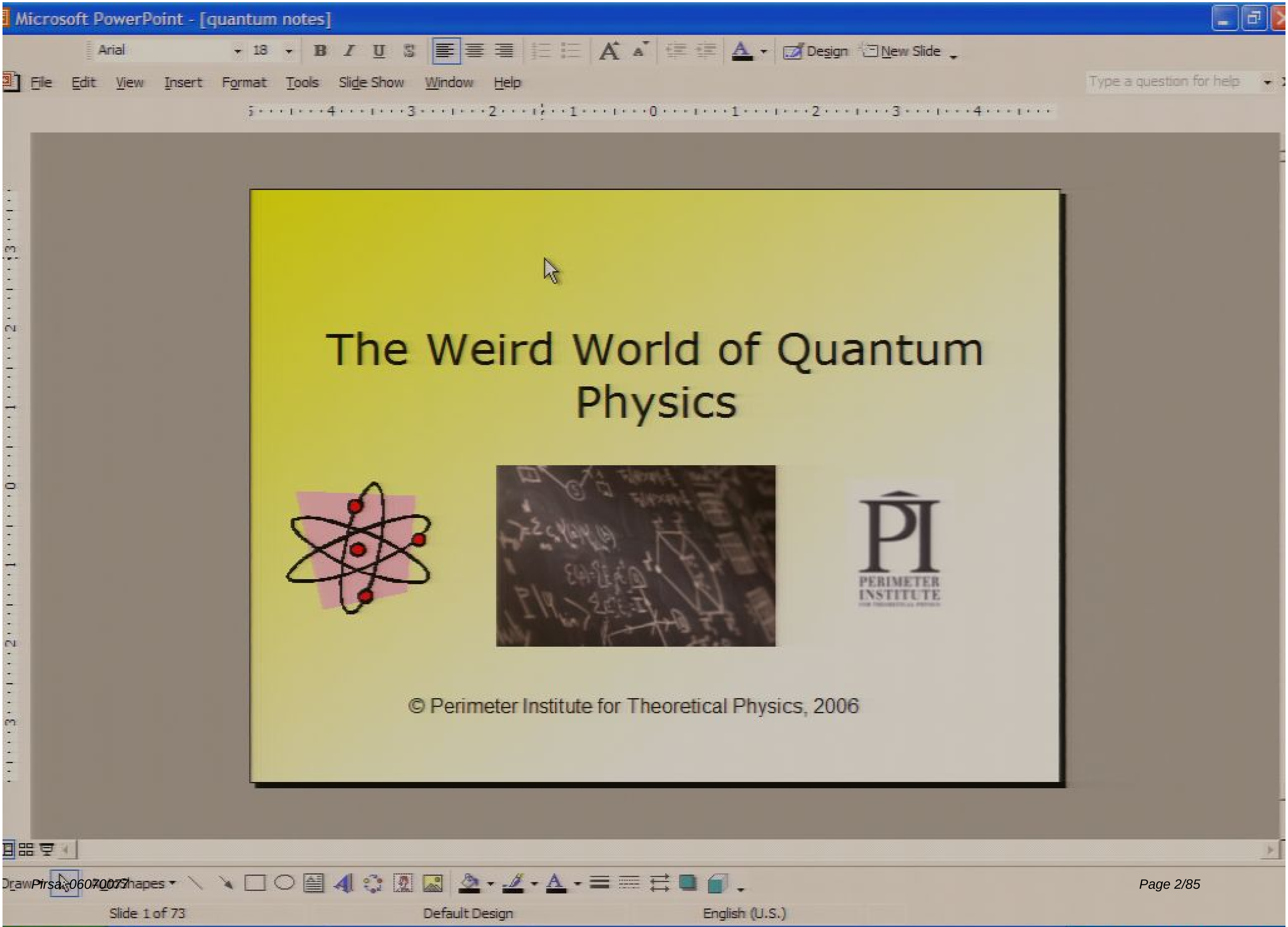
Title: The Weird World of Quantum Physics - Part 7

Date: Jul 27, 2006 09:00 AM

URL: http://pirsa.org/06070077

Abstract:


Microsoft PowerPoint - [quantum notes]
File Edit View Insert Format Tools Slide Show Window Help
The Weird World of Quantum Physics
PERIMETER INSTITUTE
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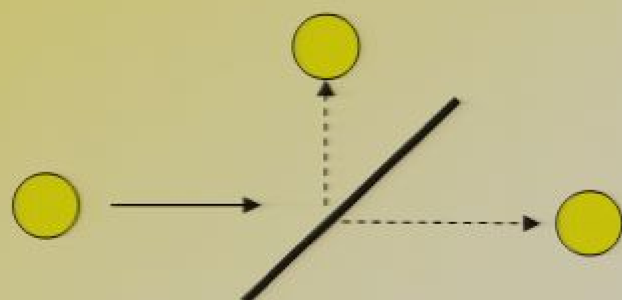
Slide 1 of 73
Default Design
English (U.S.)

Does the 2x2 matrix make sense?

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} \rightarrow \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{i}{\sqrt{2}} \end{bmatrix}$$

This is precisely the combination state of affairs we encountered before.



$$\begin{bmatrix} 0 \\ 1 \end{bmatrix} \rightarrow \begin{bmatrix} \frac{i}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$$

Another "state" in which the photon is taking both paths.

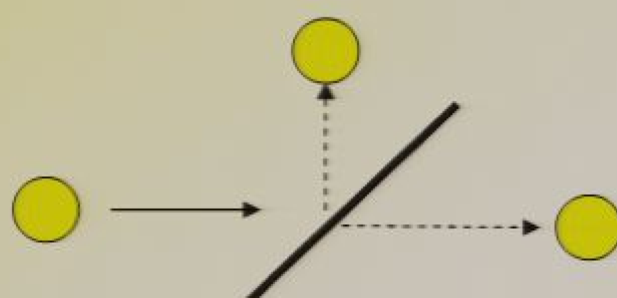
Core feature 1: Superposition

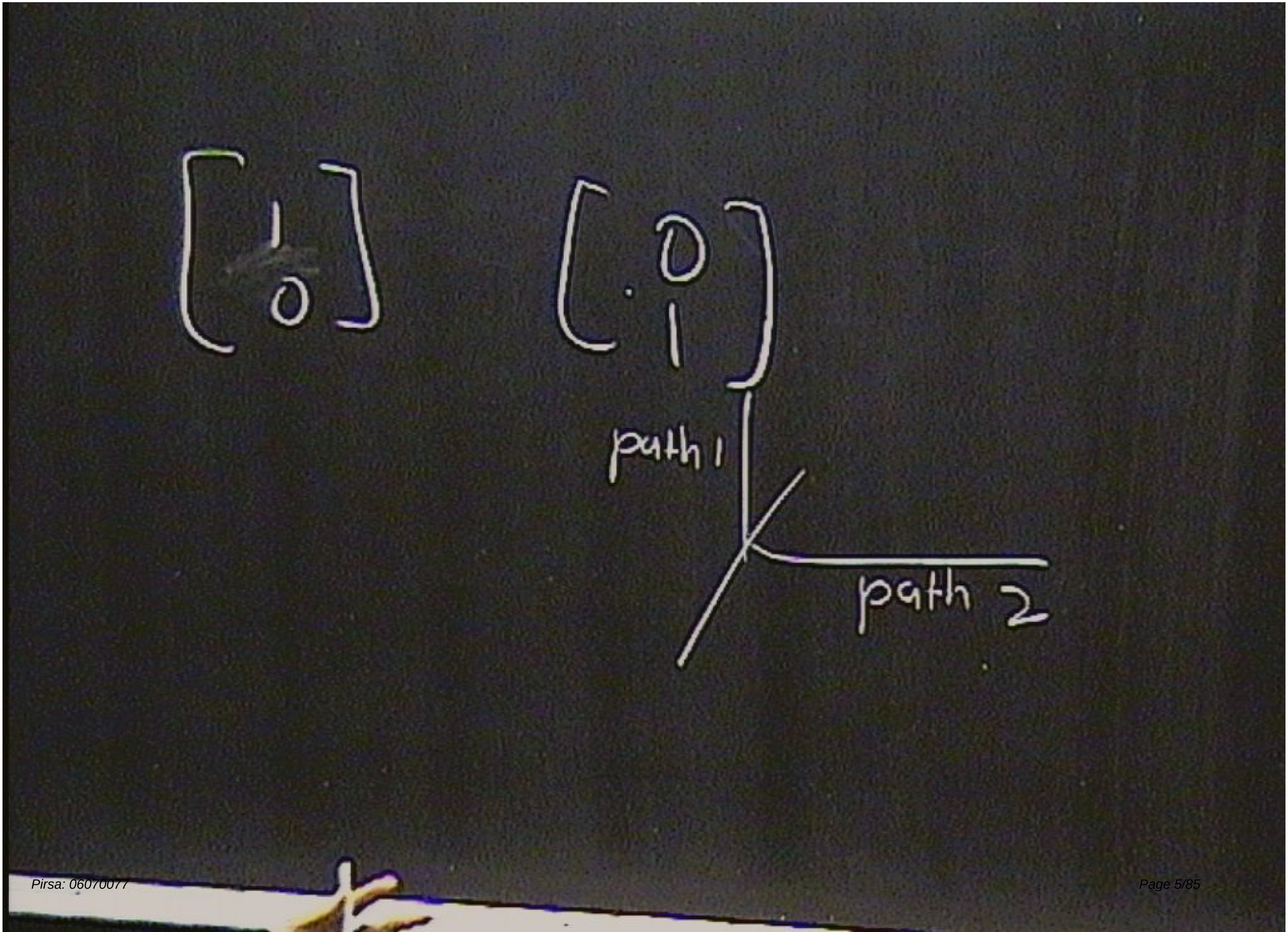


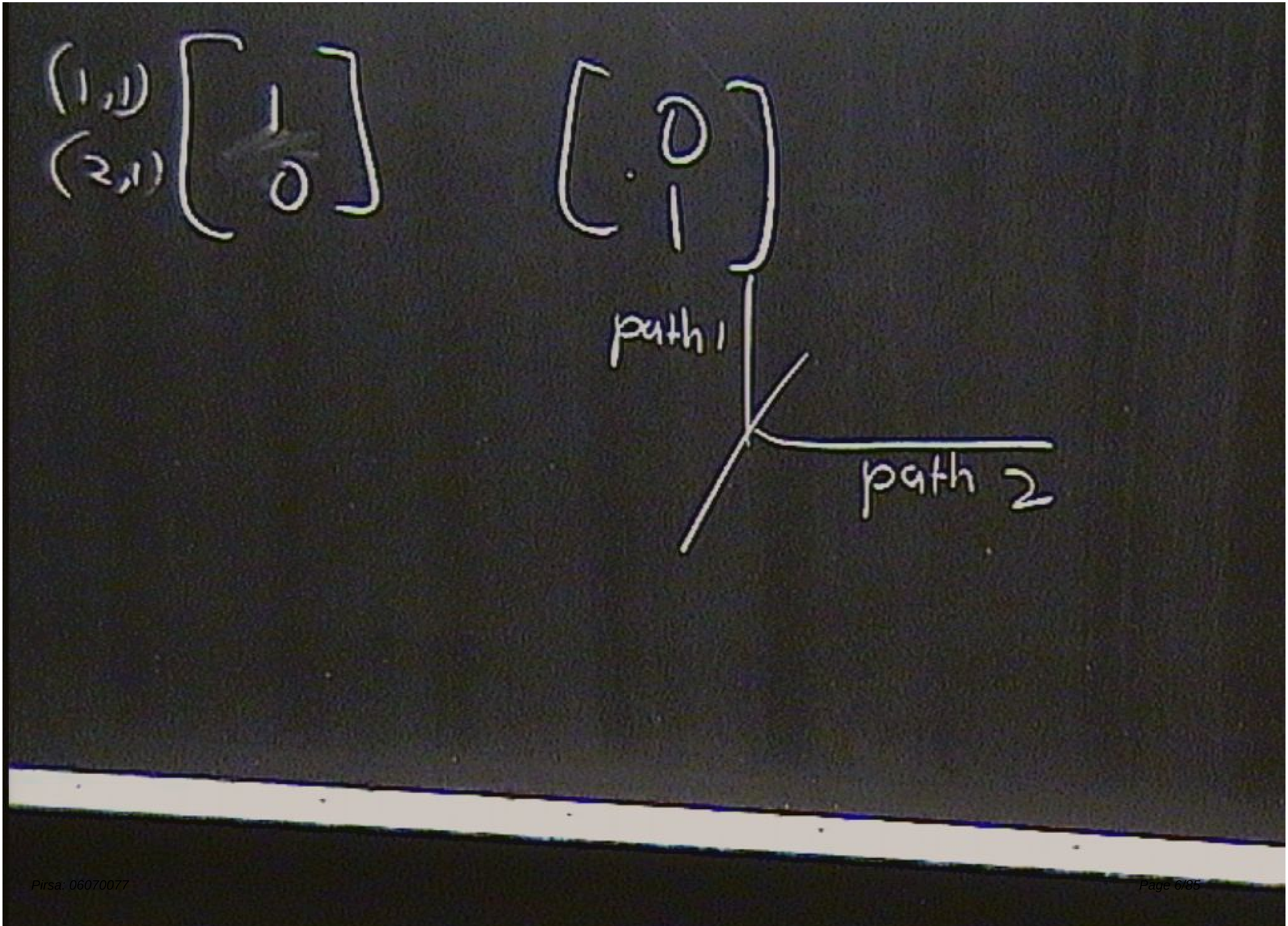
- Everyday objects such as baseballs, cars and trees are constrained to only exist in one place at any given time.

- 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.

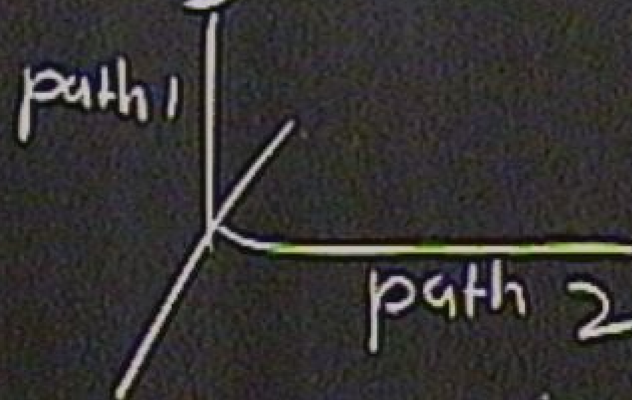


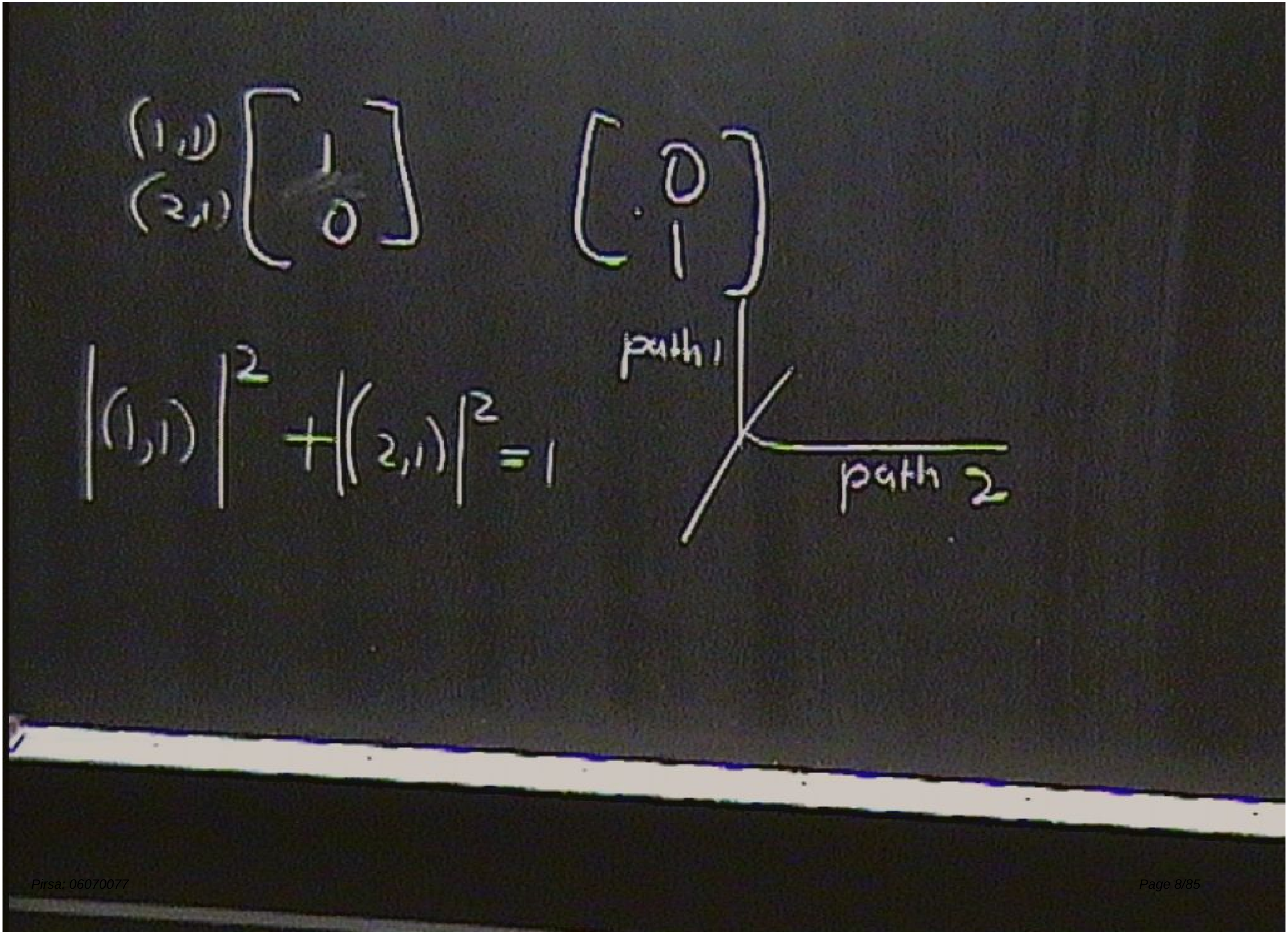

path 1
path 2

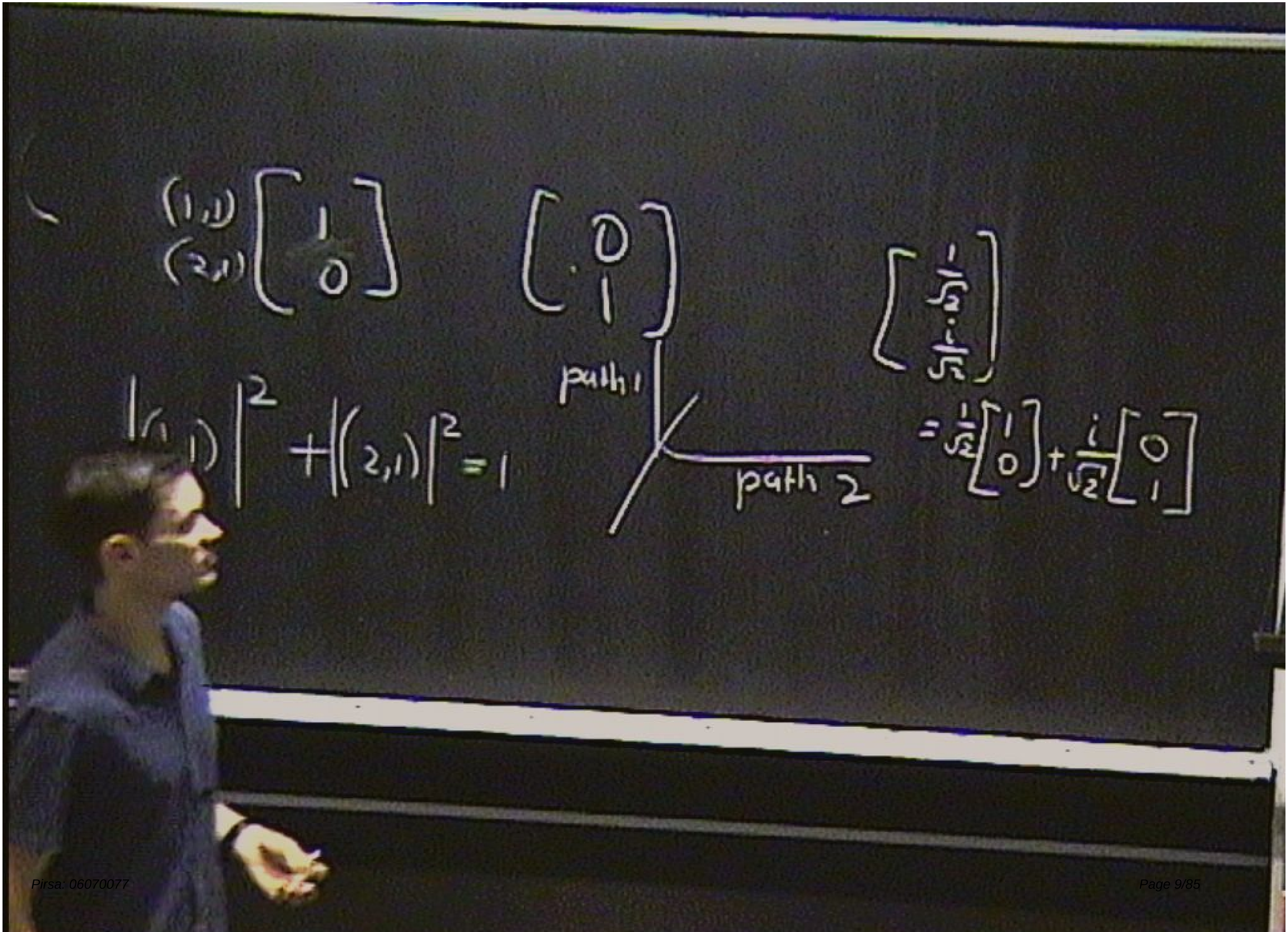

(1,1)
(2,1)
path 1
path 2

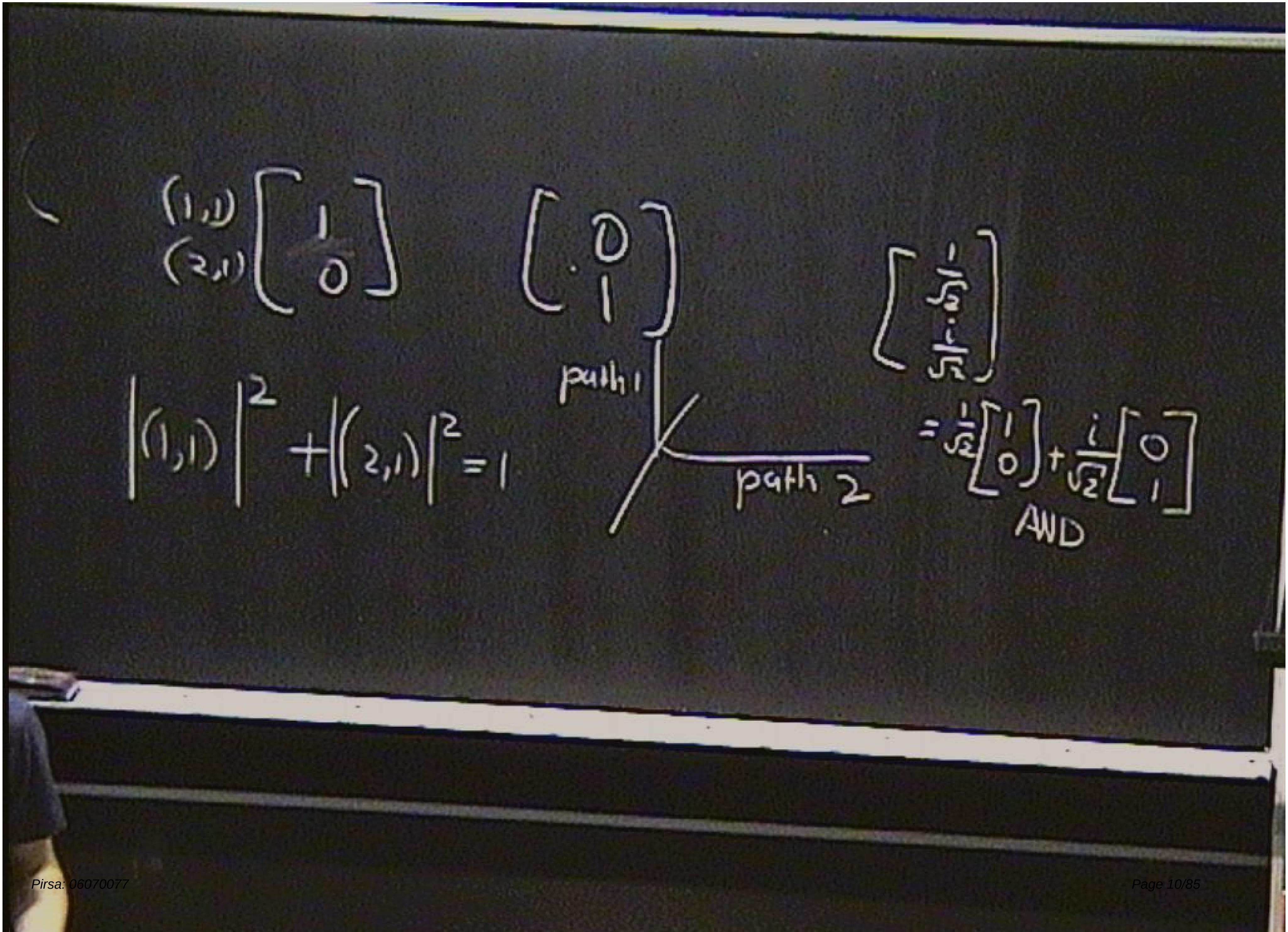
$$\begin{matrix}(1,1)\\(2,1)\end{matrix}\begin{bmatrix}1\\0\end{bmatrix} \qquad \begin{bmatrix}0\\1\end{bmatrix}$$

