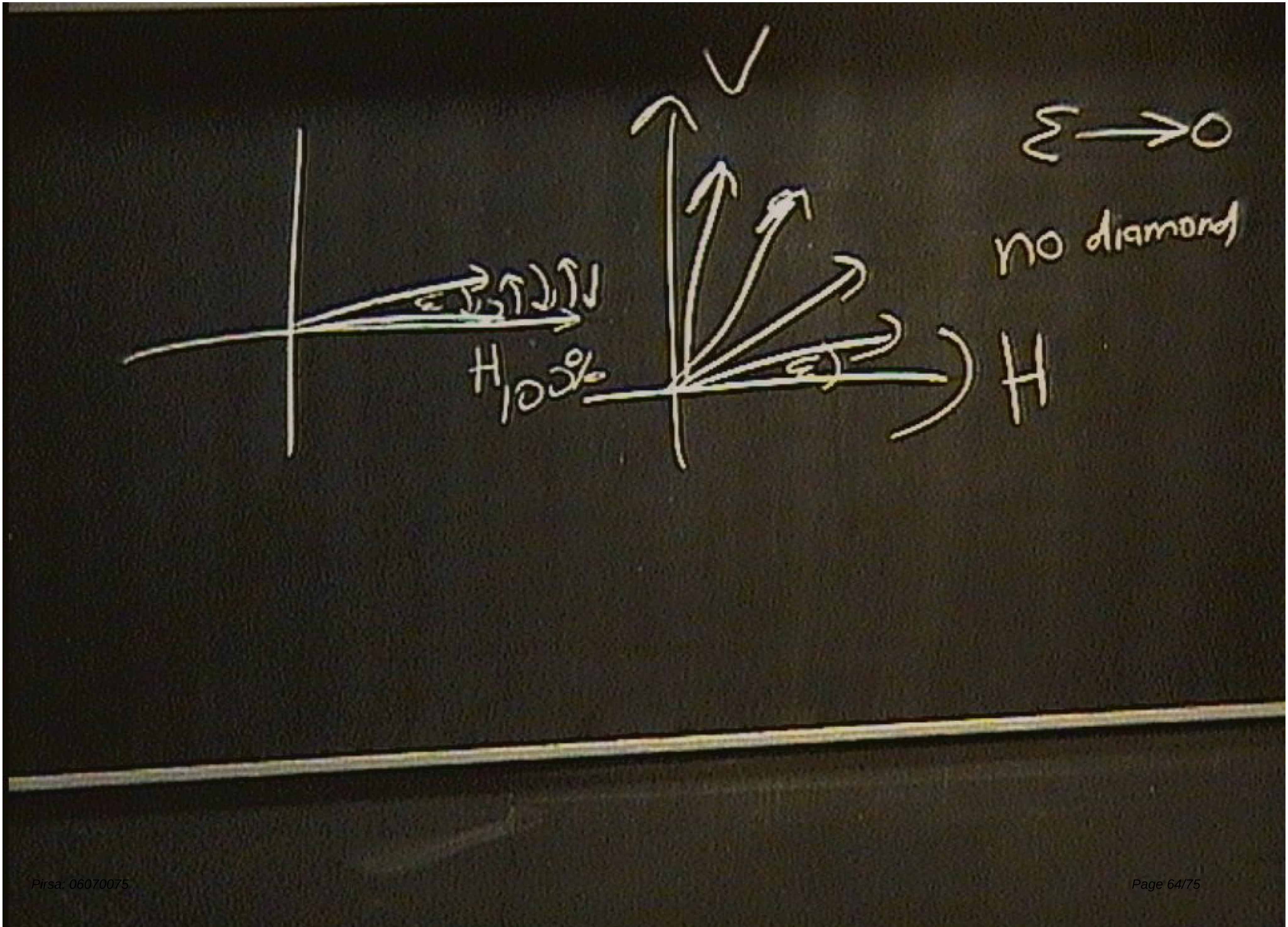
mirror
Horizontal
polarizing beam splitter
H
PHOTON
V
no cycles =
recombines
vertical = no diamond
horizontal = diamond