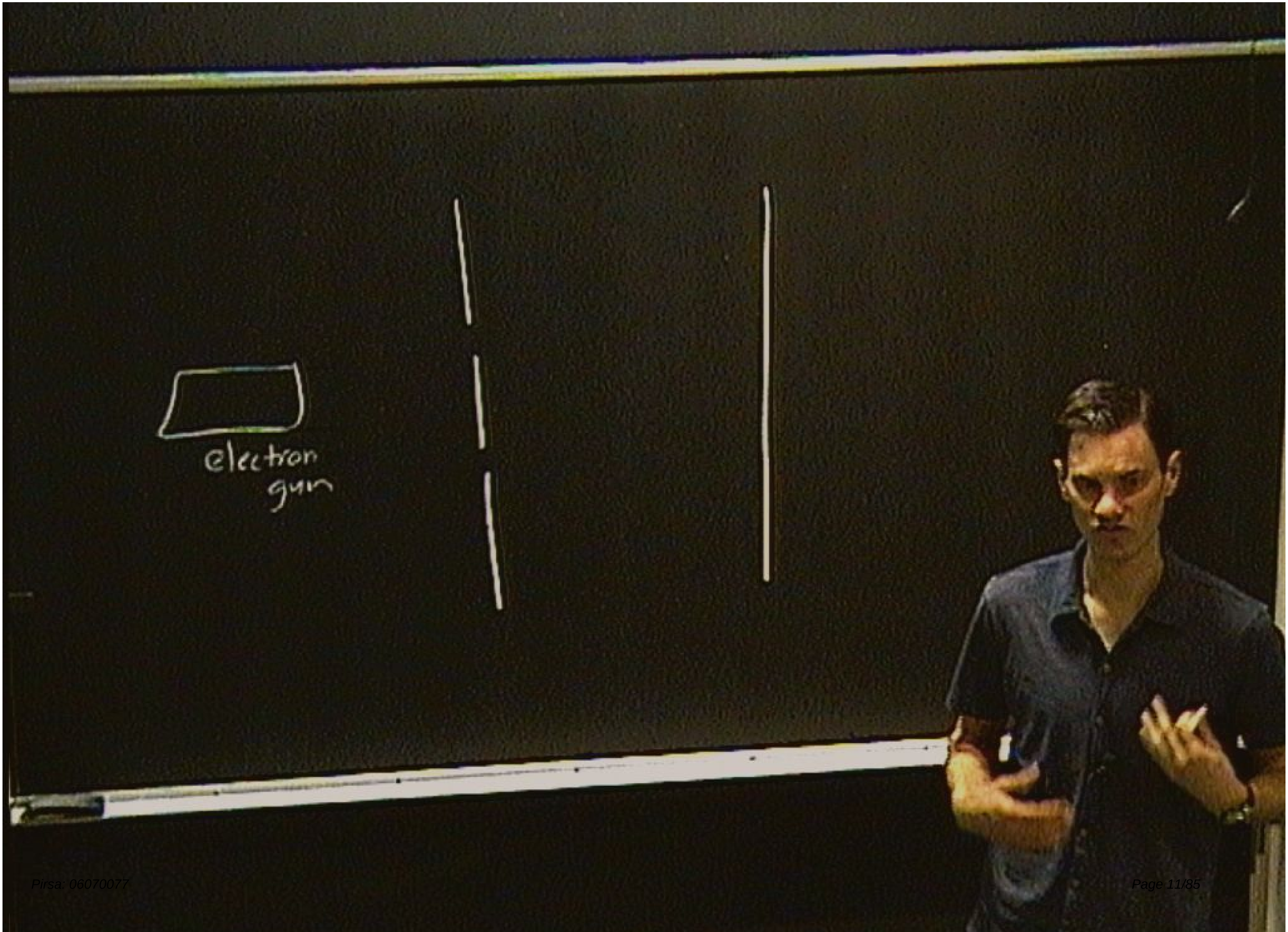
$$|(1,1)|^2+|(2,1)|^2=1$$

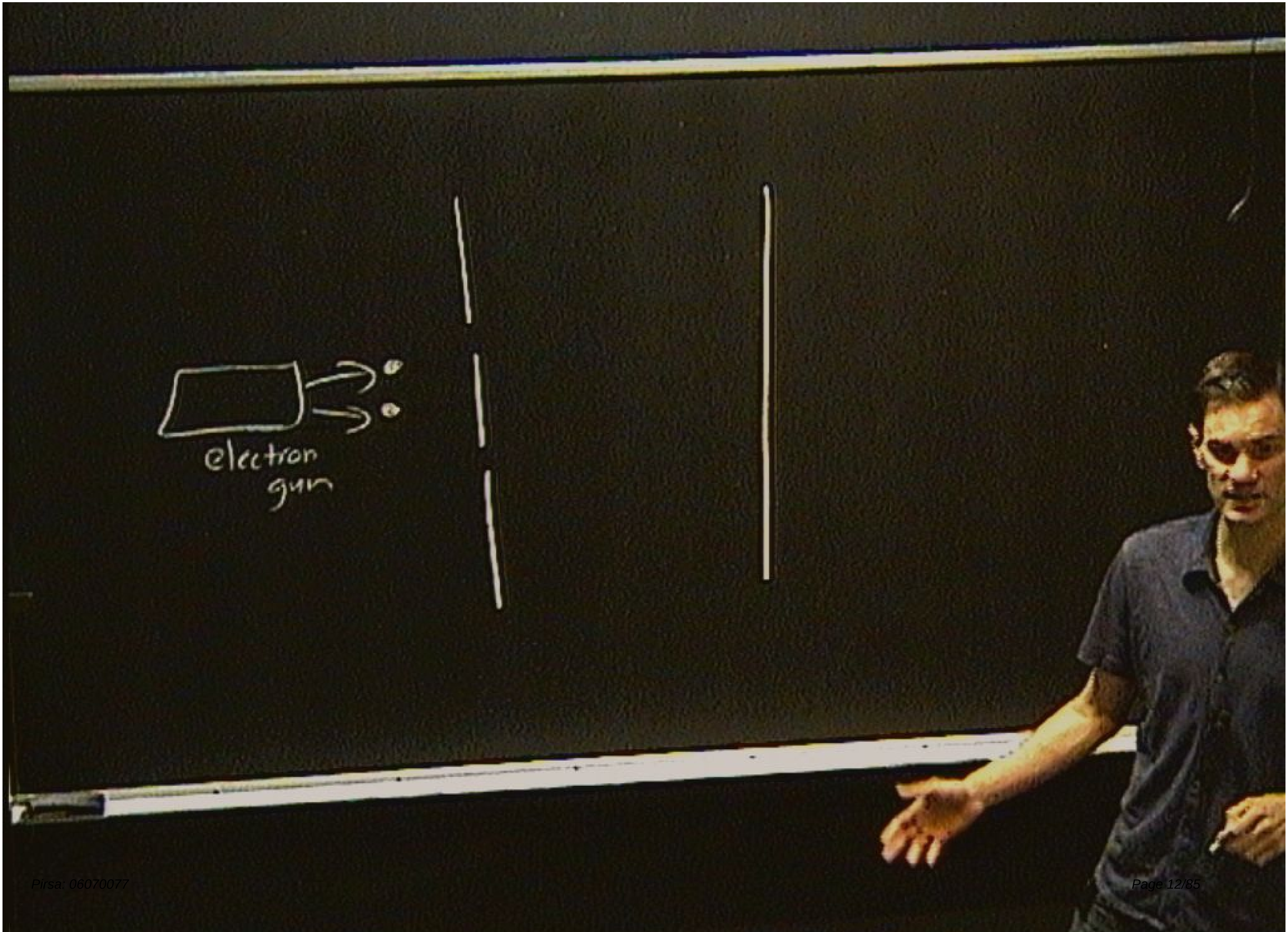


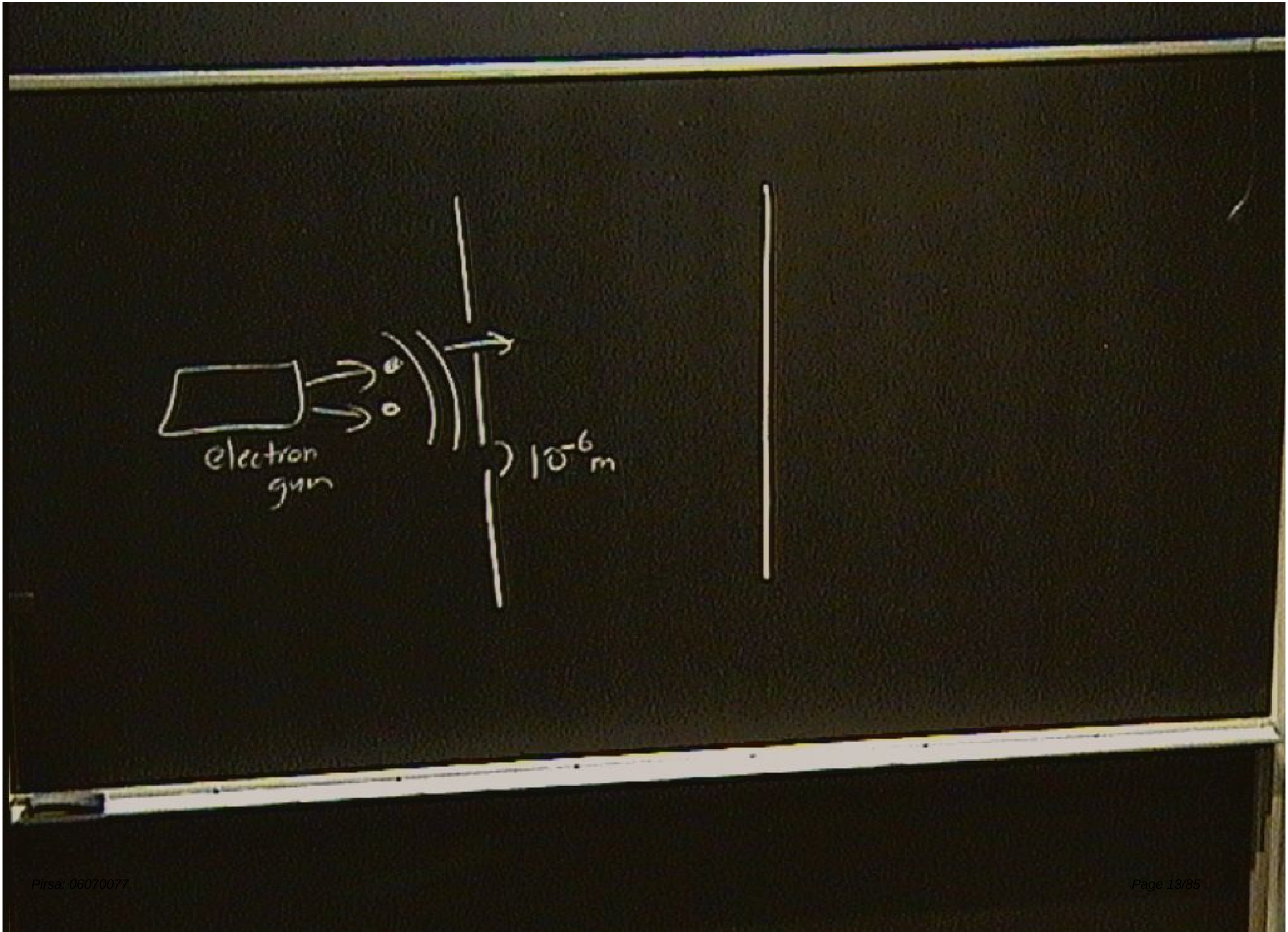

(1,1)
(2,1)
[1 0]
[0 1]
path 1
path 2
|(1,1)|² + |(2,1)|² = 1

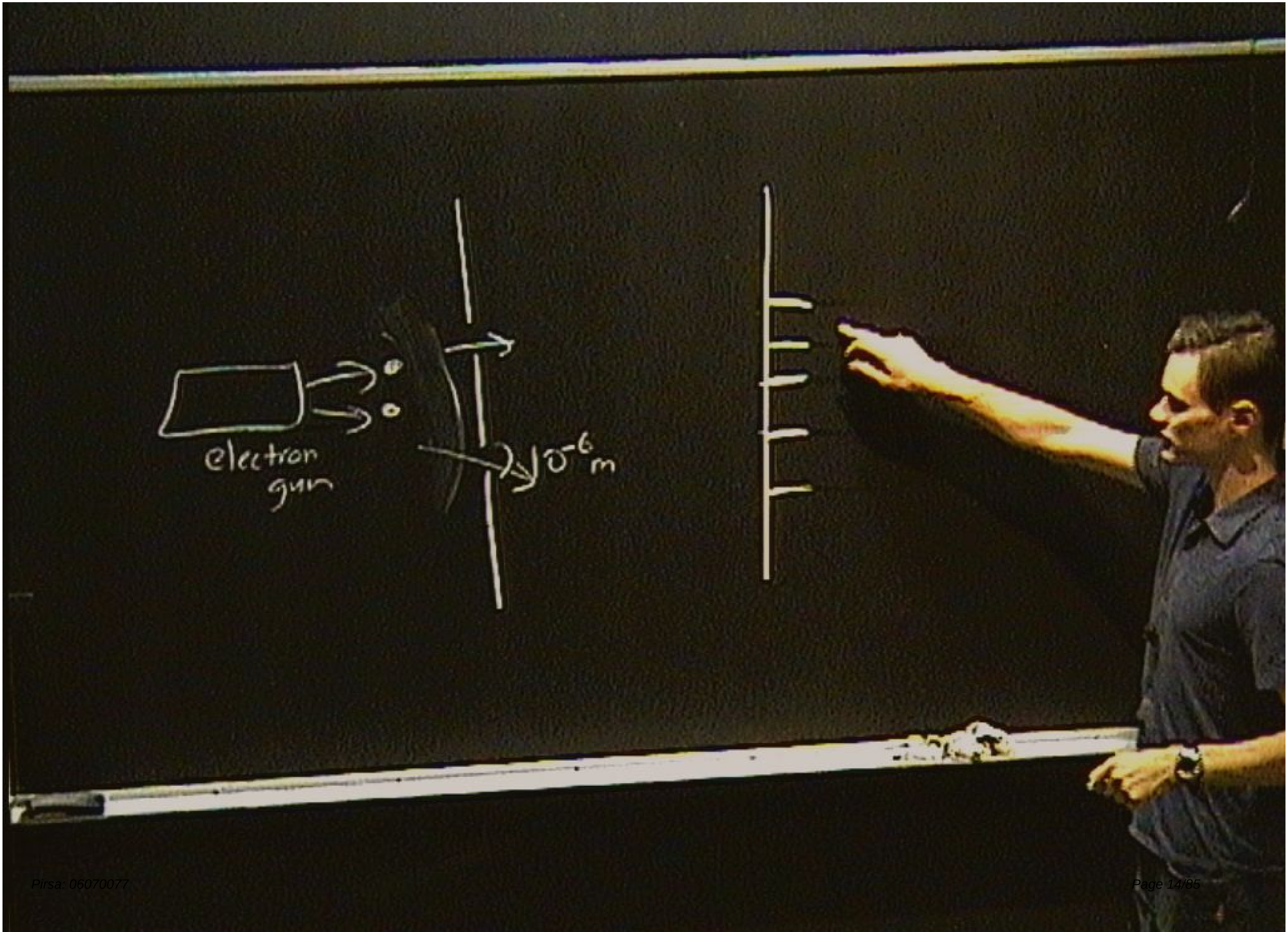

(1,1)
(2,1)
path 1
path 2
$|(1,1)|^2 + |(2,1)|^2 = 1$
$= \frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\end{bmatrix} + \frac{i}{\sqrt{2}}\begin{bmatrix}0\\1\end{bmatrix}$

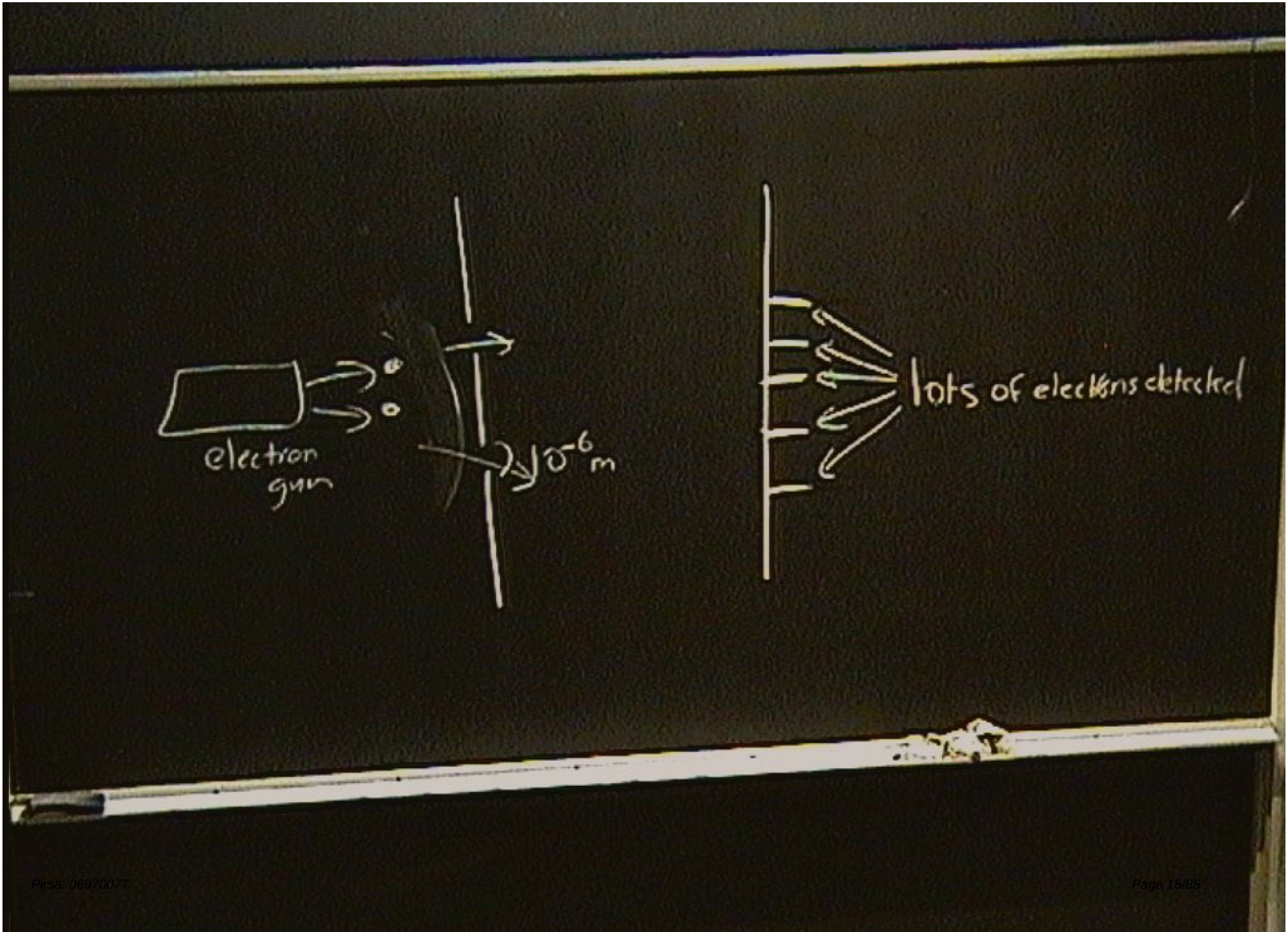

(1,1)
(2,1)
|(1,1)|^2 + |(2,1)|^2 = 1
path 1
path 2
= 1/√2 [1 0] + i/√2 [0 1]
AND

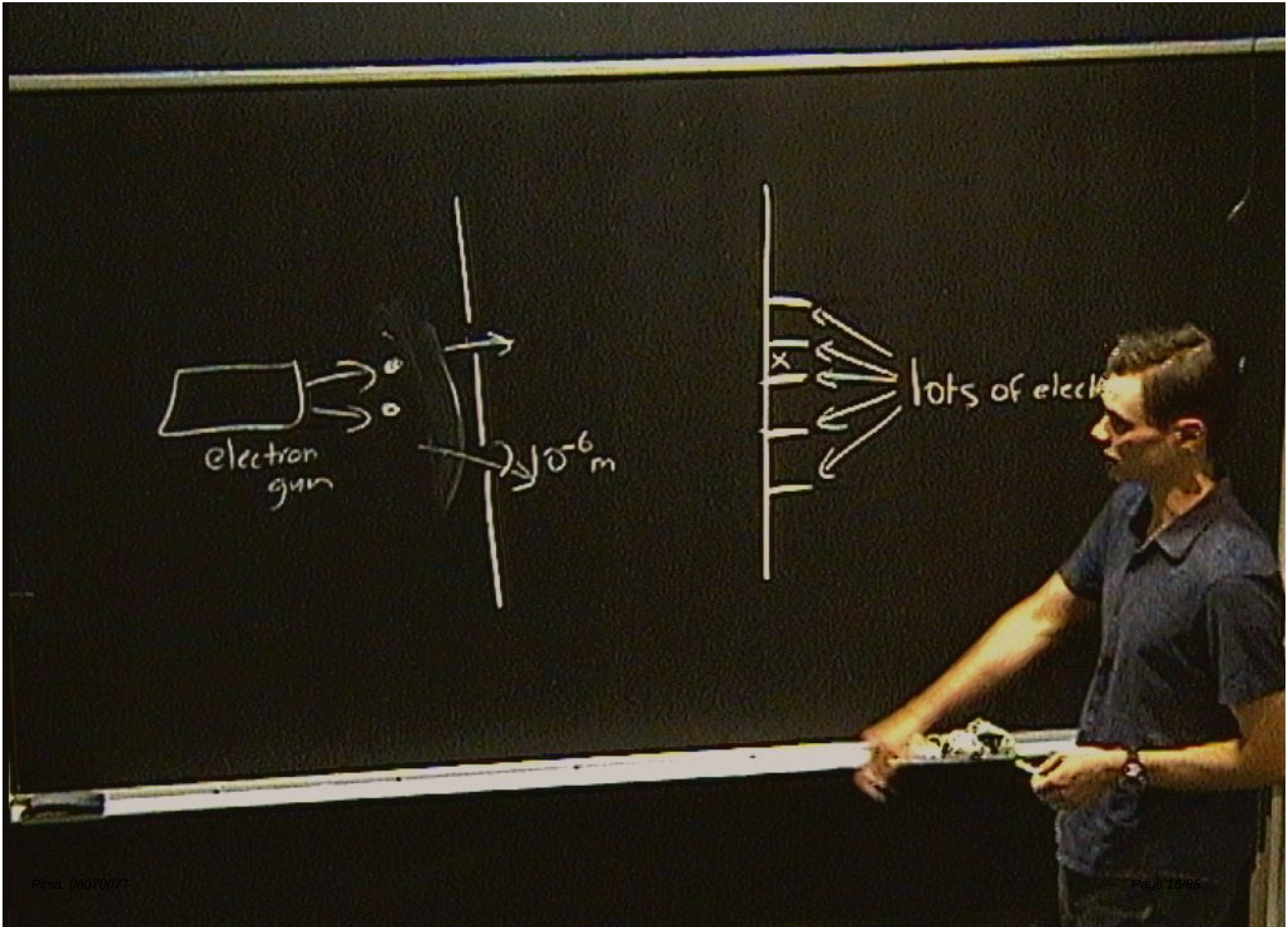

electron
gun

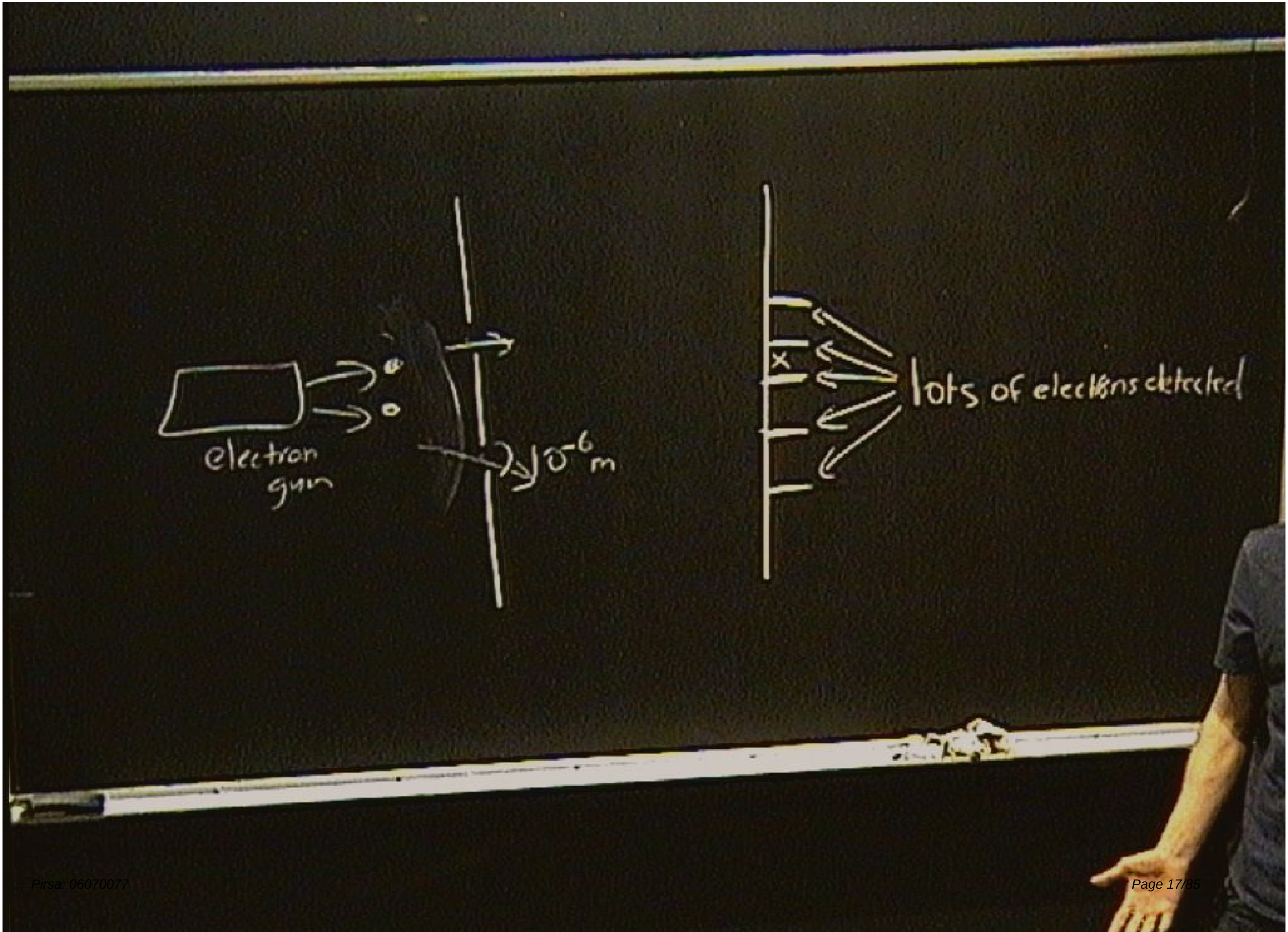

electron
gun

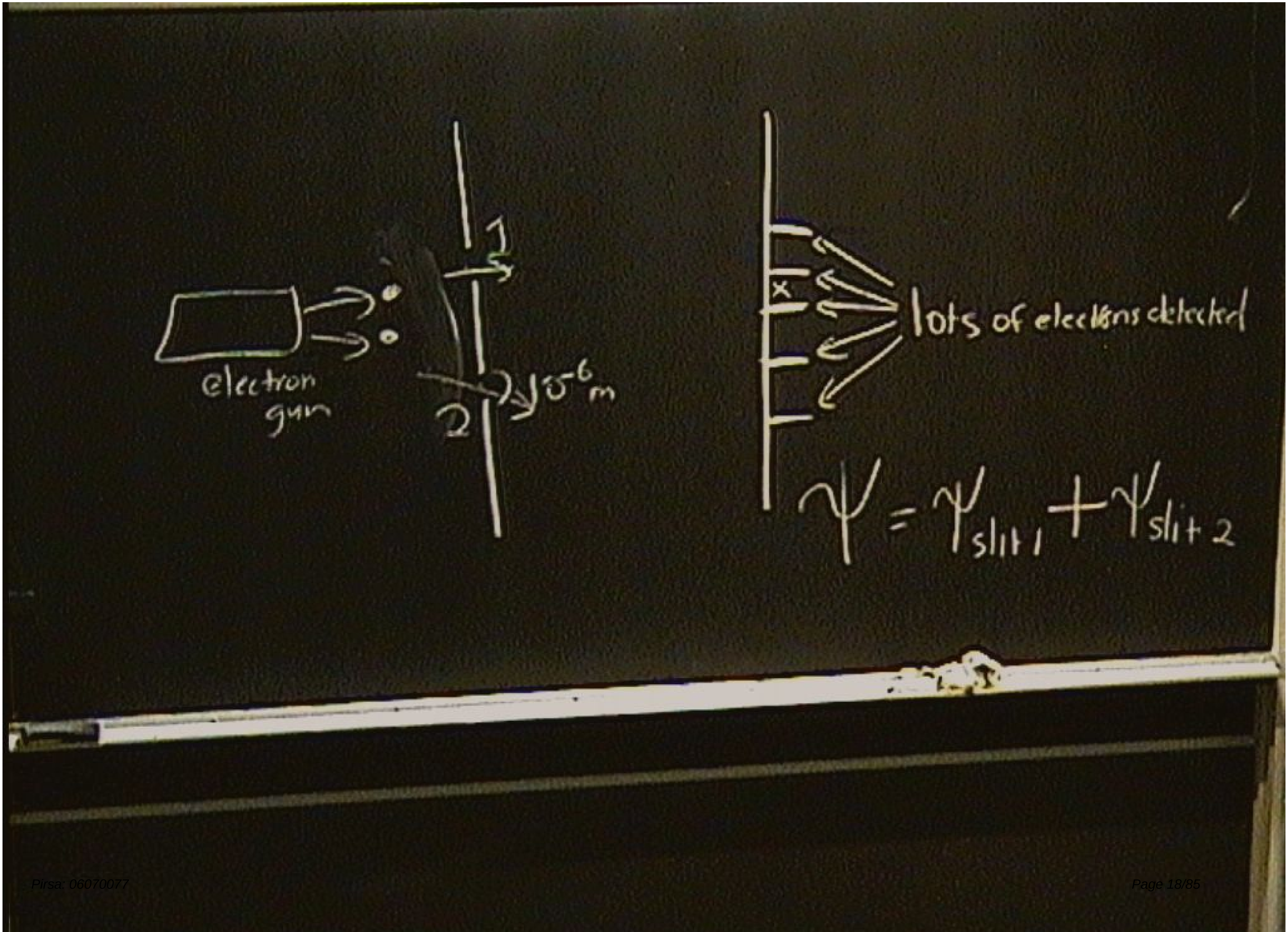

electron gun
10-6 m


electron
gun
10^{-6} m


electron gun
10^{-6} m
lots of electrons detected


electron gun
10^{-6} m
lots of elect


electron
gun
10^{-6} m
lots of electrons detected


electron gun
1
2
10^{-6} m
lots of electrons detected
$\psi = \psi_{slit\ 1} + \psi_{slit\ 2}$

- Superposition is a core defining feature of quantum theory (*The* defining feature?)
- Core aspect of quantum phenomena such as entanglement, quantum tunnelling and quantum interference in general

Core feature 2: Genuine Randomness

- Let us think about, say, the 467th photon to pass through the first half-silvered mirror.

- Can we predict whether it will take path 1 or 2?

- Surely we can as physics is predictable and 'deterministic'?

Core feature 1: Superposition

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- 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
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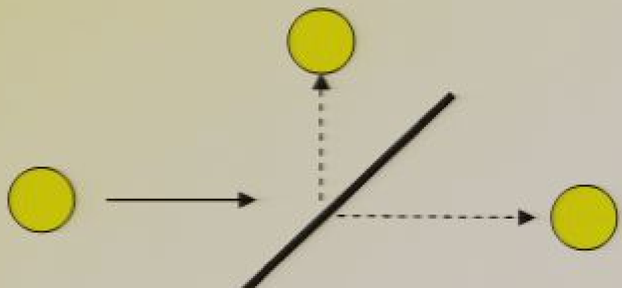

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- *"We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at any given moment knew all of the forces that animate nature and the mutual positions of the beings that compose it, if this intellect were vast enough to submit the data to analysis, could condense into a single formula the movement of the greatest bodies of the universe and that of the lightest atom; for such an intellect nothing could be uncertain and the future just like the past would be present before its eyes."*
  — Marquis Pierre Simon de Laplace.

- Quantum physics says no.

- 50-50 probability that it will take each path. *Genuinely random event.*
- Radically different from Newtonian physics.
- Second core defining feature of quantum theory.
- "The quantum casino."
- Another example, radioactive decay

- Commerically available quantum random number generators. Genuinely random numbers.

- Idquantique, Geneva, Switzerland.
- http://www.idquantique.com

- “When random numbers cannot be left to chance!”

- Uses include “gambling, lotteries”

- when we have a photon or any other quantum entity in a "superposition state" that includes multiple paths, it is impossible to predict with certainty which one we will measure the entity to take.
- Cannot predict with certain whether we will see Schroedinger's cat as being dead or alive upon opening the box.
- Genuine randomness (indeterminism) runs throughout quantum theory
- deep philosophical consequences. Is the world, fundamentally, one big casino?

Core feature 1: Superposition

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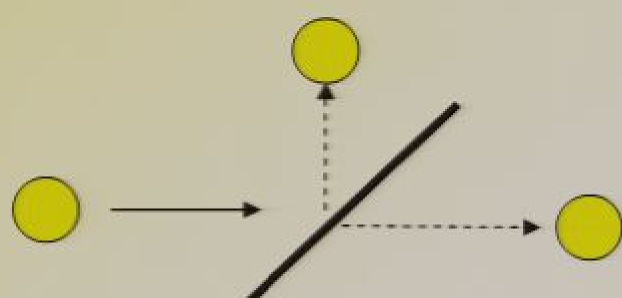


- when we have a photon or any other quantum entity in a “superposition state” that includes multiple paths, it is impossible to predict with certainty which one we will measure the entity to take.

- Cannot predict with certain whether we will see Schroedinger’s cat as being dead or alive upon opening the box.

- Genuine randomness (indeterminism) runs throughout quantum theory

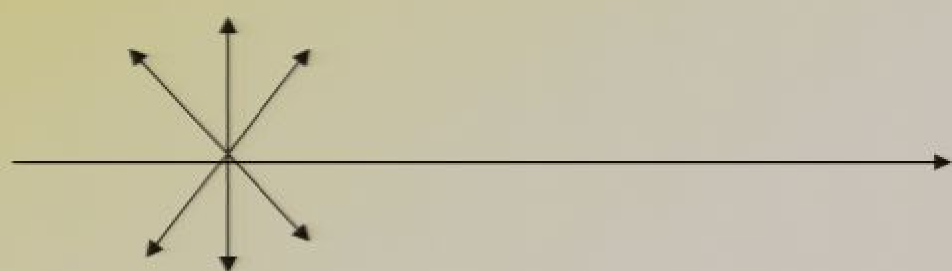
- deep philosophical consequences. Is the world, fundamentally, one big casino?

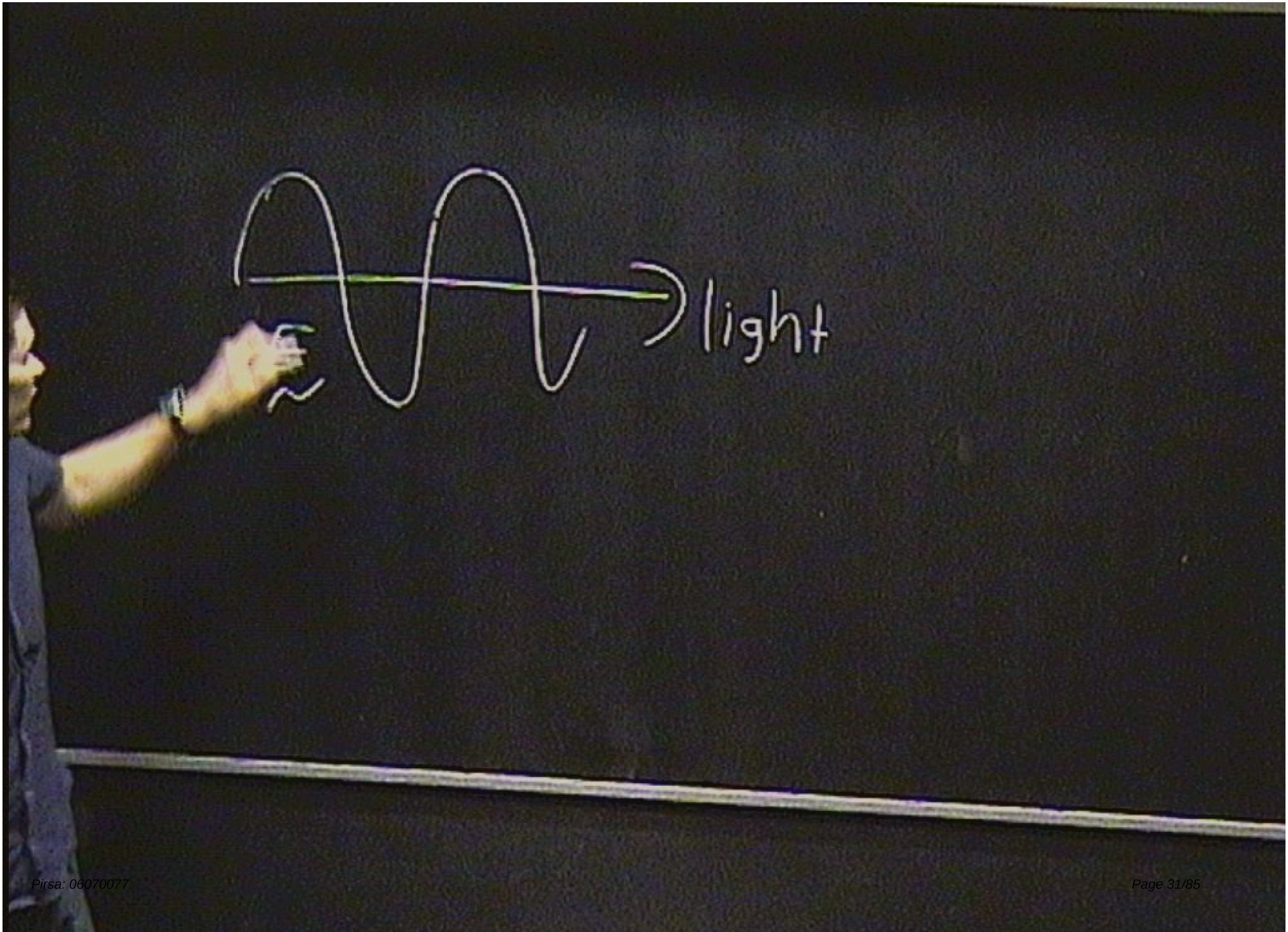
- Hard to get one’s head around the idea of things just happening for no reason whatsoever.
- Just spontaneously occur (acausal)
- Is this really possible philosophically (metaphysically)?

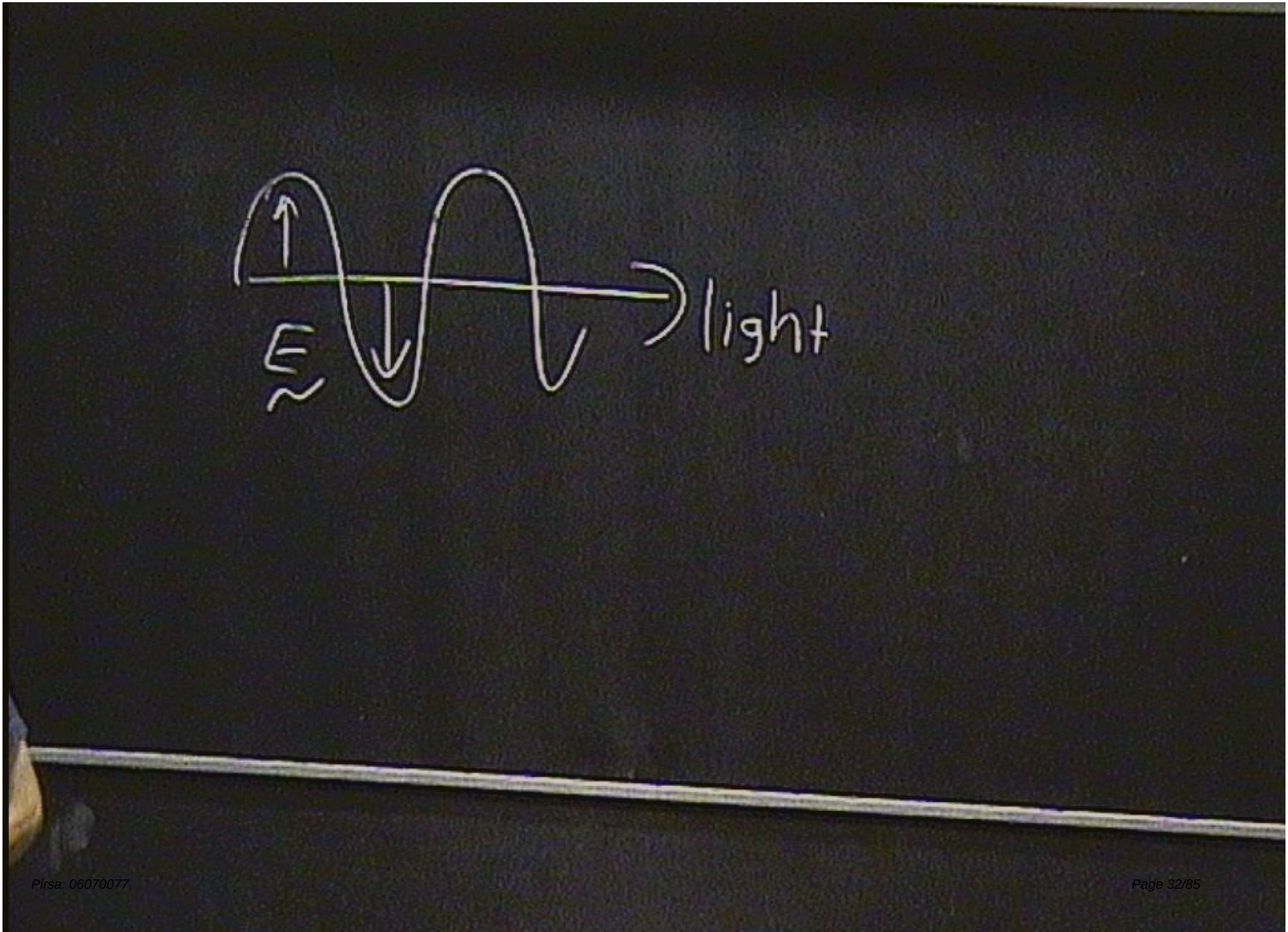
Polarization

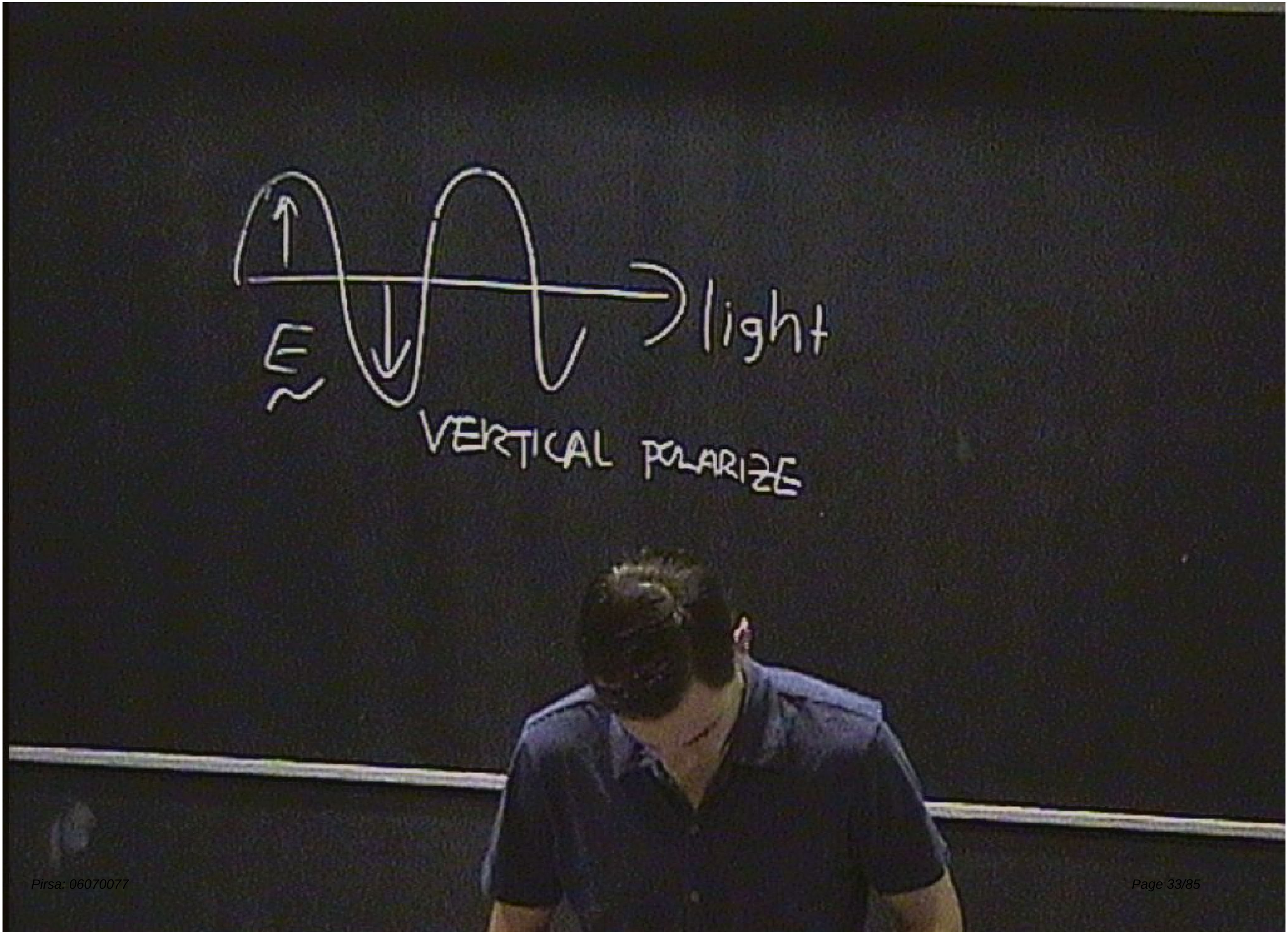
- We can think of light as consisting of transverse wave-like oscillations