V
no diamond
H

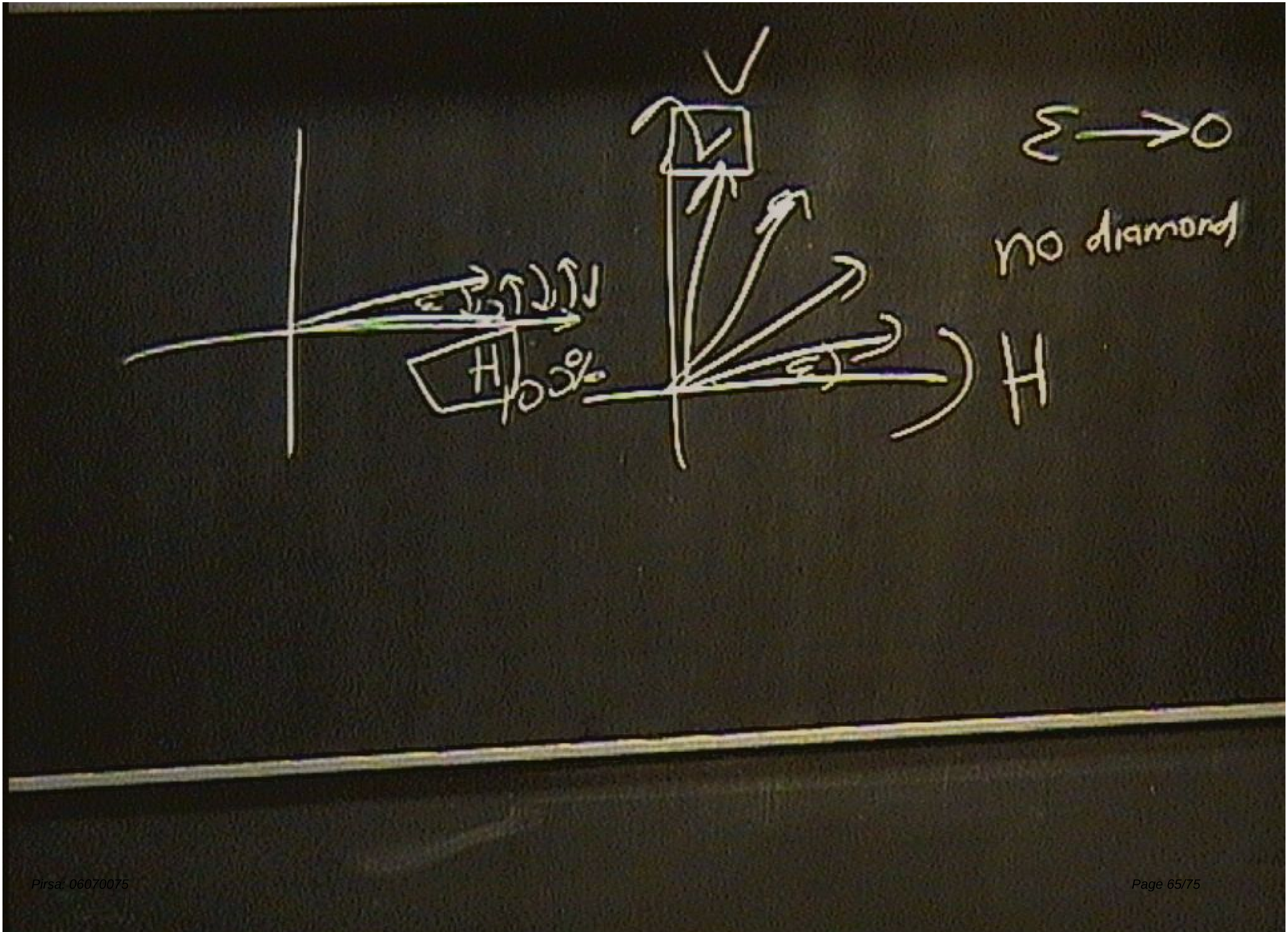

V
no diamond
H

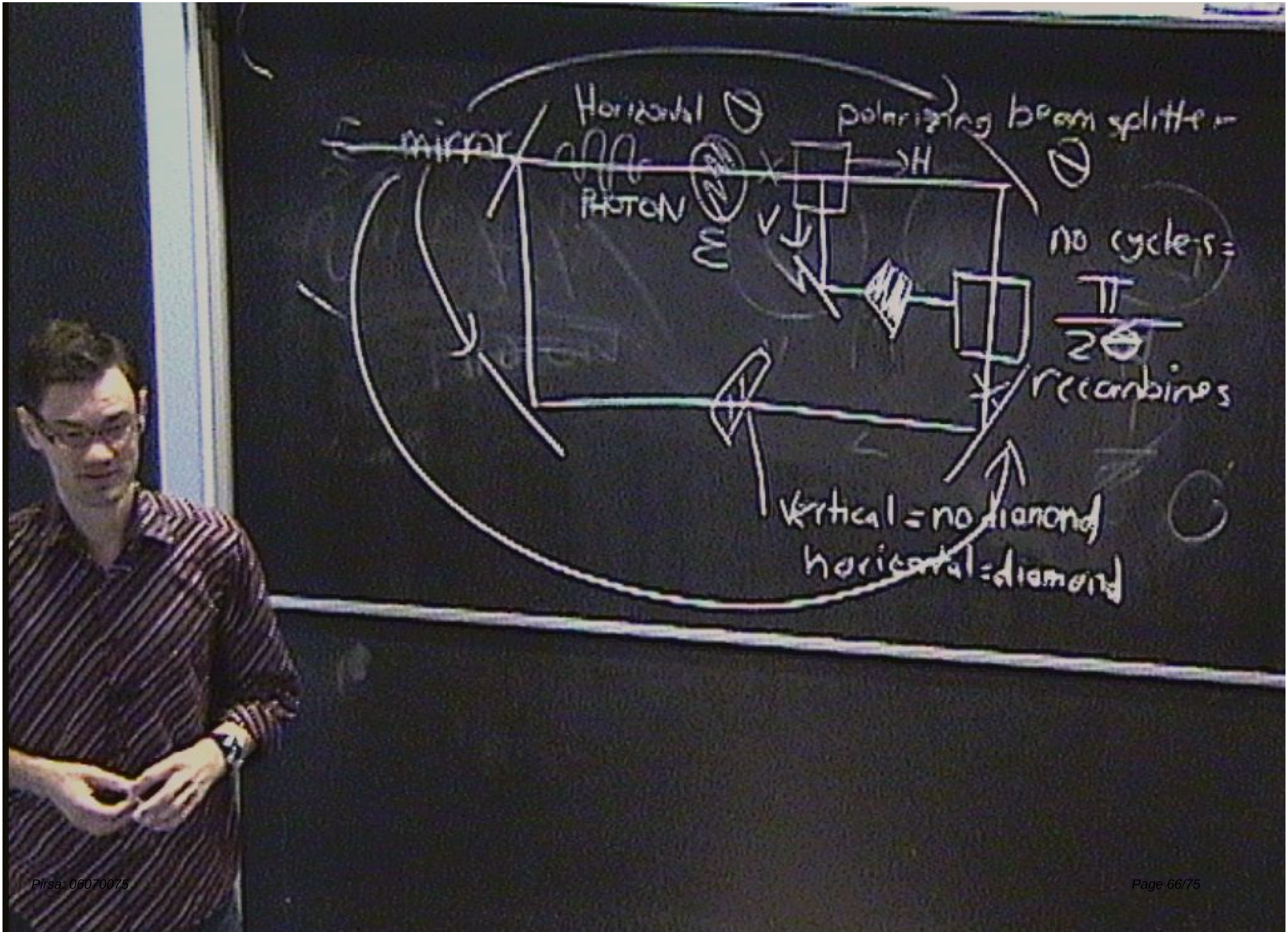

V
no diamond
H


V
ε → 0
no diamond
H
ε



V
ε → 0
no diamond
H
H,100%


V
ε → 0
no diamond
H



Horizontal
polarizing beam splitter
mirror
PHOTON
H
V
no cycles =
recombines
vertical = no diamond
horizontal = diamond

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Demonstrating this phenomenon in an actual experiment required several modifications (see Fig. 2). A horizontally-polarized laser pulse was coupled into the system by a highly reflective mirror. The light was attenuated so that the average photon number per pulse after the mirror was between 0.1 and 0.3. The photon then bounced between this recycling mirror and one of the mirrors making up a polarization Michelson interferometer. At each cycle a waveplate rotated the polarization by $\Delta\theta$. After the desired number of cycles N, the photon was switched out of the system by applying a high-voltage pulse to a Pockels cell in each interferometer arm, thereby rotating the polarization of the photon by 90°, so that it exited via the other port of the polarizing beam splitter. The exiting photon was then analyzed by