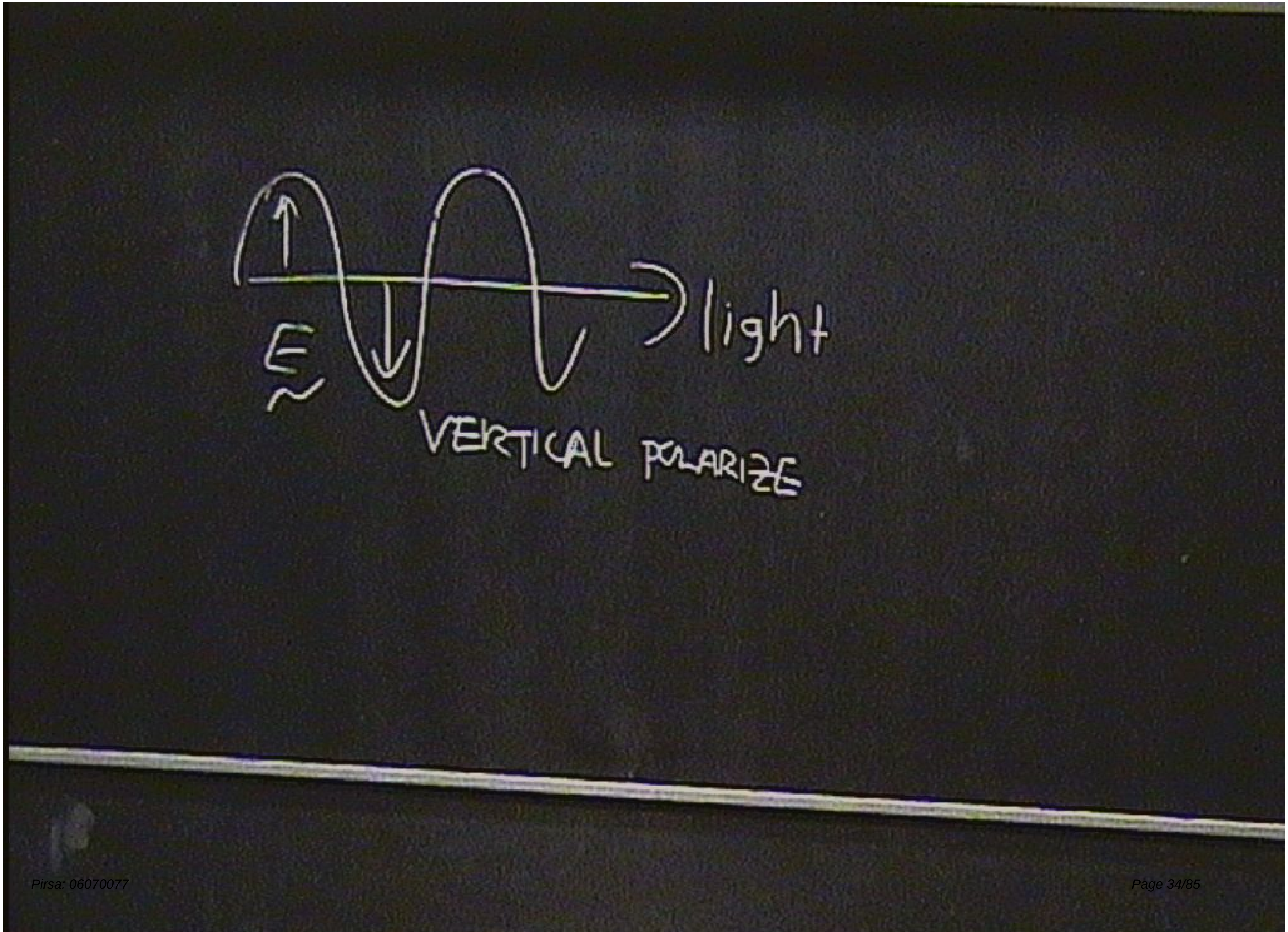
- For *polarized light*, these oscillations occur in just one plane.

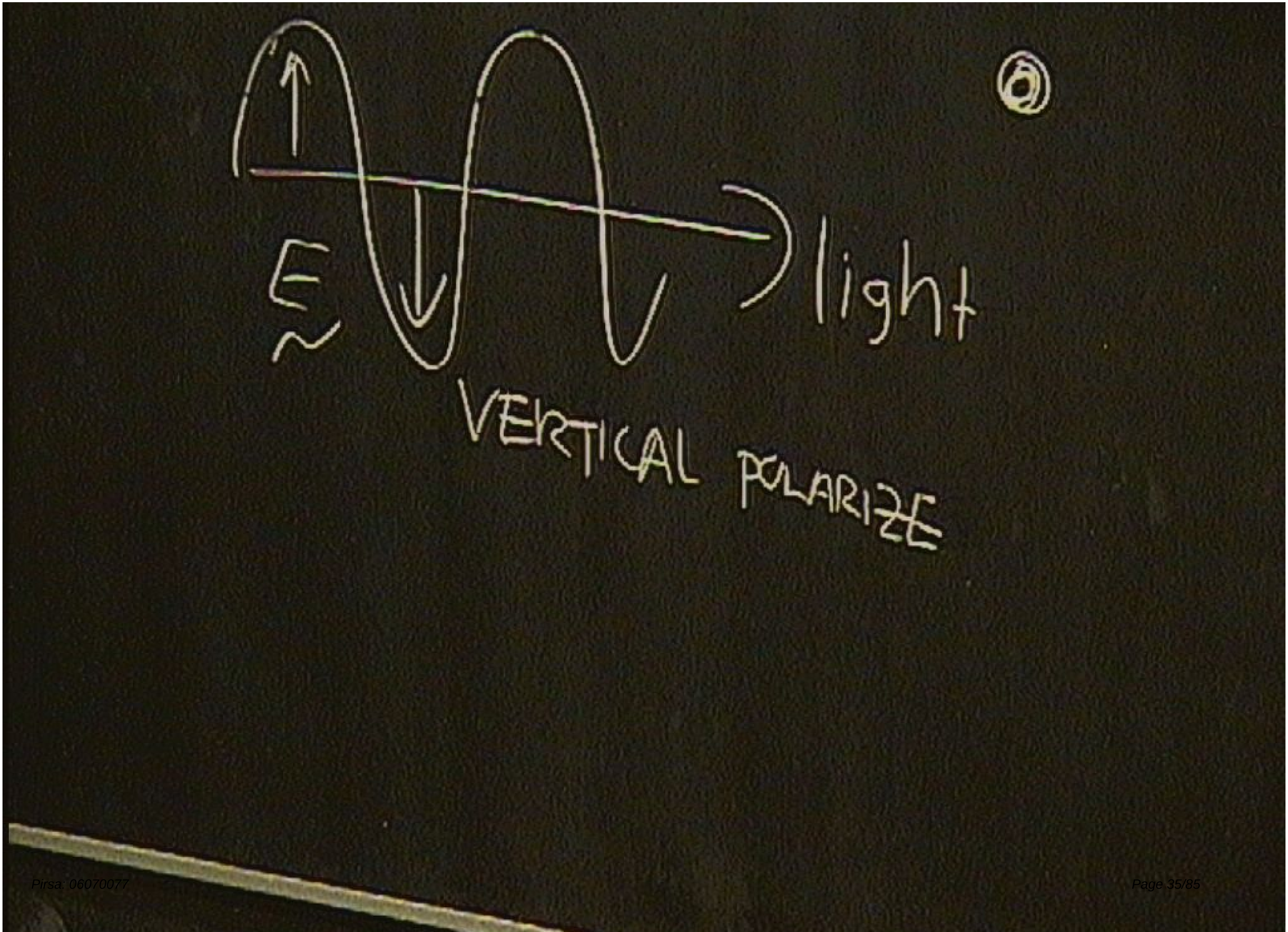


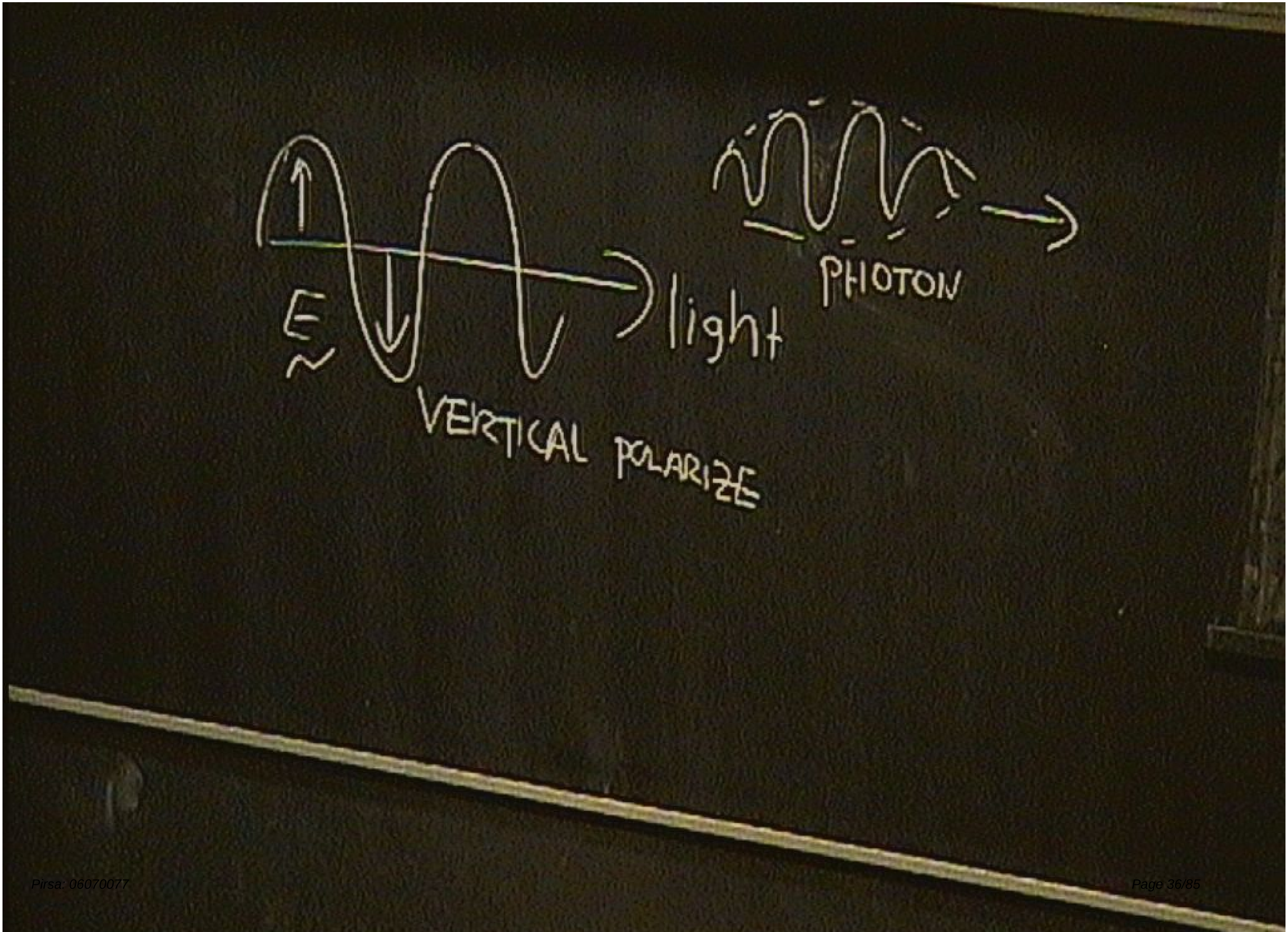

light

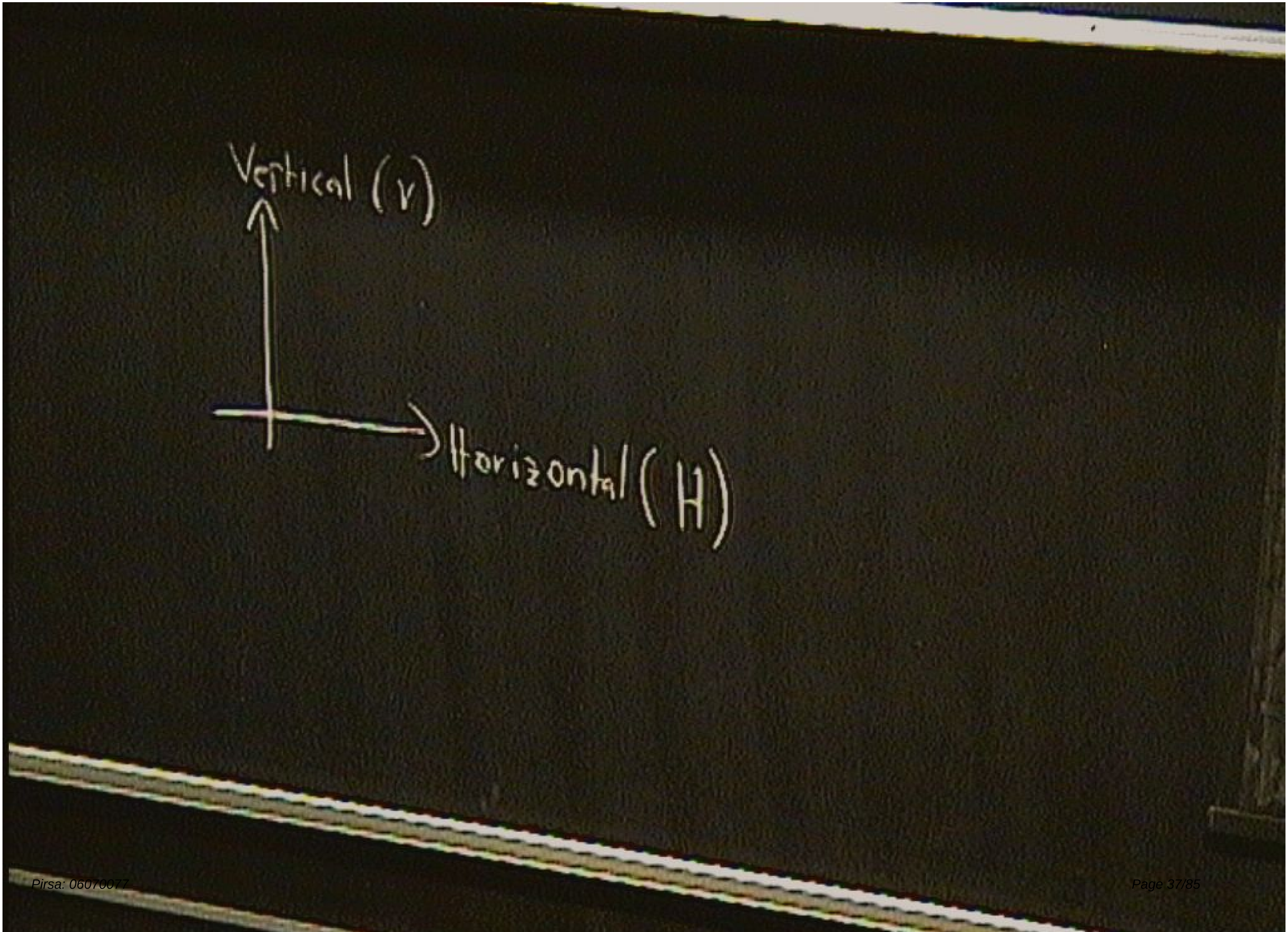

E
light

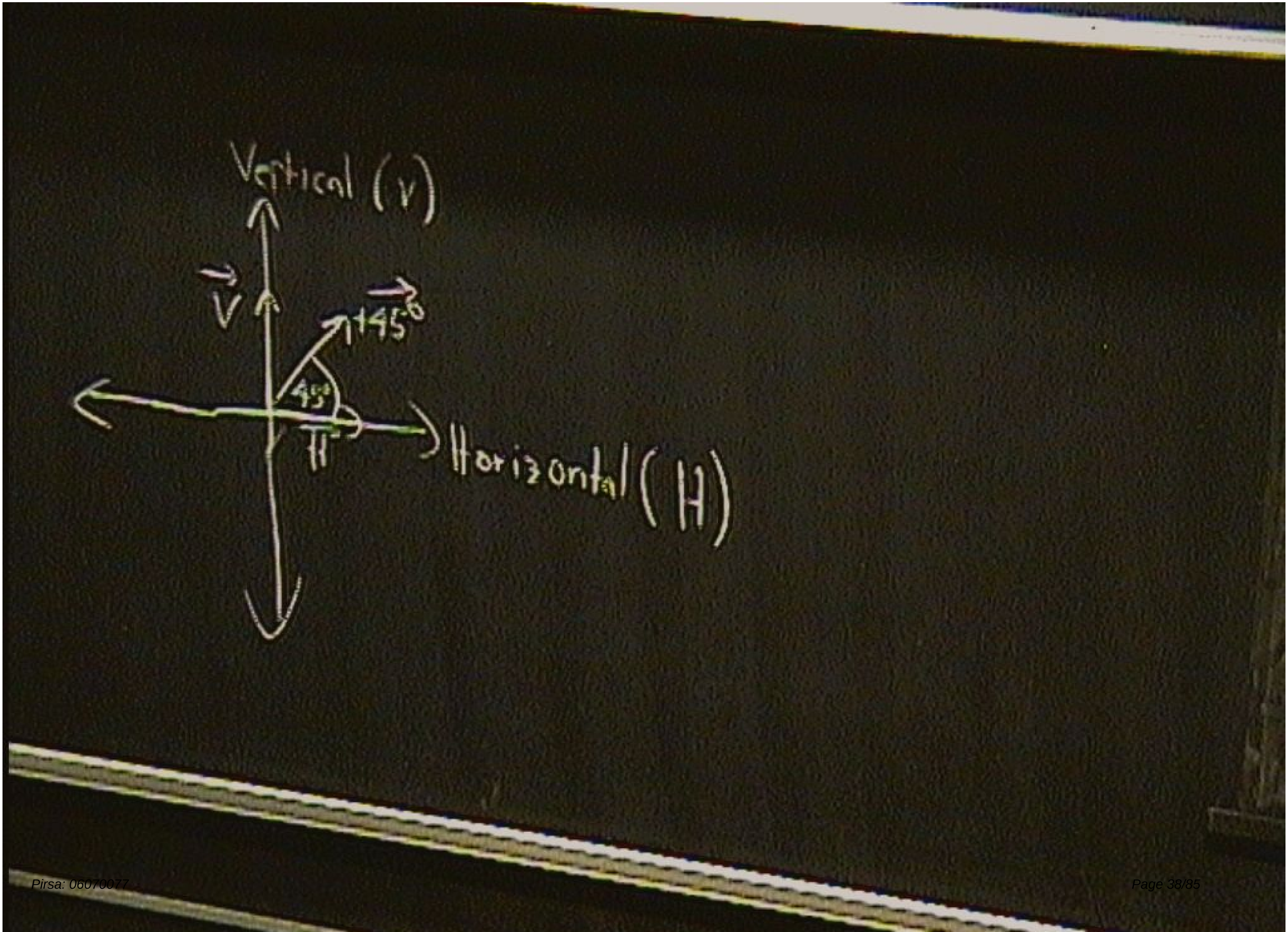

E
light
VERTICAL POLARIZE

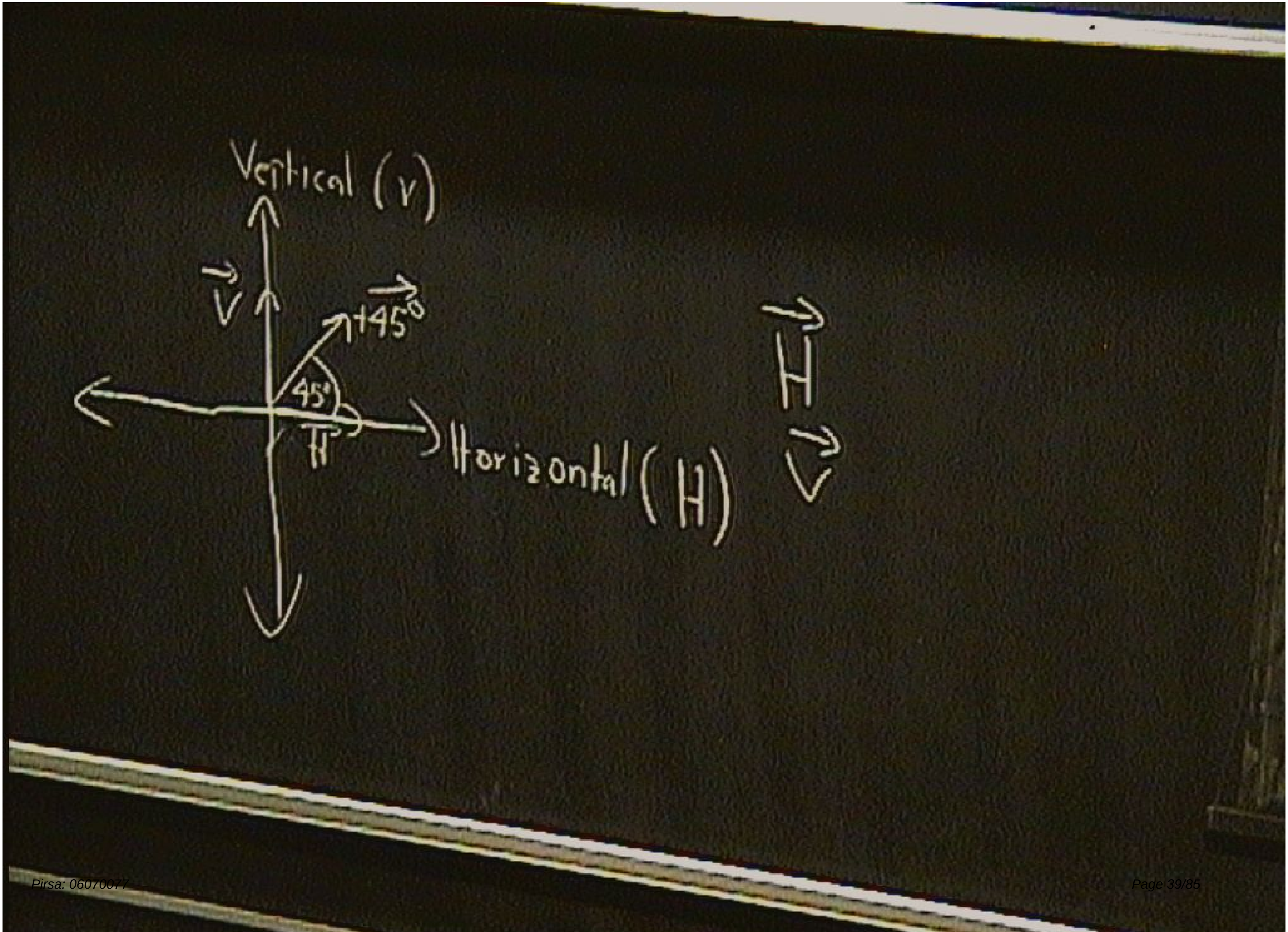

E
light
VERTICAL POLARIZE


E
light
VERTICAL POLARIZE

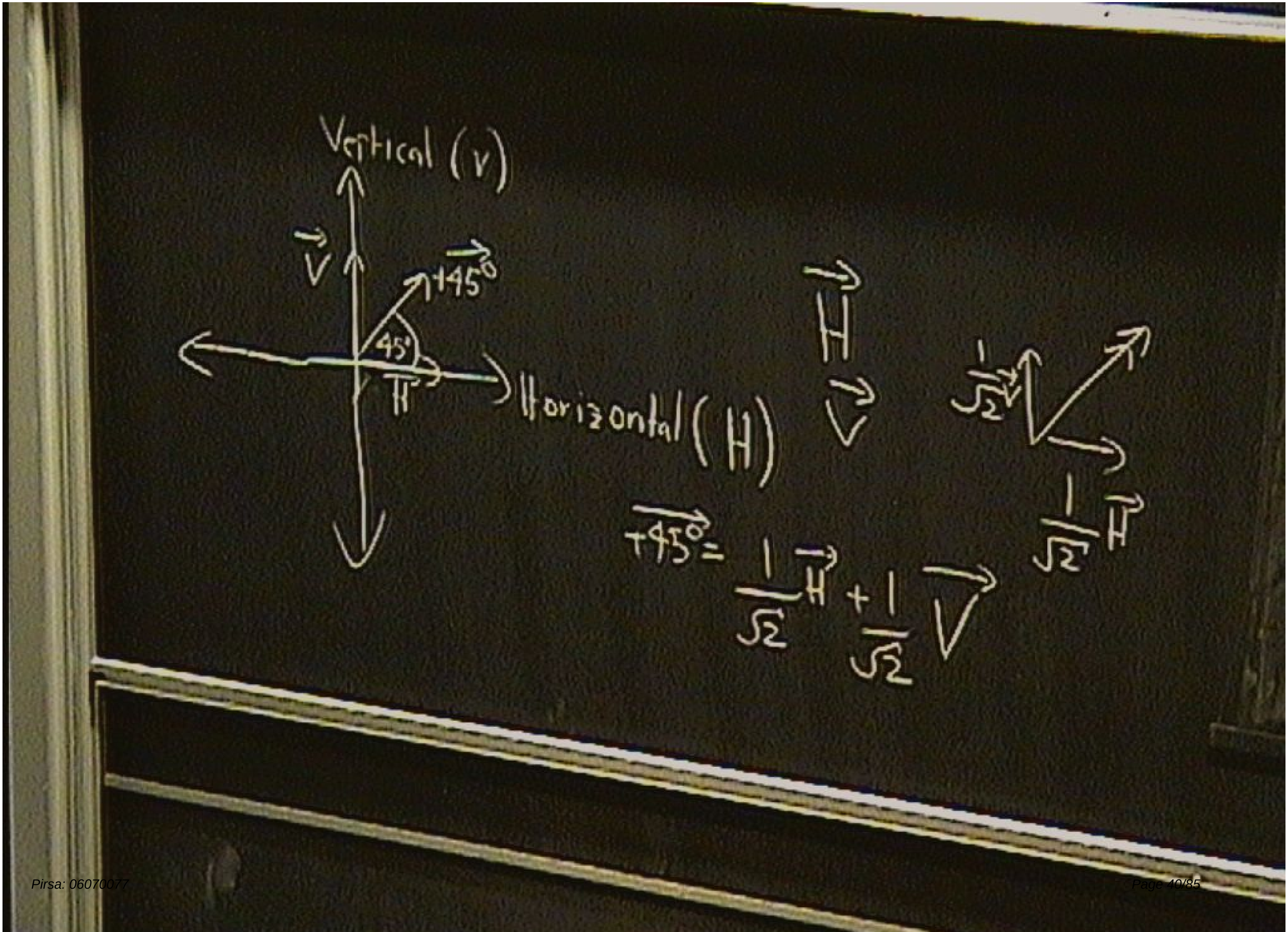

E
light
VERTICAL POLARIZE
PHOTON


Vertical (V)
Horizontal (H)

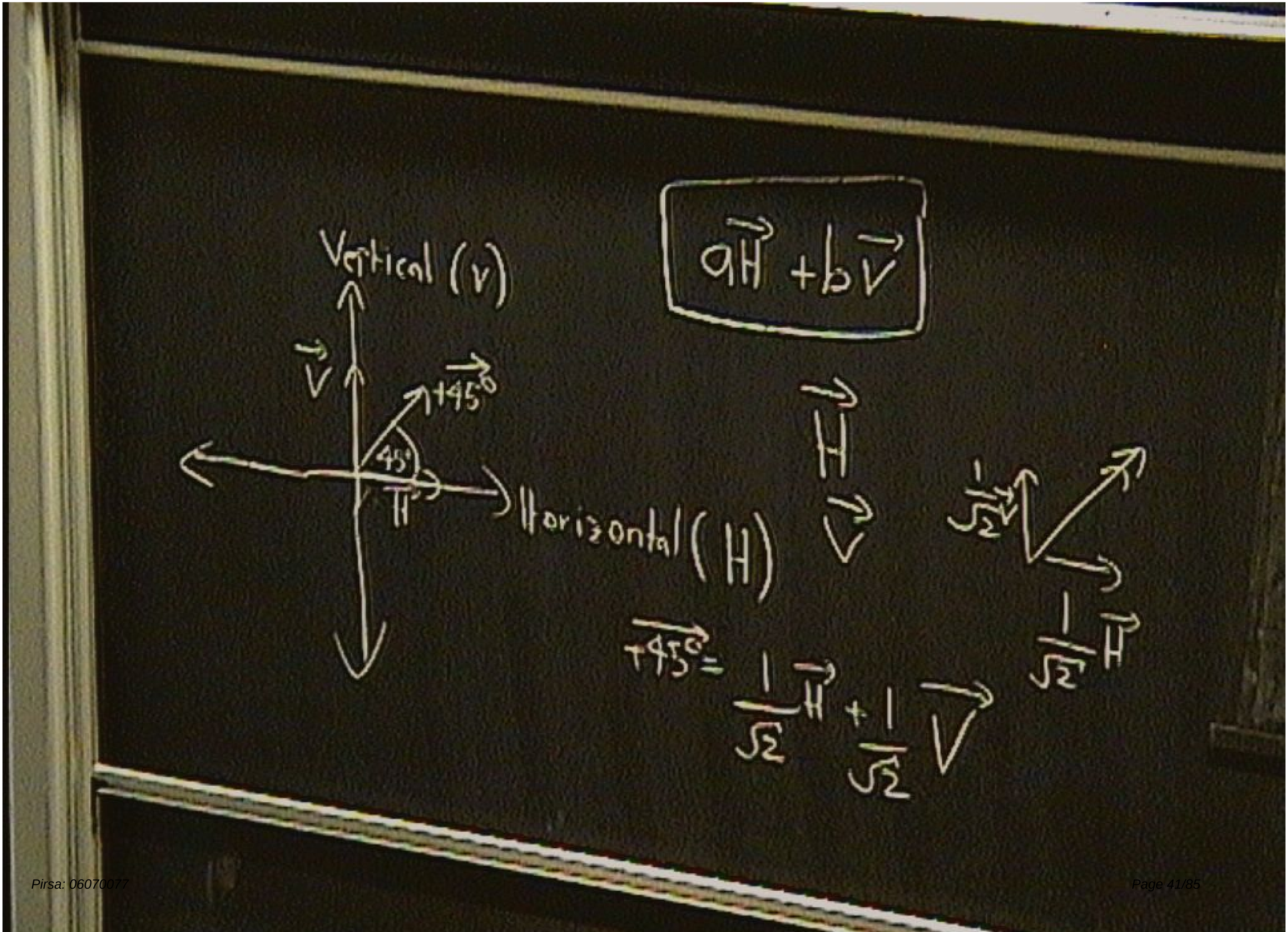

Vertical (V)
$\vec{V}$
$\vec{+45°}$
45°
H
Horizontal (H)



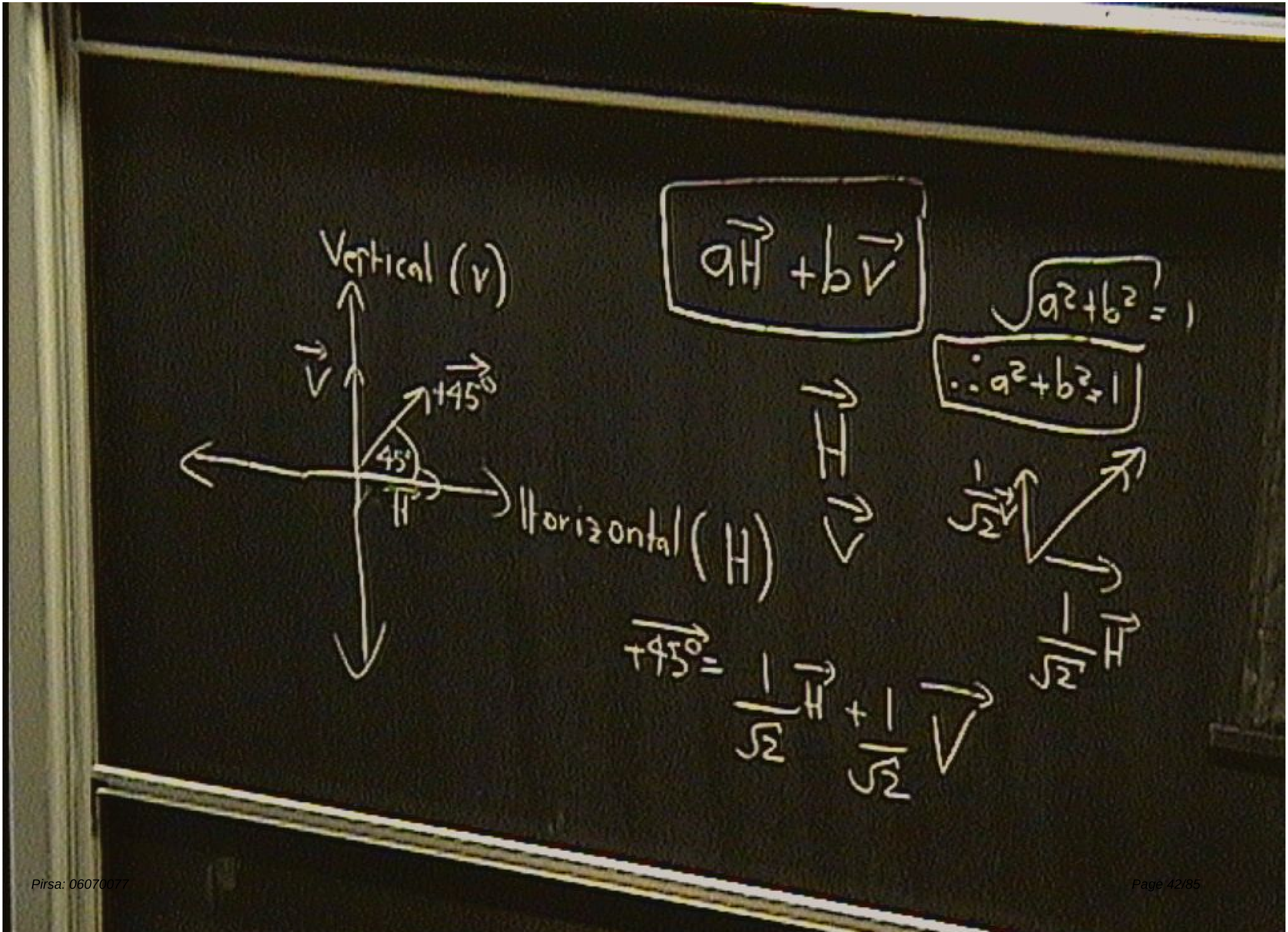
Vertical (V)
$\vec{V}$
$\overrightarrow{+45°}$
45°
$\vec{H}$
Horizontal (H)
$\vec{H}$
$\vec{V}$

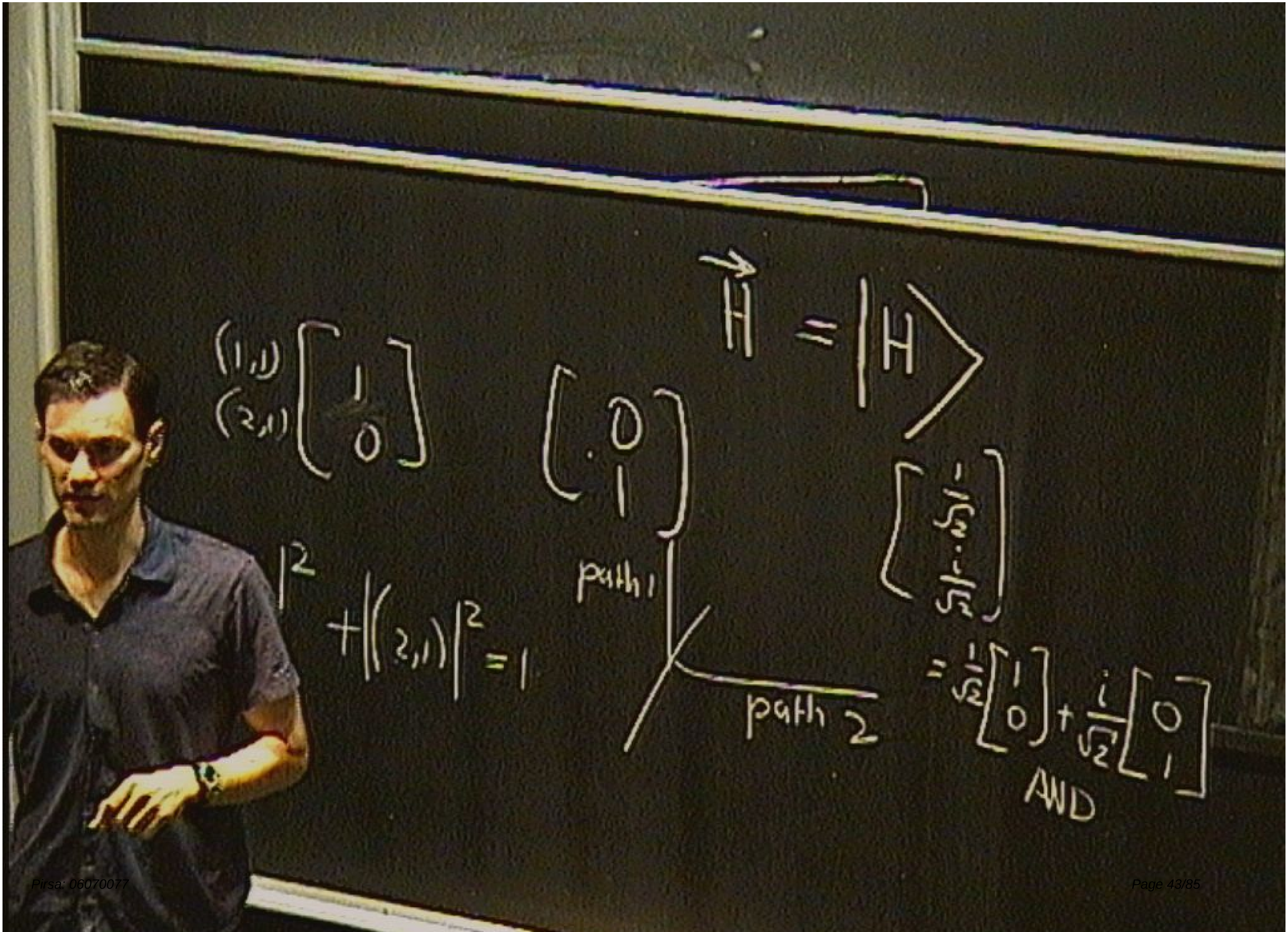


Vertical (V)
$\vec{V}$
$\vec{+45^\circ}$
45°
$\vec{H}$
Horizontal (H)
$\vec{H}$
$\vec{V}$
$\frac{1}{\sqrt{2}}\vec{V}$
$\frac{1}{\sqrt{2}}\vec{H}$
$\vec{+45^\circ} = \frac{1}{\sqrt{2}}\vec{H} + \frac{1}{\sqrt{2}}\vec{V}$

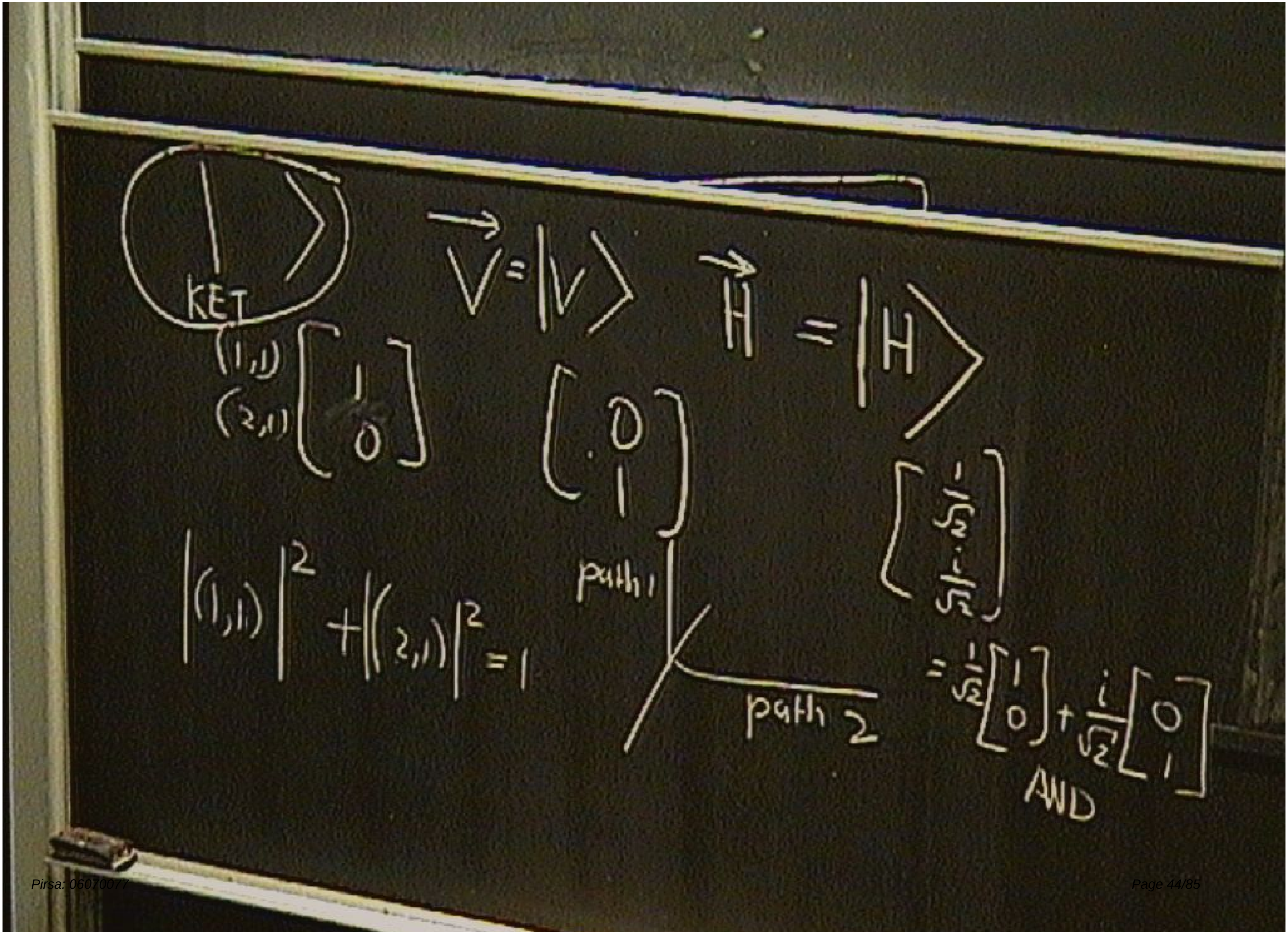


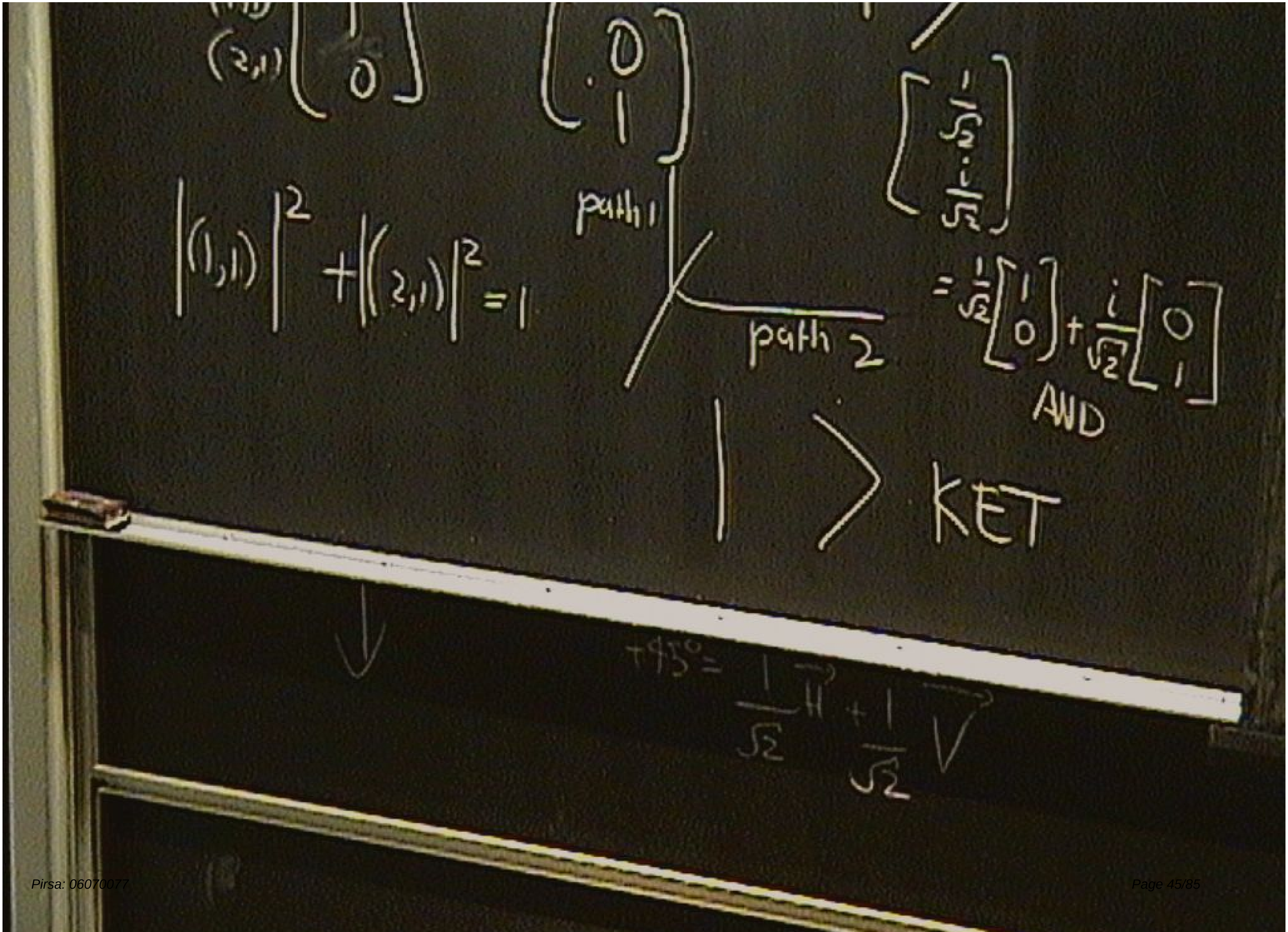
$a\vec{H} + b\vec{V}$
Vertical (v)
Horizontal (H)
$\vec{V}$
$\vec{H}$
$\vec{+45^\circ}$
45°
$\vec{+45^\circ} = \frac{1}{\sqrt{2}}\vec{H} + \frac{1}{\sqrt{2}}\vec{V}$
$\frac{1}{\sqrt{2}}\vec{V}$
$\frac{1}{\sqrt{2}}\vec{H}$