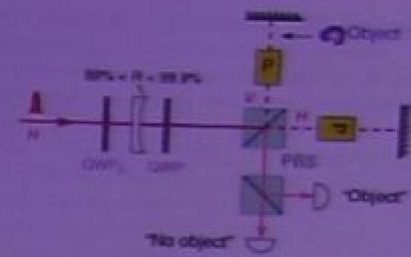

FIG. 2. Experimental system to demonstrate high-efficiency quantum interrogation. Photons from a pulsed laser at 670nm are coupled into the recycling system via a high-reflectivity recycling mirror (initially flat, later curved; see Fig. 3). A double pass through the quarter waveplate (QWP) served to rotate the polarization by a fixed amount each cycle; an extra waveplate ($\mathrm{QWP}_\perp$) in the entrance beam was used to compensate for the initial pass. On each cycle the photon passed through a polarization interferometer (with a polarizing beamsplitter [PBS]); to fine tune the interferometer phase, one mirror was mounted on a piezoelectric "bimorph". The Pockels cells (P) were used to switch the photons out after a desired number of cycles – a ~ 3 kV pulse was applied, which after the double pass rotated the polarization of the photon by 90°, so that it exited via the other port of the PBS. The exiting photon was then analyzed by the adjustable polarizer and single-photon detector (EG&G #SPCM-AQ-141, preceded by an interference filter [10nm FWHM, centered at 670nm] to reduce background). The final polarization of the detected photon indicates the presence (**V**-polarized) or absence (**H**-polarized) of an object in the reflected arm of the interferometer. (Not shown: active feedback Helium Neon laser which ran below the plane of the 670nm light, to stabilize the interferometer.)

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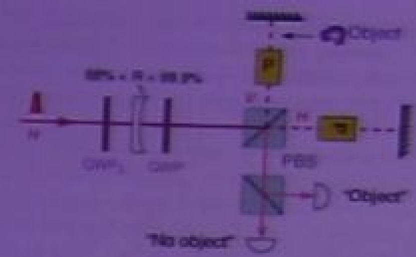

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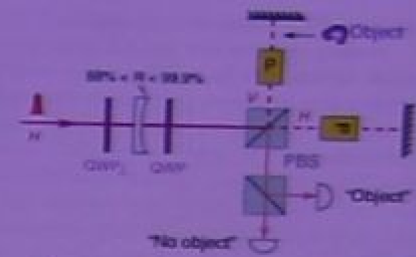

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...Institute for Experimental Physics, University of Innsbruck, Innsbruck 6020, Austria
(to appear in Phys. Rev. Lett; submitted June 11, 1999)

The phenomenon of quantum interrogation allows one to optically detect the presence of an absorbing object, without the measuring light interacting with it. In an application of the quantum Zeno effect, the object inhibits the otherwise coherent evolution of the light, such that the probability that an interrogating photon is absorbed can in principle be arbitrarily small. We have implemented this technique, demonstrating efficiencies exceeding the 50% theoretical-maximum of the original "interaction-free" measurement proposal. We have also predicted and experimentally verified a previously unsuspected dependence on loss; efficiencies of up to 73% were observed and the feasibility of efficiencies up to 85% was demonstrated.

PACS numbers: 03.65.Bz,03.65.-a,42.50.-p,42.25.Hz

"Negative result" measurements were discussed by Renninger [1] and later by Dicke [2], who analyzed the change in an atom's wavefunction by the *nonscattering* of a photon from it. In 1993 Elitzur and Vaidman (EV) showed that the wave-particle duality of light could allow "interaction-free" quantum interrogation of classical objects, in which the presence of a non-transmitting object is ascertained seemingly without interacting with it [3], i.e., with no photon absorbed or scattered by the object. In the basic EV technique, an interferometer is aligned to give complete destructive interference in one output port – the "dark" output – in the absence of an object. The presence of an opaque object in one arm of the interferometer eliminates the possibility of interference so that a photon may now be detected in this output. If the object is completely non-transmitting, any photon detected in the dark output port must have come from the path *not* containing the object. Hence, the measurements were deemed "interaction-free", though we stress that this term is sensible only for objects that completely block the beam. For measurements on partially-transmitting (and quantum) objects, we suggest the more general terminology "quantum interrogation". In any event there is necessarily a coupling between light and object (formally describable by some interaction Hamiltonian) – somewhat paradoxically, in the high-efficiency schemes discussed below, it is crucial that the *possibility* of an interaction exist, in order to reduce the probability that such an interaction actually occurs.