Vertical (V)
Horizontal (H)
+45°
45°
$a\vec{H} + b\vec{V}$
$\sqrt{a^2+b^2} = 1$
$\therefore a^2+b^2=1$
$\vec{+45^\circ} = \frac{1}{\sqrt{2}}\vec{H} + \frac{1}{\sqrt{2}}\vec{V}$
$\frac{1}{\sqrt{2}}\vec{V}$
$\frac{1}{\sqrt{2}}\vec{H}$

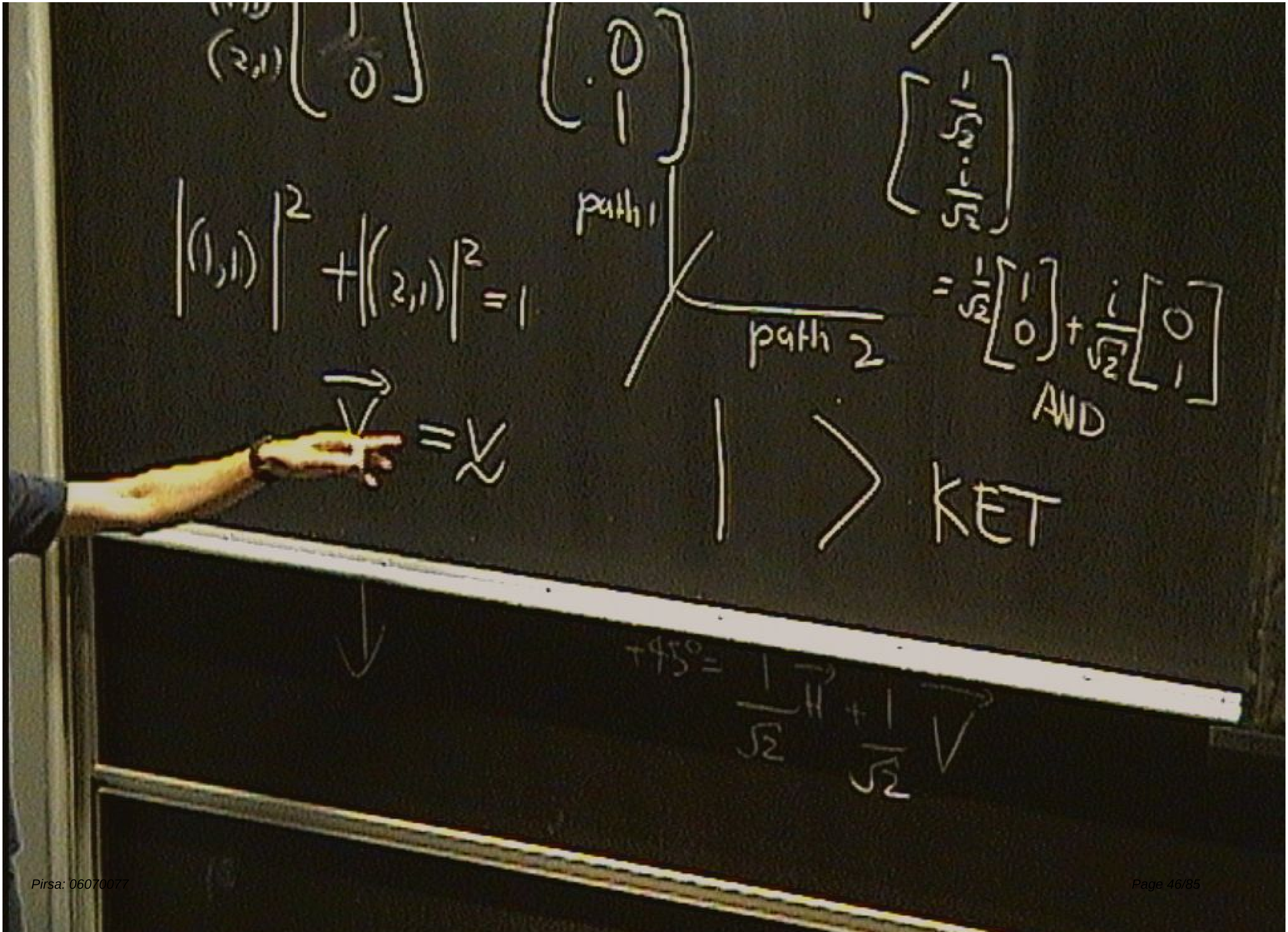


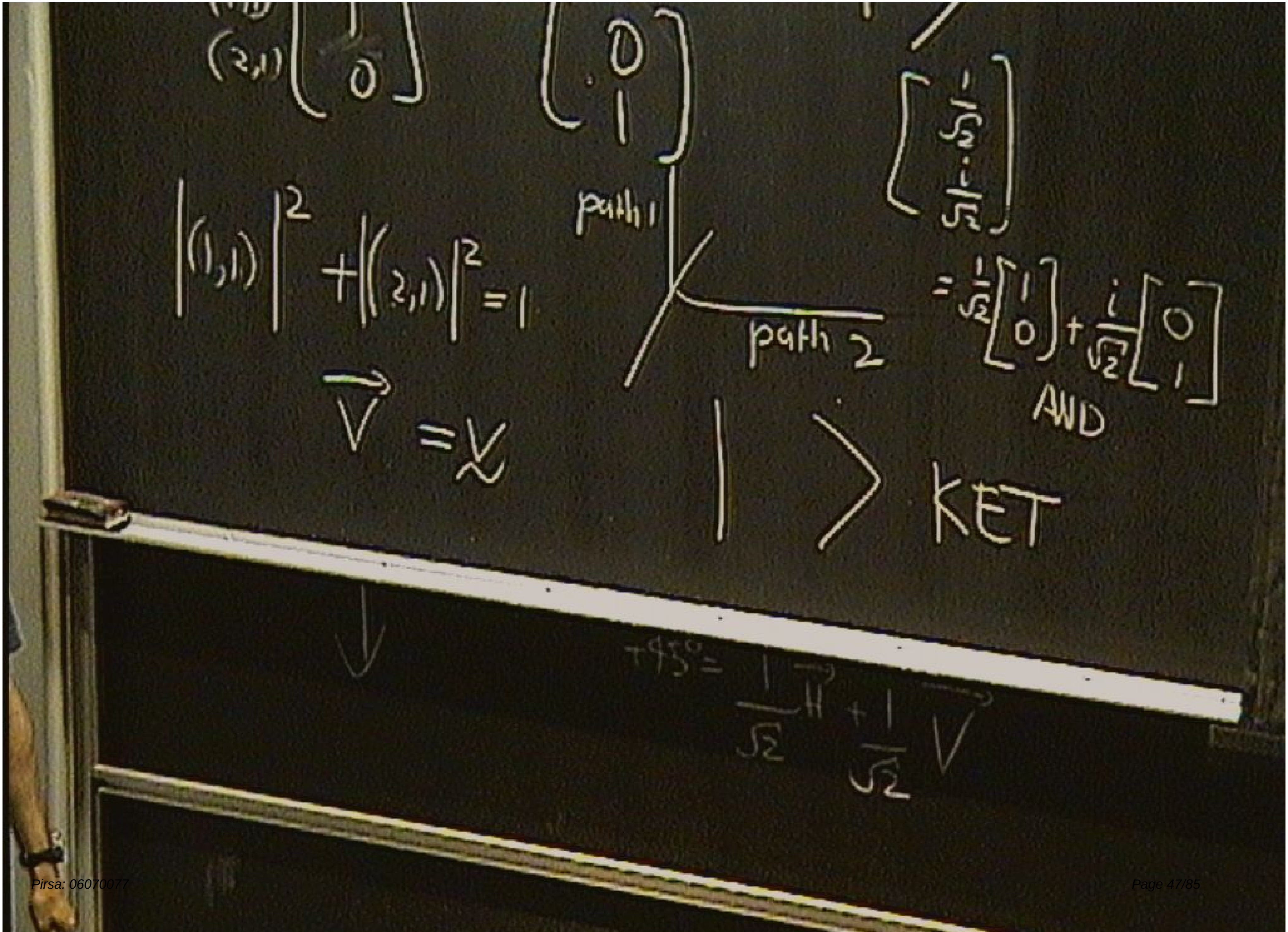
H = |H⟩
(1,1)
(2,1)
+|(2,1)|² = 1
path 1
path 2
AND