The EV gedanken experiment has been realized using true single-photon states [4] and with a classical light beam attenuated to the single-photon level [5], as well as in neutron interferometry [6]. This methodology has even been employed to investigate the possibility of performing "absorption-free" imaging [7]. The EV technique suffers two serious drawbacks, however. First, the measurement result is ambiguous at least half of the time – a photon may be detected in the non-dark output port whether or not there is an object. Second, at most half of the measurements are interaction-free [4,7]. Following Elitzur and Vaidman [3], we define a figure of merit $\eta = P(QI)/[P(QI) + P(abs)]$ to characterize the "efficiency" of a given scheme, where P(QI) is the probability that the photon is detected in the otherwise dark port, and P(abs) is the probability that the object absorbs or scatters the photon. Physically, η is the *fraction* of measurements that are "interaction-free". The maximum achievable efficiency, obtained by adjusting the reflectivities of the EV interferometer beamsplitters, is $\eta = 50\%$ [3,4,7].

It was proposed that one could circumvent these limitations by using a hybrid scheme [4], combining the interferometric ideas of EV and incorporating an optical version of the *quantum Zeno effect* [8], in which a weak, repeated measurement inhibits the otherwise coherent evolution of the interrogating photon. Our specific embodiment of the Zeno effect is based on an inhibited polarization rotation [9], although the only generic requirement is a weakly-coupled multi-level system. A photon with

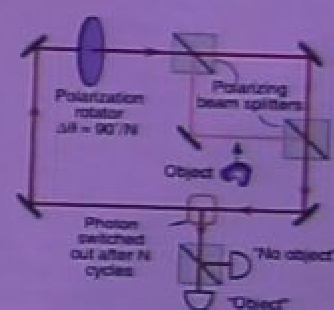
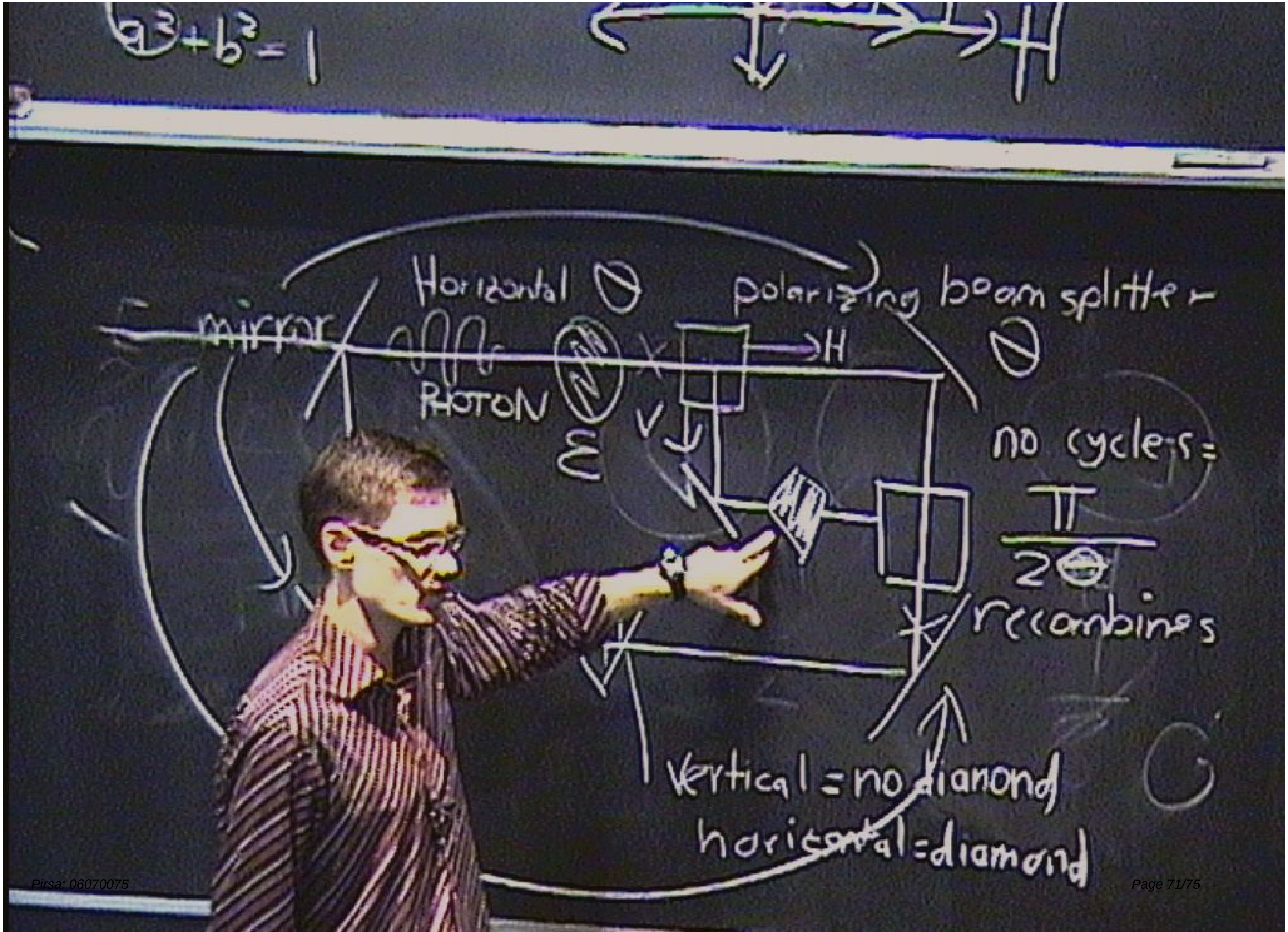