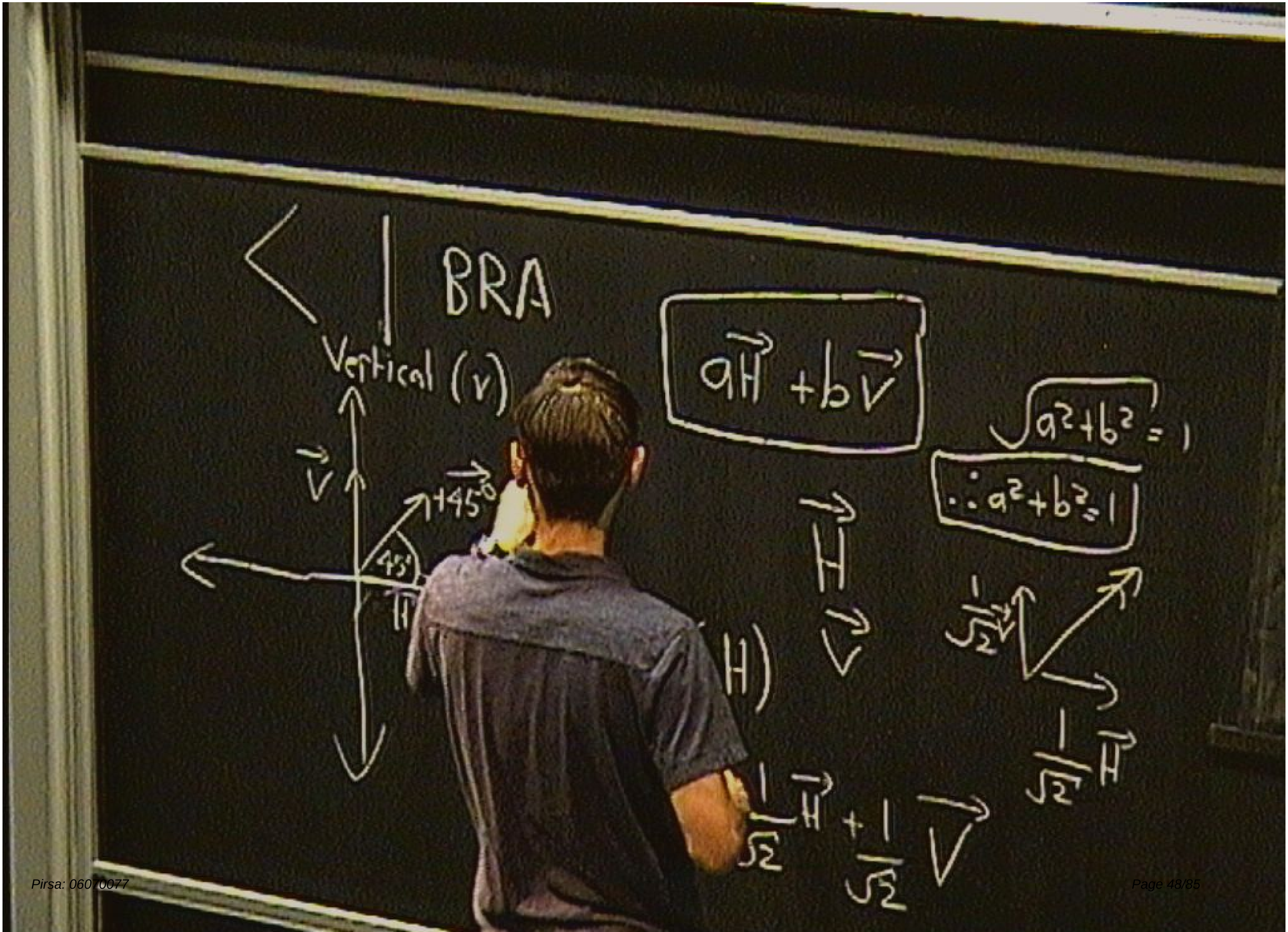

KET
path 1
path 2
AND

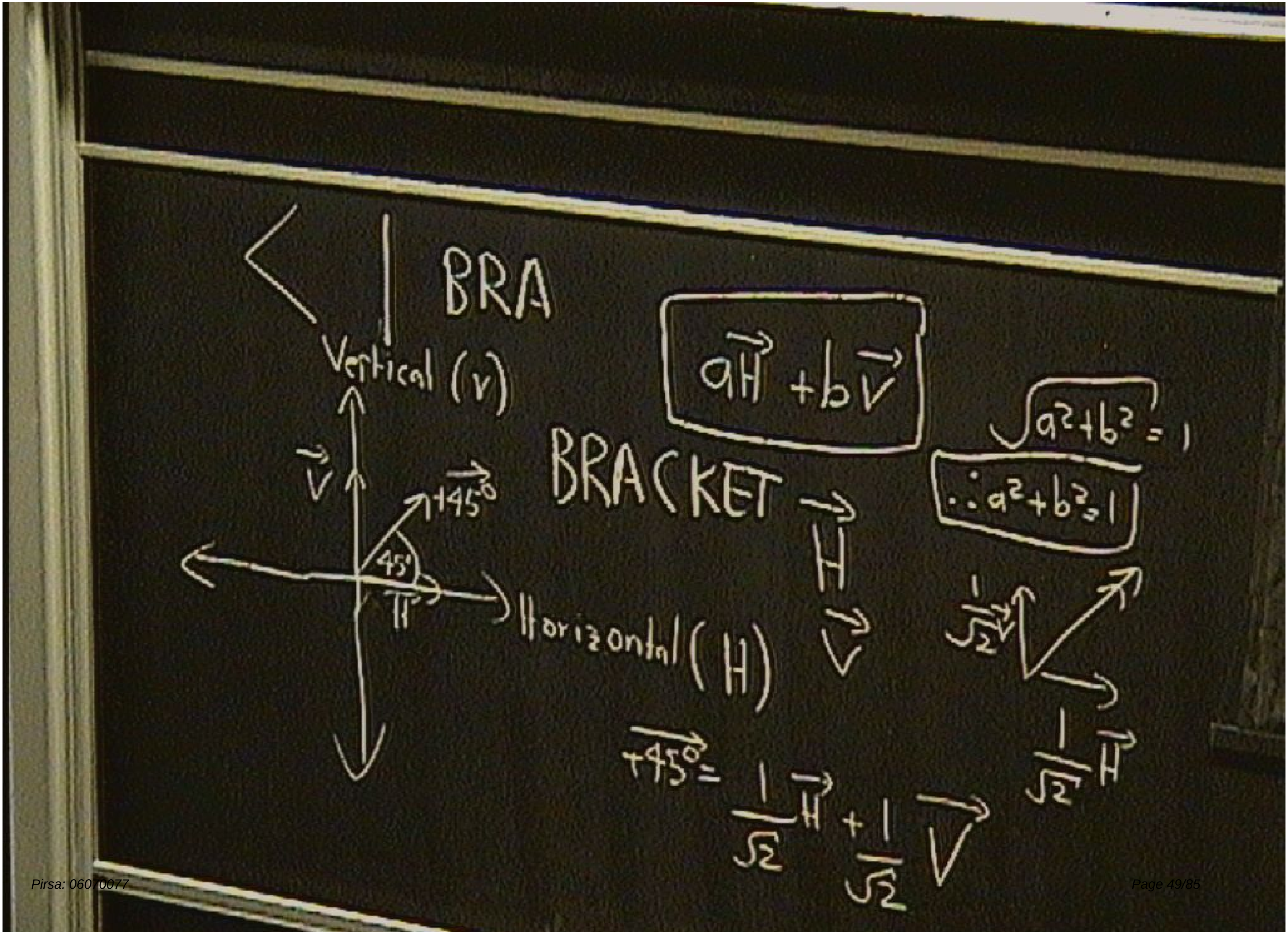


path 1
path 2
AND
KET

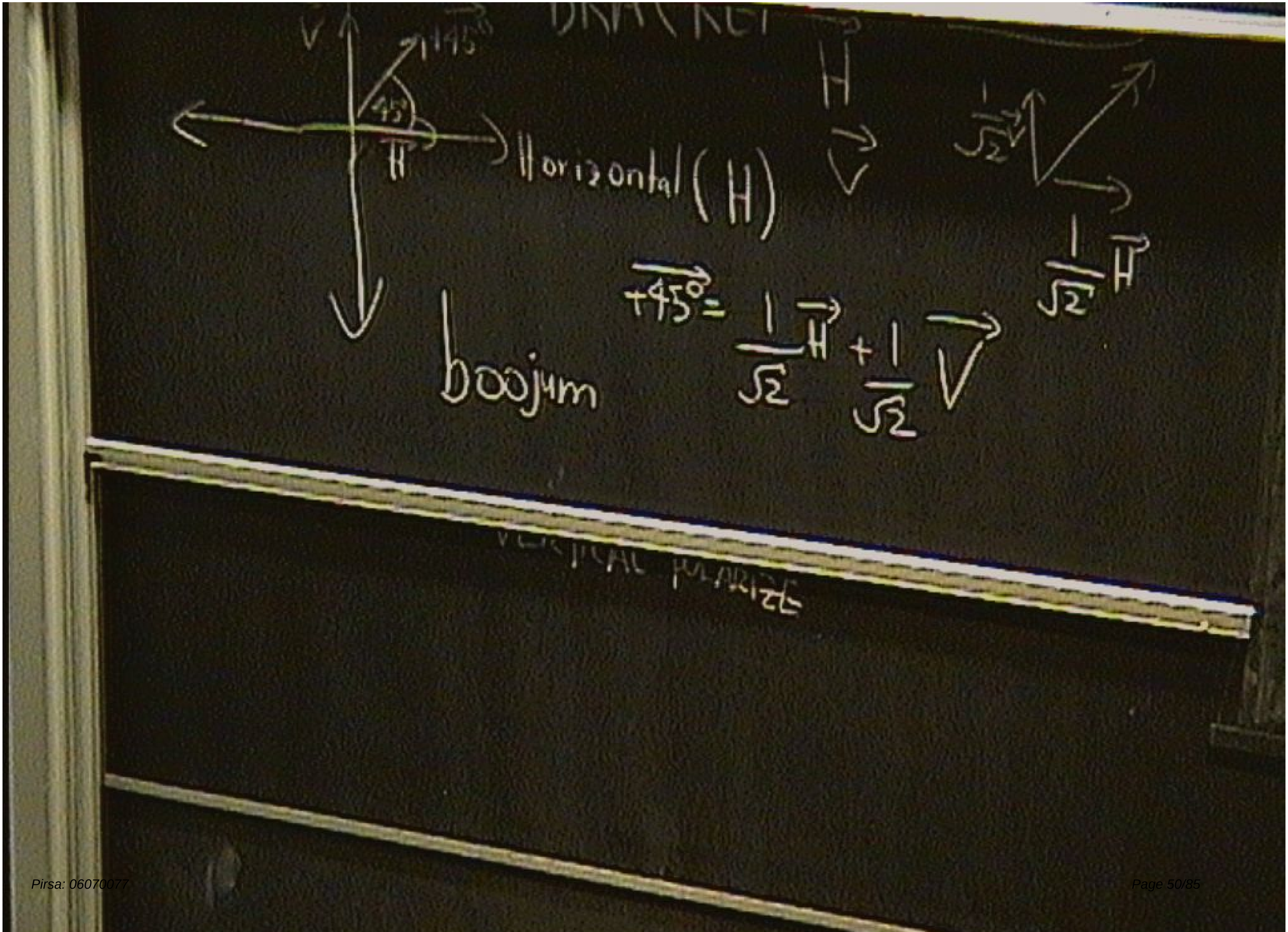

(2,1)
path 1
path 2
AND
KET
+45° =

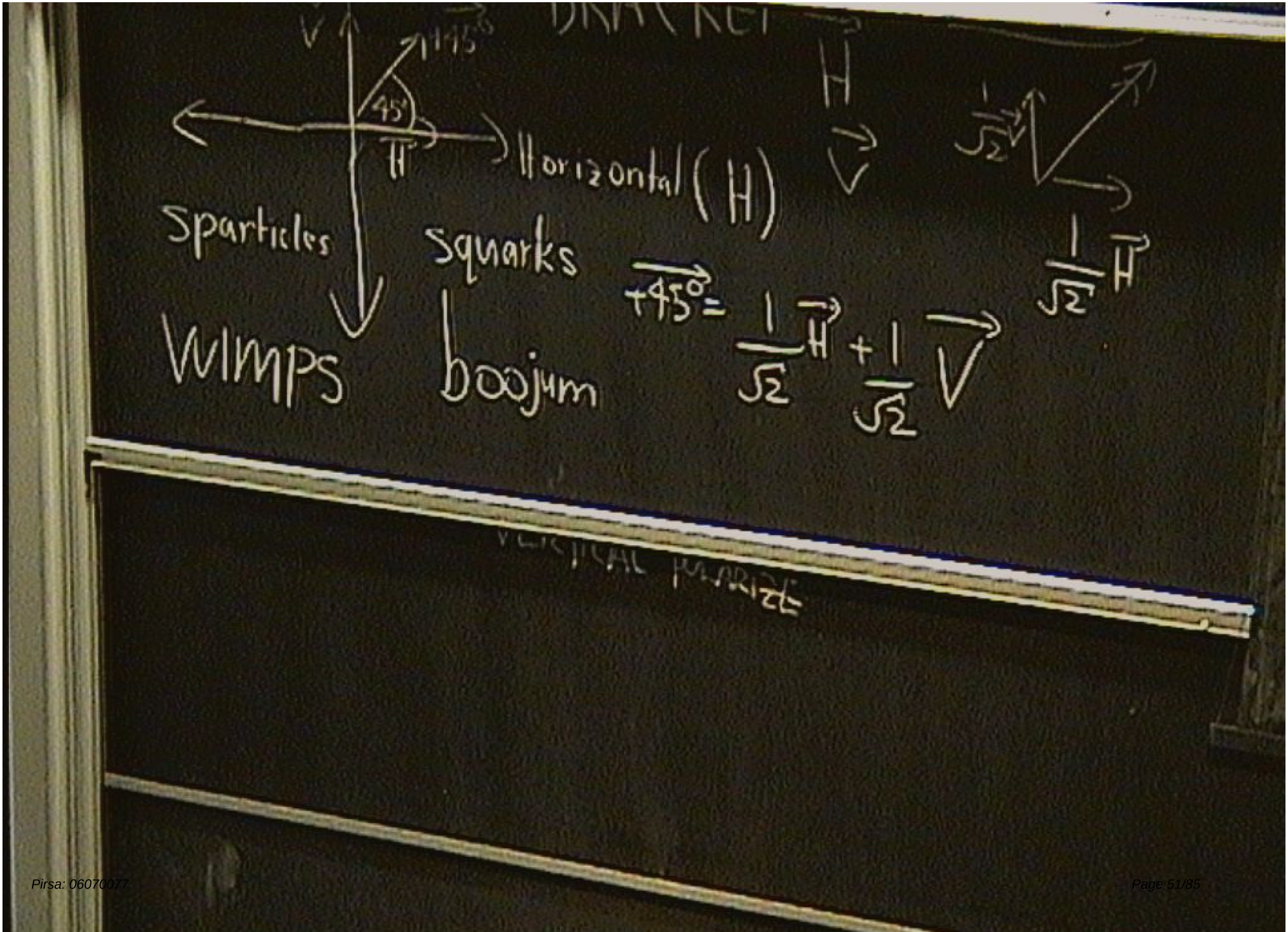

(2,1)
|(1,1)|² + |(2,1)|² = 1
path 1
path 2
AND
KET
+45° =

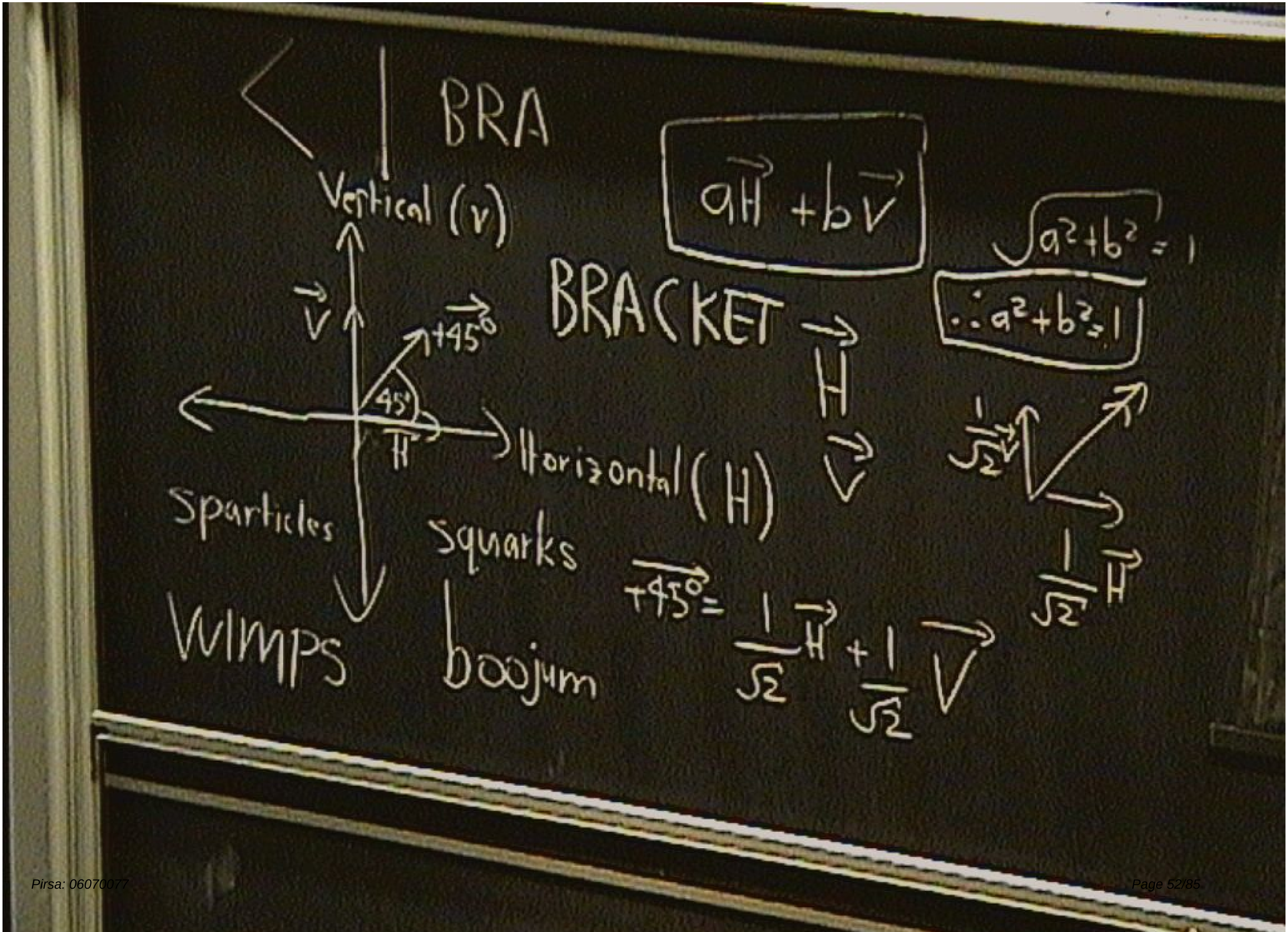

BRA
Vertical (v)
$\vec{V}$
$\vec{+45°}$
45°
H
$a\vec{H} + b\vec{V}$
$\sqrt{a^2+b^2} = 1$
$\therefore a^2+b^2=1$
$\vec{H}$
$\vec{V}$
(H)
$\frac{1}{\sqrt{2}}\vec{V}$
$\frac{1}{\sqrt{2}}\vec{H}$
$\frac{1}{\sqrt{2}}\vec{H} + \frac{1}{\sqrt{2}}\vec{V}$



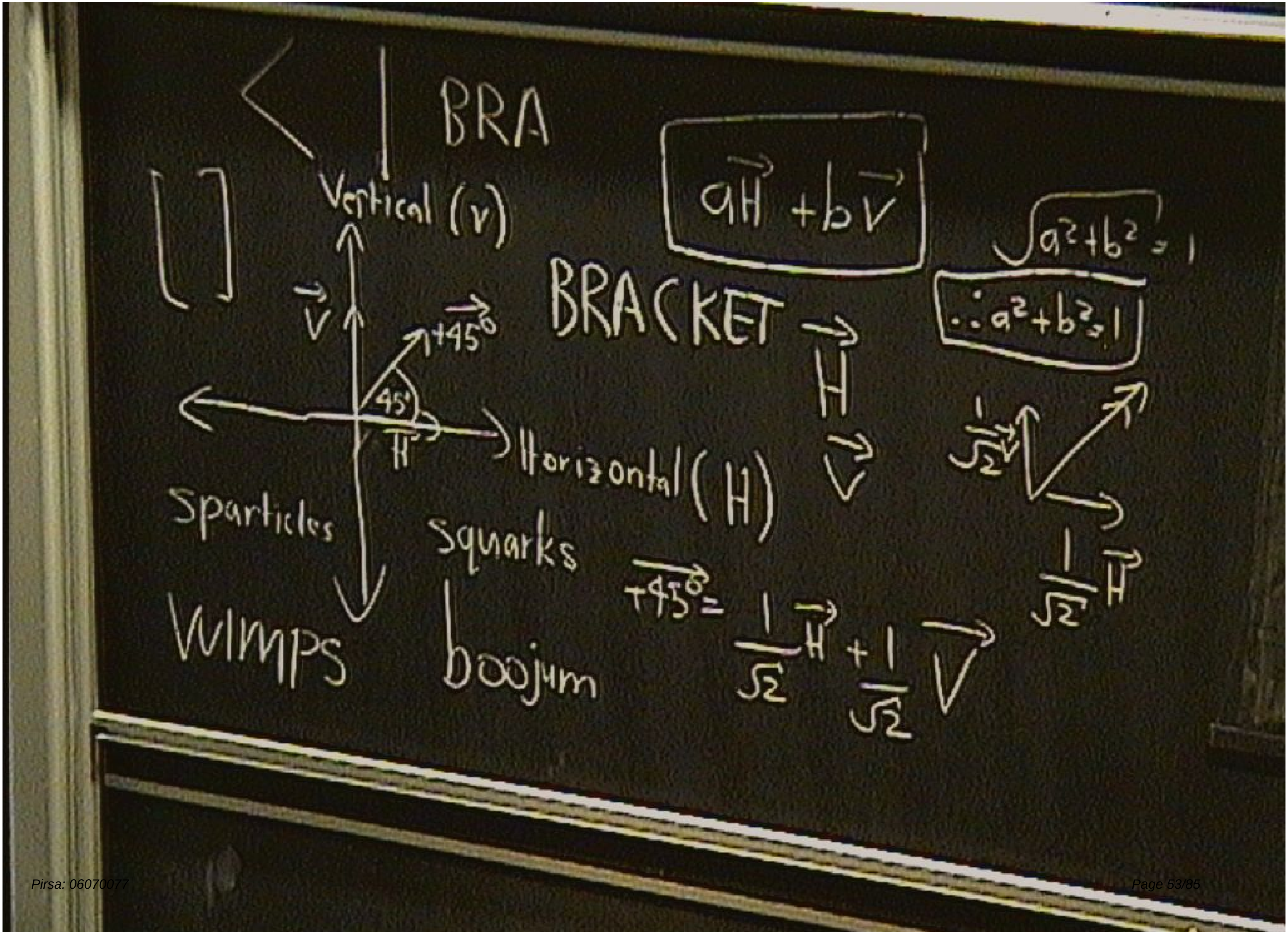
BRA
Vertical (V)
+45°
45°
Horizontal (H)
aH + bV
BRACKET
√(a²+b²) = 1
∴ a²+b²=1
+45° = 1/√2 H + 1/√2 V

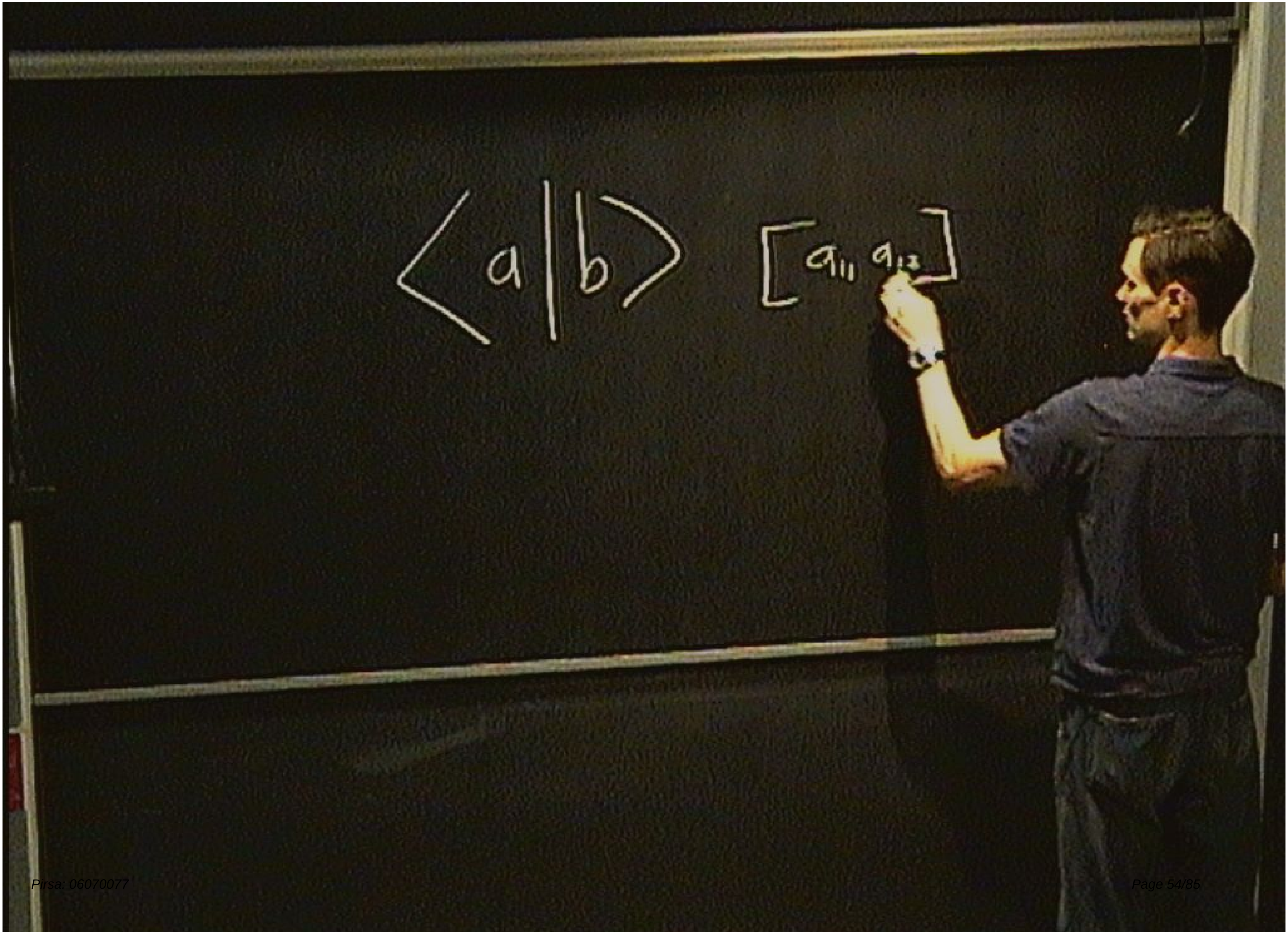

V
+45°
45°
H
Horizontal (H)
H
V
1/√2 V
1/√2 H
+45° = 1/√2 H + 1/√2 V
boojum

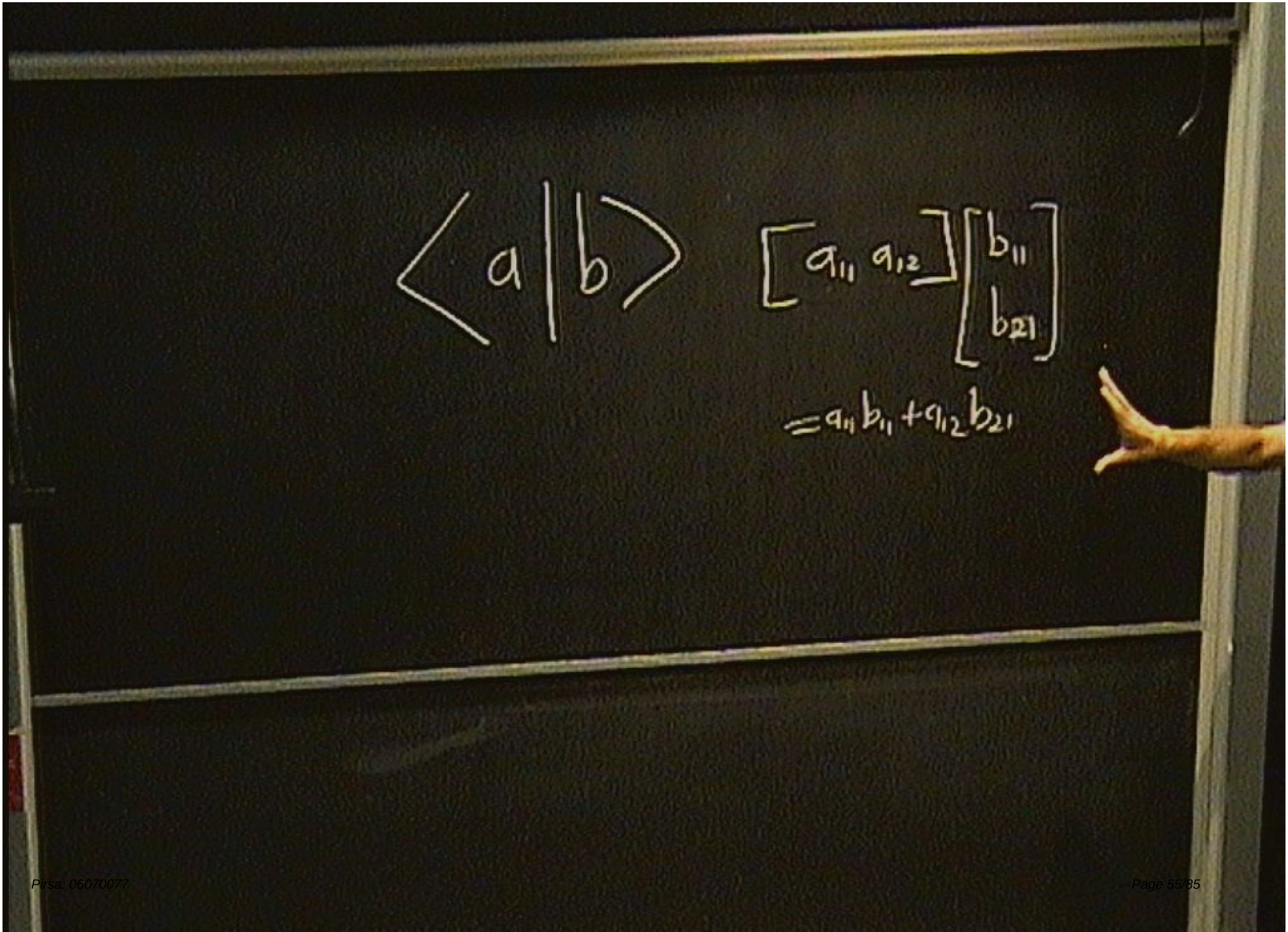

V
+45°
45°
H
Horizontal (H)
Sparticles
squarks
WIMPS
boojum
+45° = 1/√2 H + 1/√2 V
1/√2 V
1/√2 H
H
V



BRA
Vertical (v)
aH + bV
√(a²+b²) = 1
∴ a²+b² = 1
BRACKET
+45°
45°
Horizontal (H)
Sparticles
squarks
+45° = 1/√2 H + 1/√2 V
1/√2 V
1/√2 H
WIMPS
boojum

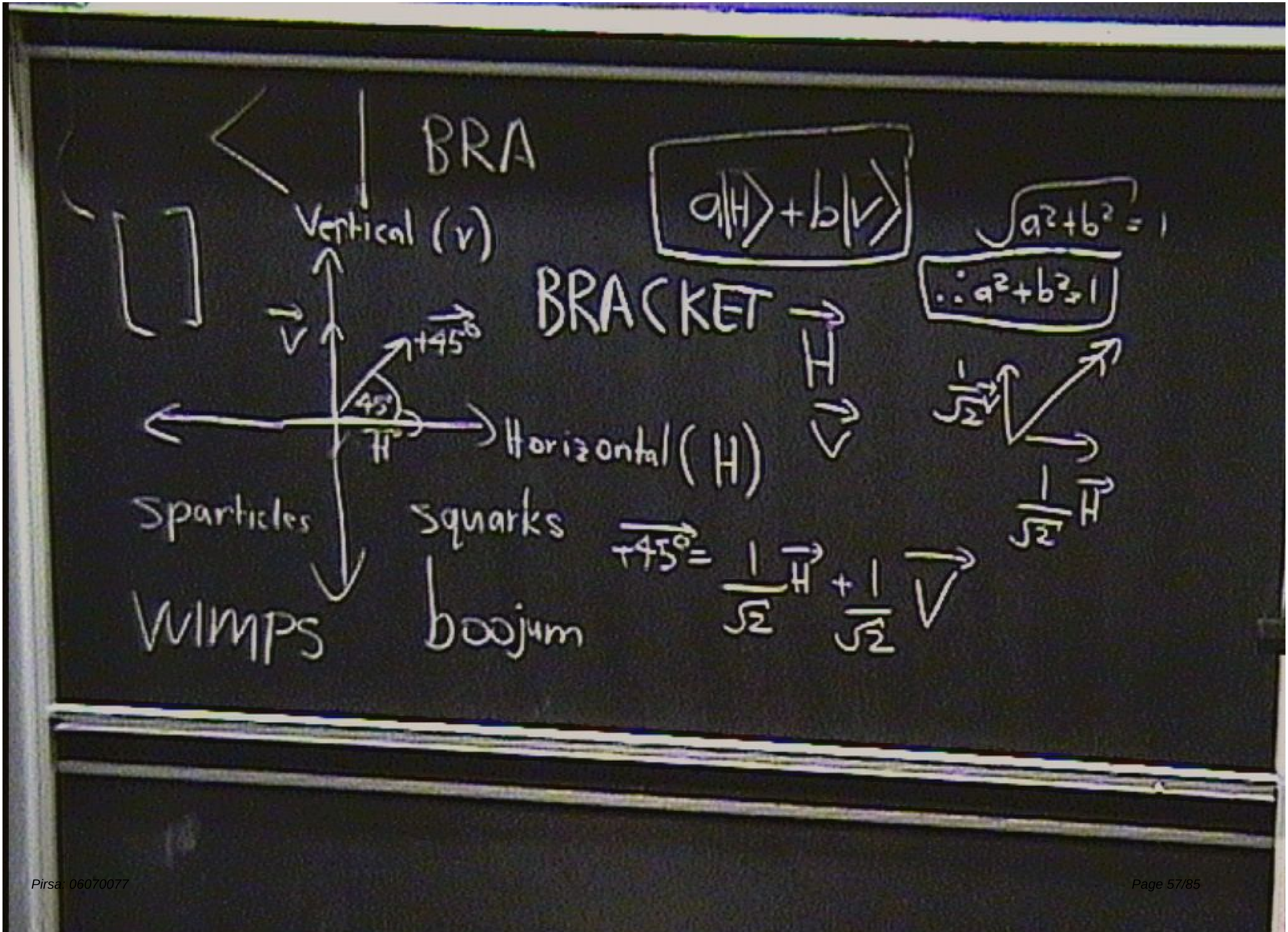

BRA
[ ]
Vertical (v)
BRACKET
Horizontal (H)
Sparticles
Squarks
WIMPS
boojum
45°
$a\vec{H} + b\vec{V}$
$\sqrt{a^2+b^2} = 1$
$\therefore a^2+b^2=1$
$\vec{+45^\circ} = \frac{1}{\sqrt{2}}\vec{H} + \frac{1}{\sqrt{2}}\vec{V}$


⟨a|b⟩
[a11 a12]

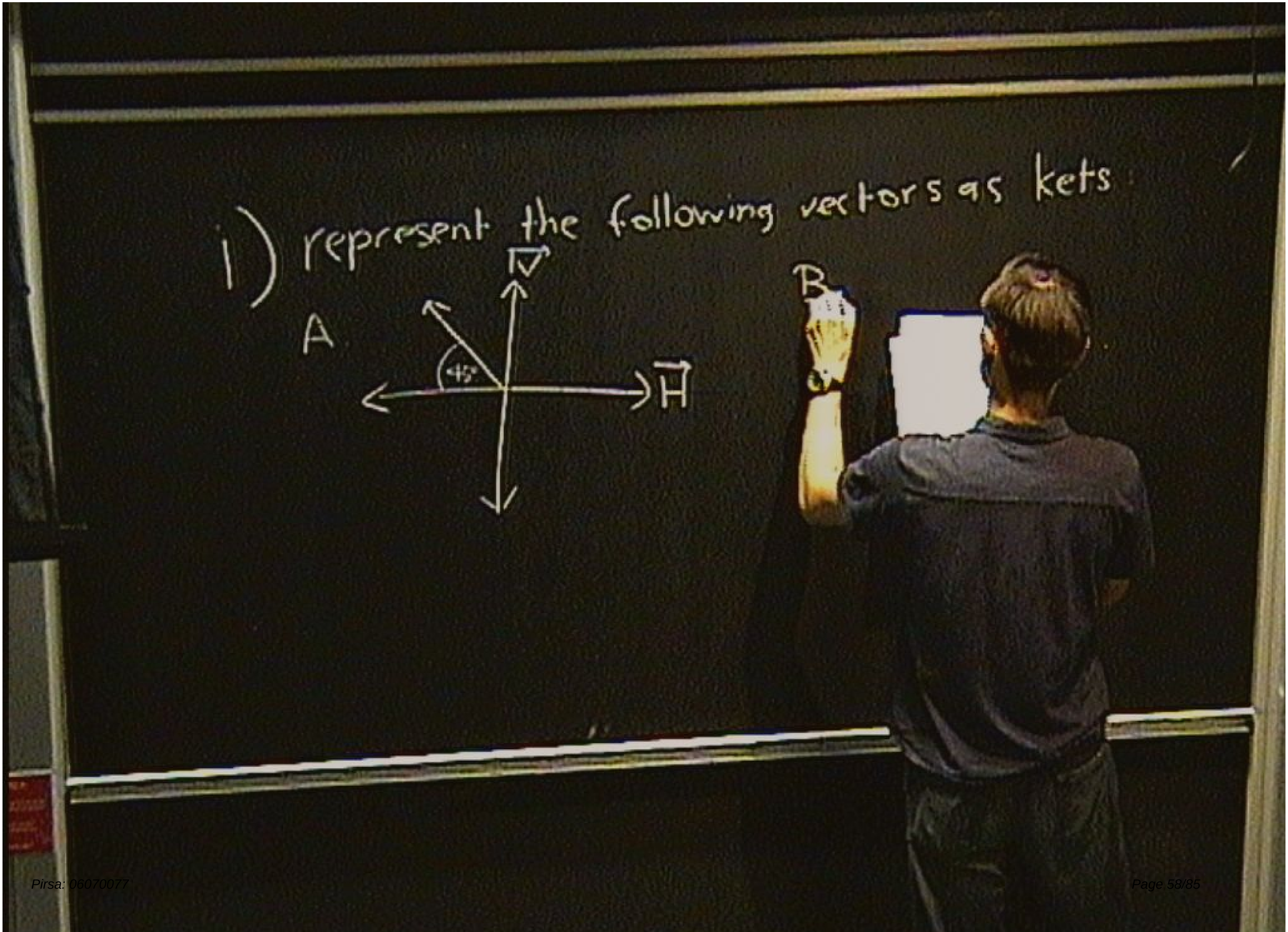

$\langle a | b \rangle$
$\begin{bmatrix} a_{11} & a_{12} \end{bmatrix} \begin{bmatrix} b_{11} \\ b_{21} \end{bmatrix}$
$= a_{11} b_{11} + a_{12} b_{21}$