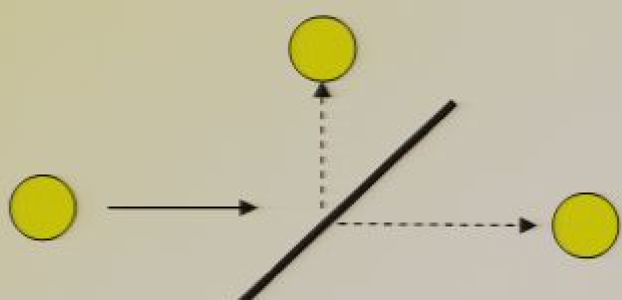
FIG. 1. Simple schematic of a hybrid scheme to allow high-efficiency quantum interrogation of the presence of an opaque object. With no object, the initial horizontal polarization of the interrogating photon is rotated stepwise to vertical. The presence of an object in the V-arm inhibits this evolution via the optical quantum Zeno effect [9], so that the final polarization after N cycles unambiguously indicates the presence or absence of the object: **V** polarization → "no object"; **H** polarization → "object".

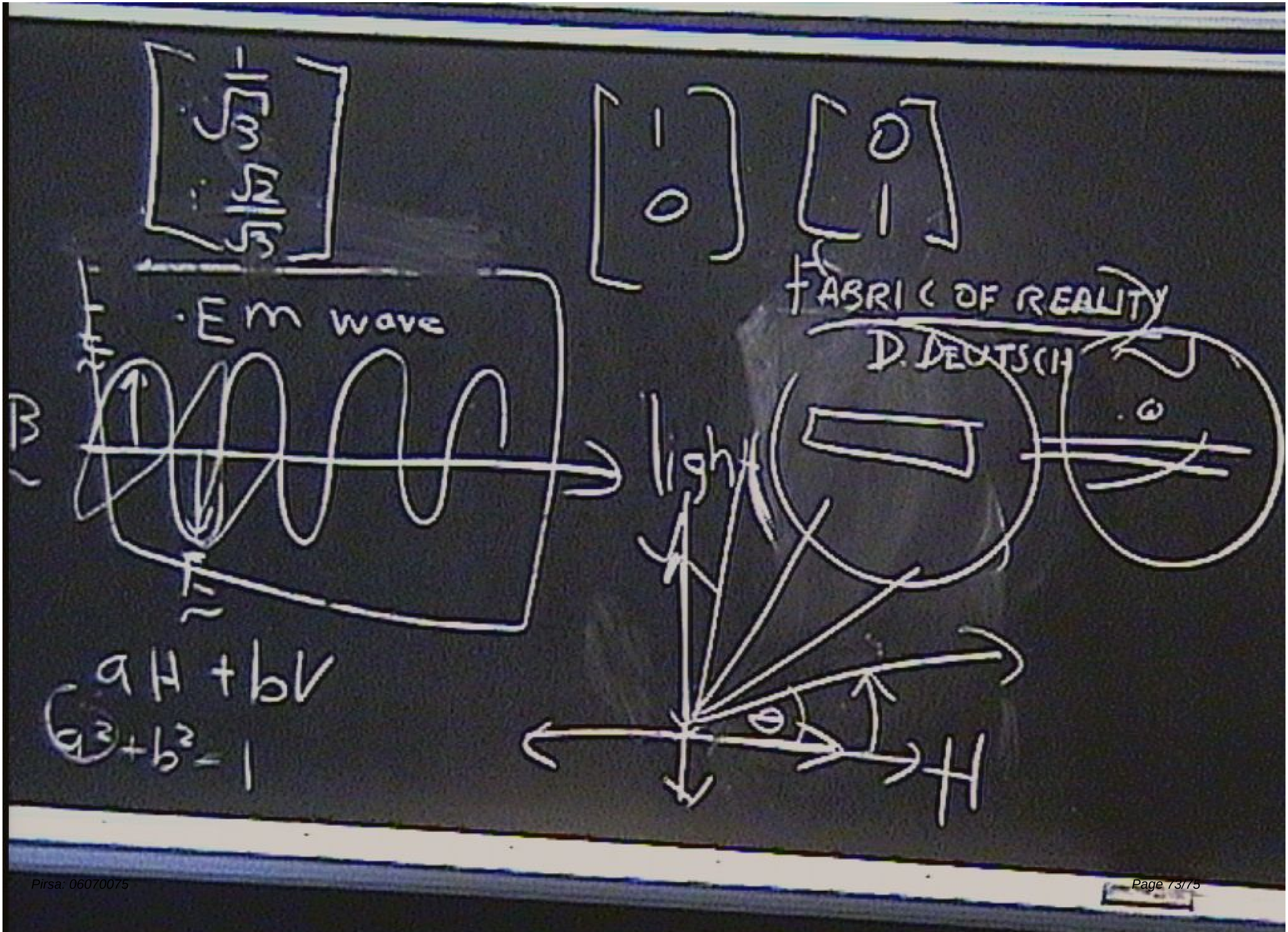

a2+b2=1
H
Horizontal
polarizing beam splitter
mirror
PHOTON
H
V
no cycles =
π
2θ
recombines
vertical = no diamond
horizontal = diamond

Core feature 1: Superposition



- Everyday objects such as baseballs, cars and trees are constrained to only exist in one place at any given time.
- Individual quantum entities such as electrons, atoms and photons, however, can exist in 'fuzzy' states called *superposition states* in which multiple possibilities are realized simultaneously
- Individual photons appear to take both paths at the same time.




Em wave
light
FABRIC OF REALITY
D. DEUTSCH
aH + bV
a²+b²=1
θ
H

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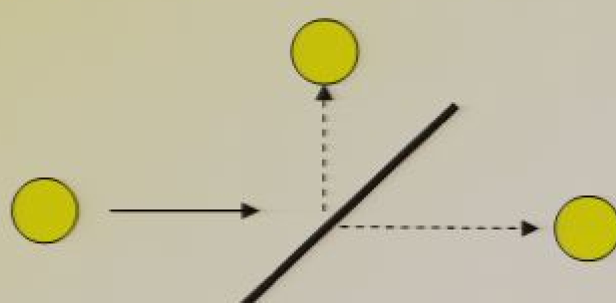

$$|(1,1)|^2 + |(2,1)|^2 = 1$$

quantum brain

no atoms: 10^{78}

no of quantum choices per second for each atom