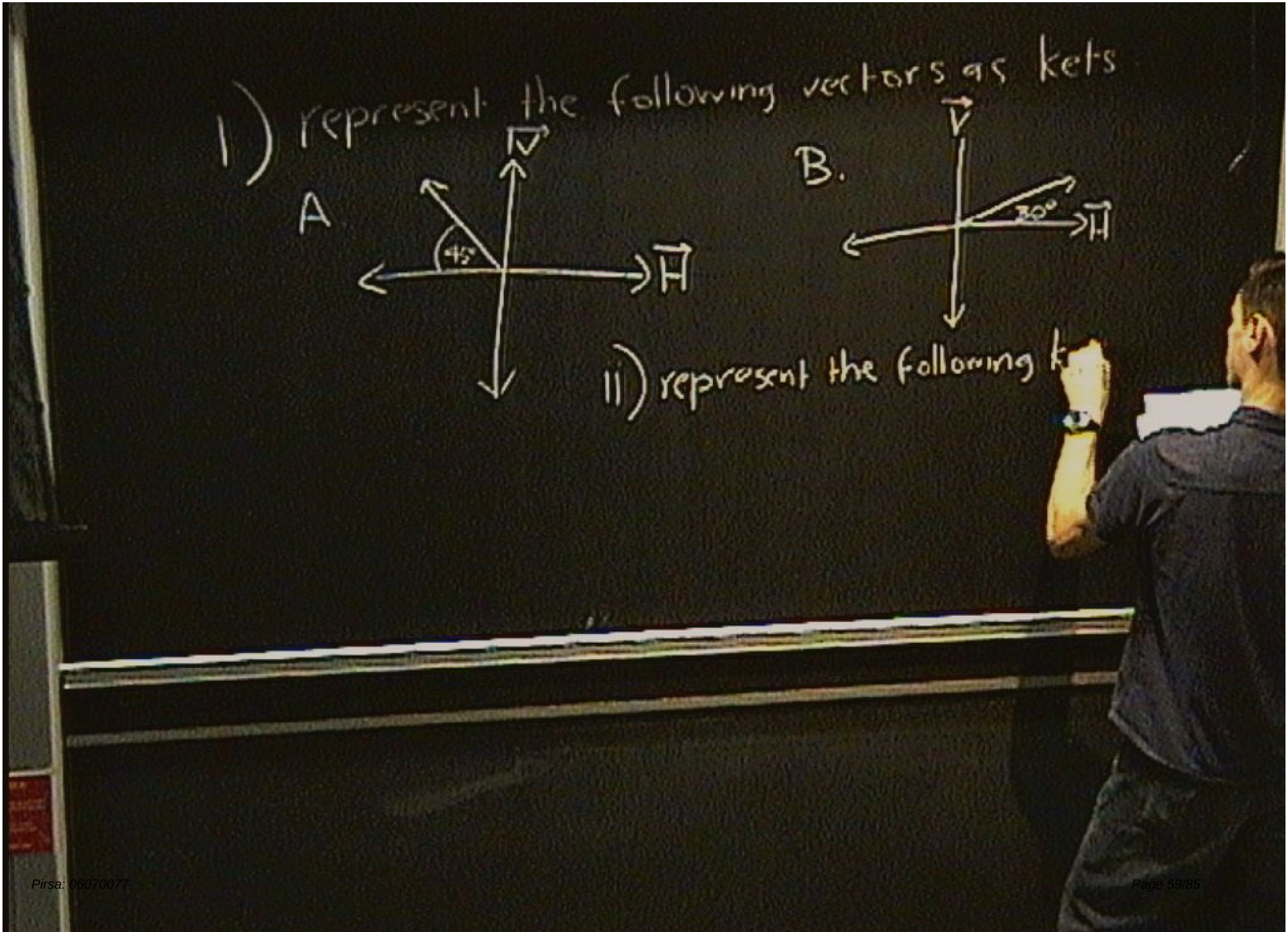
$$\langle a | b \rangle \quad \begin{bmatrix} a_{11} & a_{12} \end{bmatrix} \begin{bmatrix} b_{11} \\ b_{21} \end{bmatrix}$$

$$= a_{11} b_{11} + a_{12} b_{21}$$

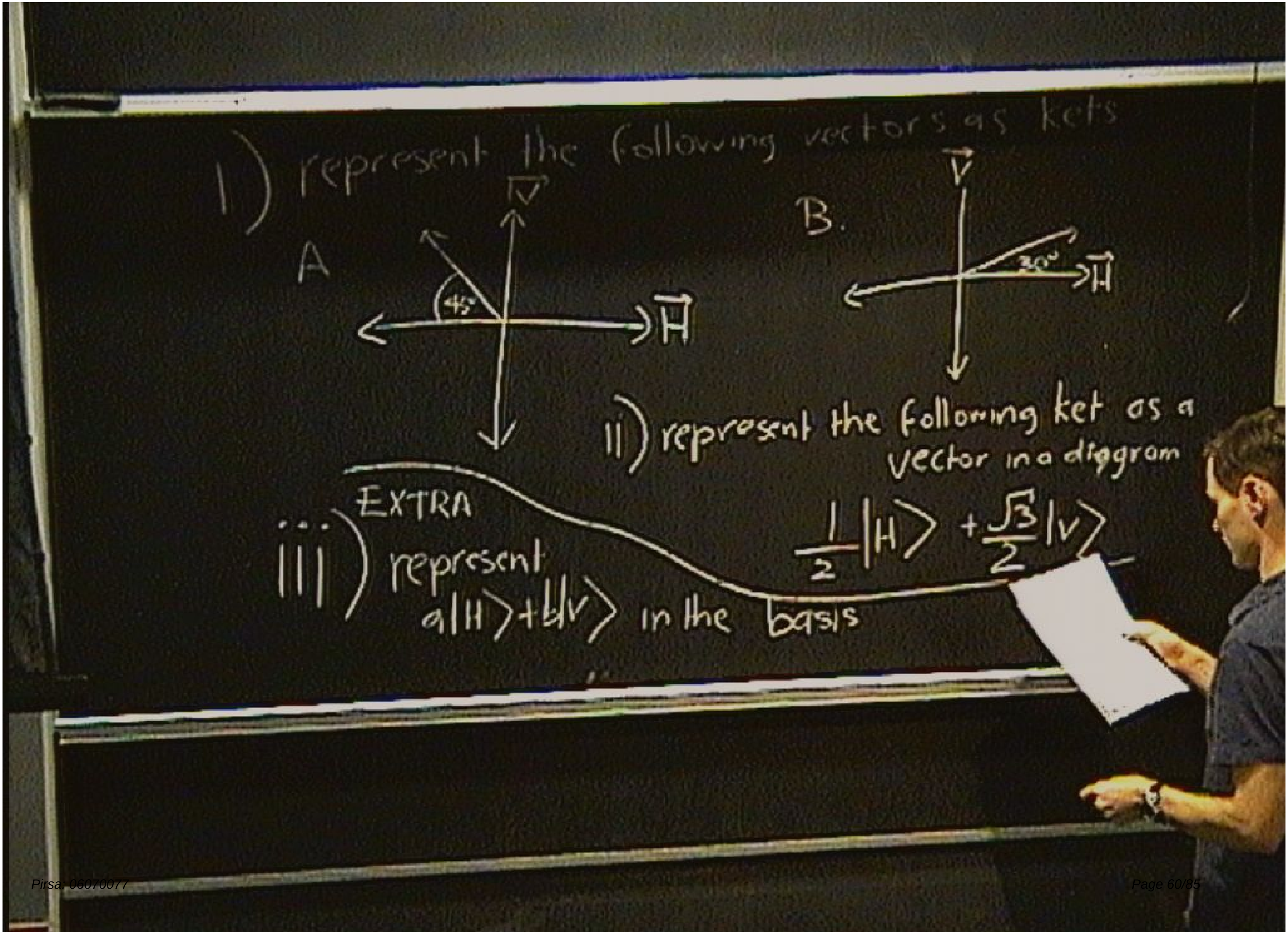


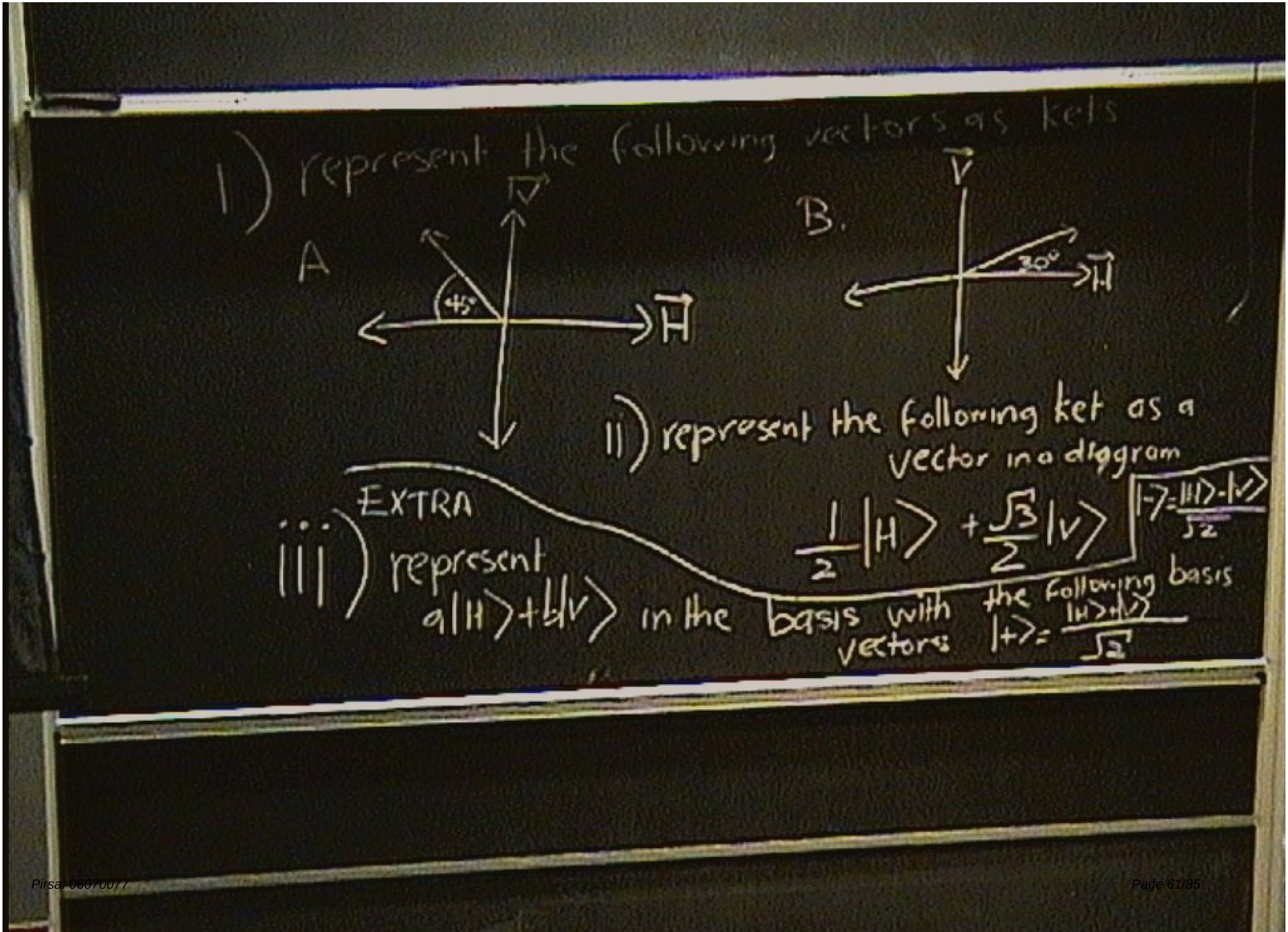
BRA
Vertical (v)
BRACKET
+45°
45°
Horizontal (H)
Sparticles
squarks
WIMPS
boojum

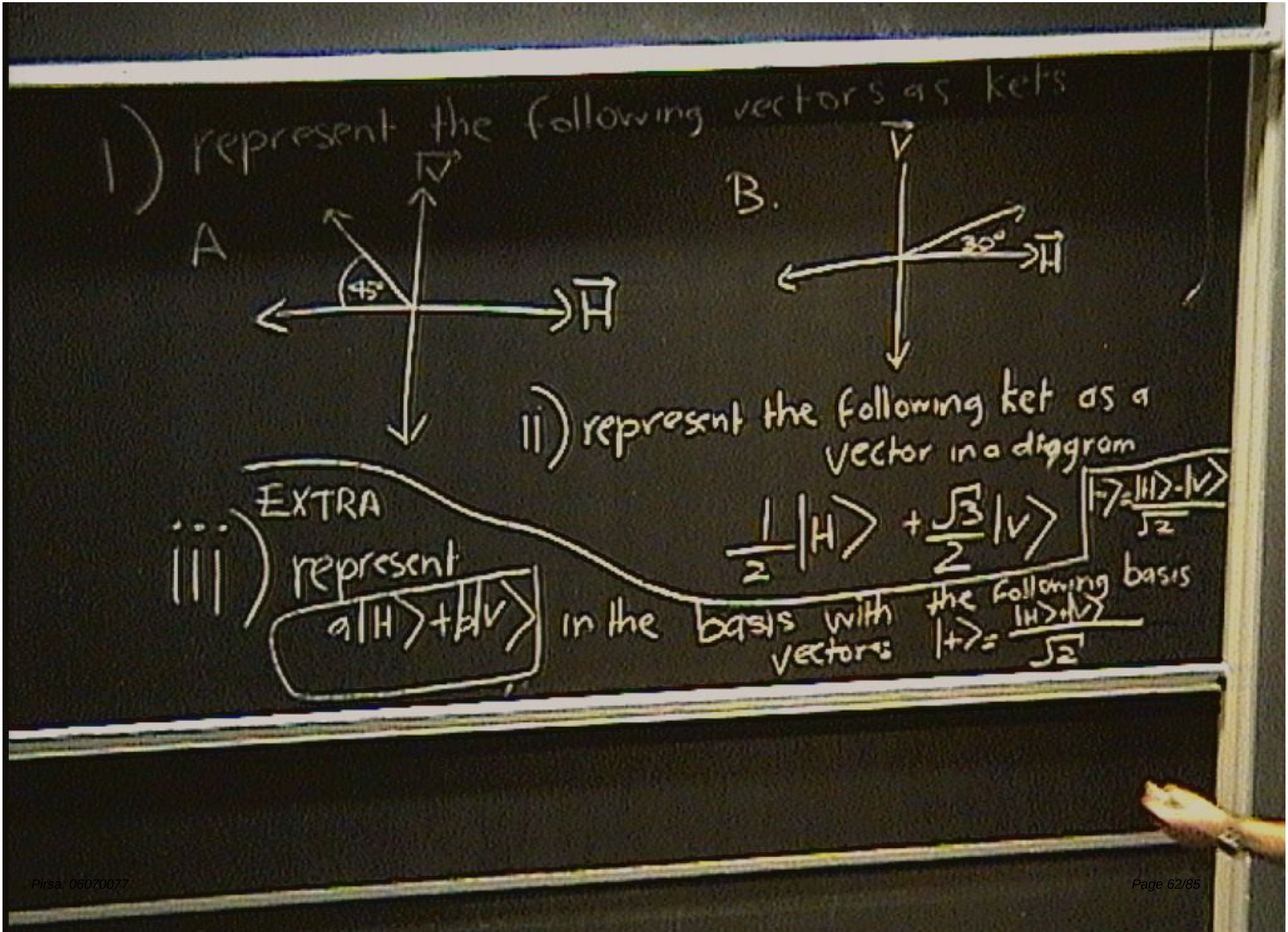

i) represent the following vectors as kets
A
45°
V
H
B

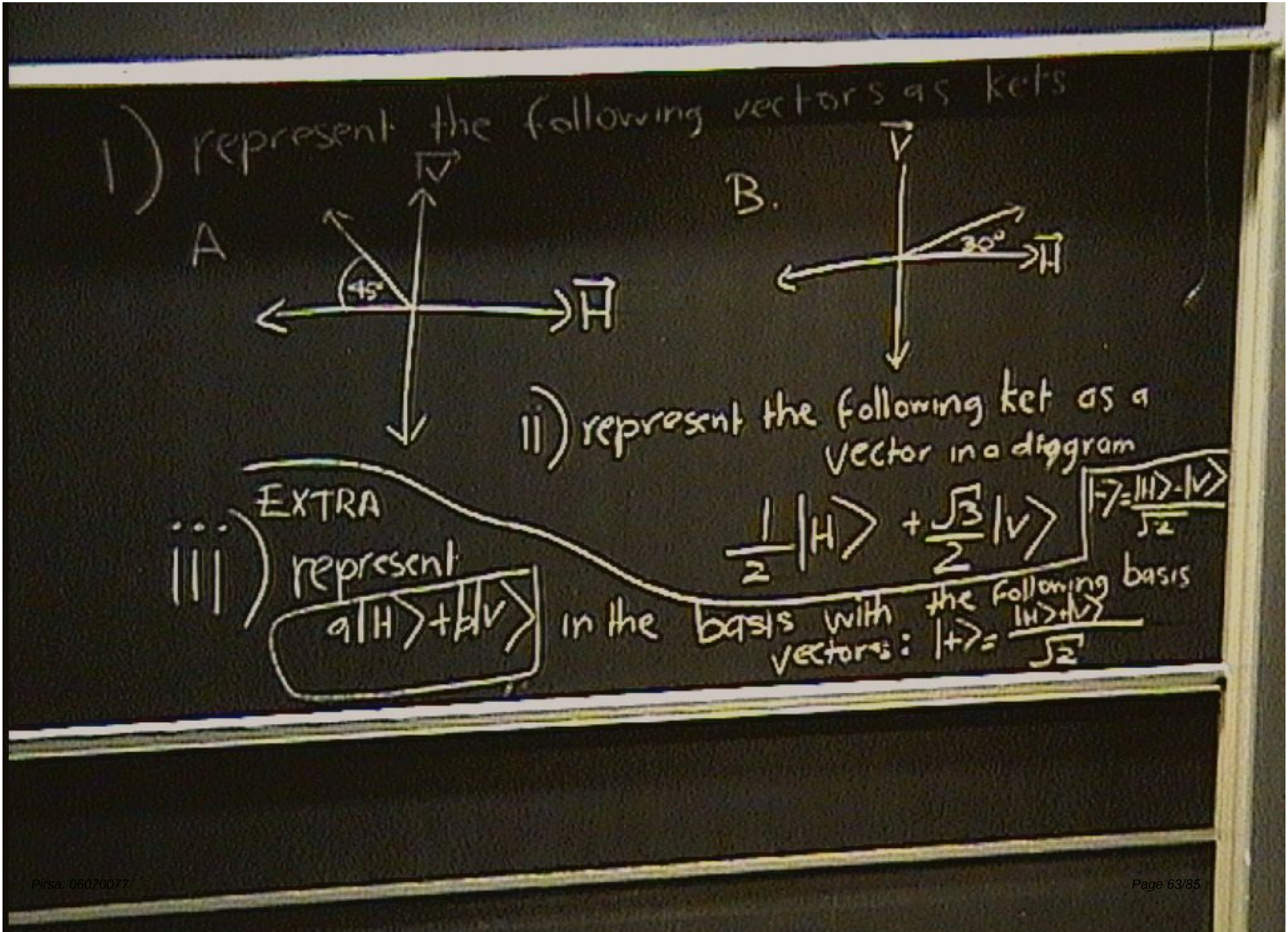


1) represent the following vectors as kets
A
45°
V
H
B.
30°
V
H
ii) represent the following

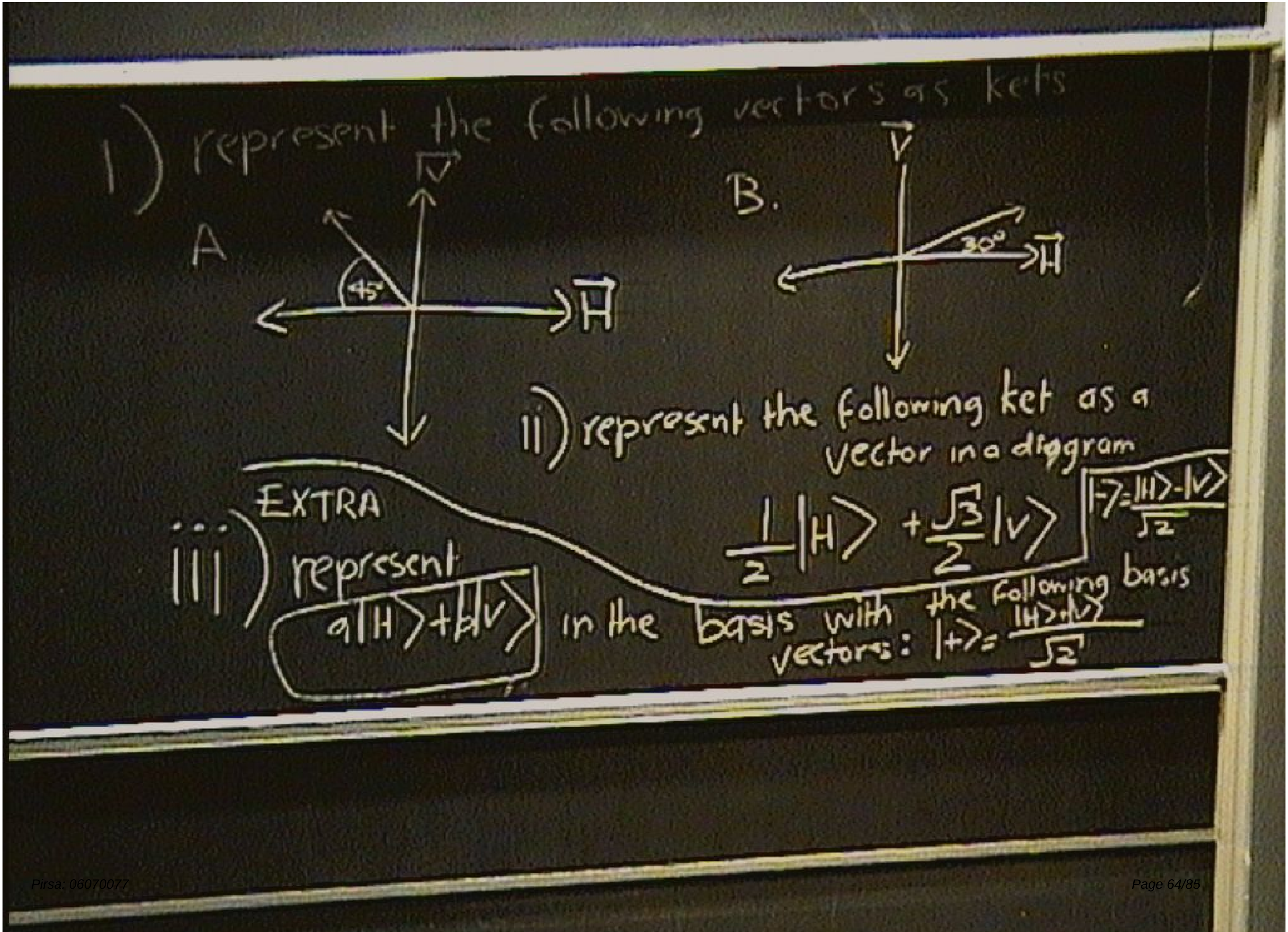

i) represent the following vectors as kets
A.
45°
V
H
B.
30°
V
H
ii) represent the following ket as a vector in a diagram
1/2 |H> + √3/2 |V>
EXTRA
iii) represent
a|H>+b|V> in the basis

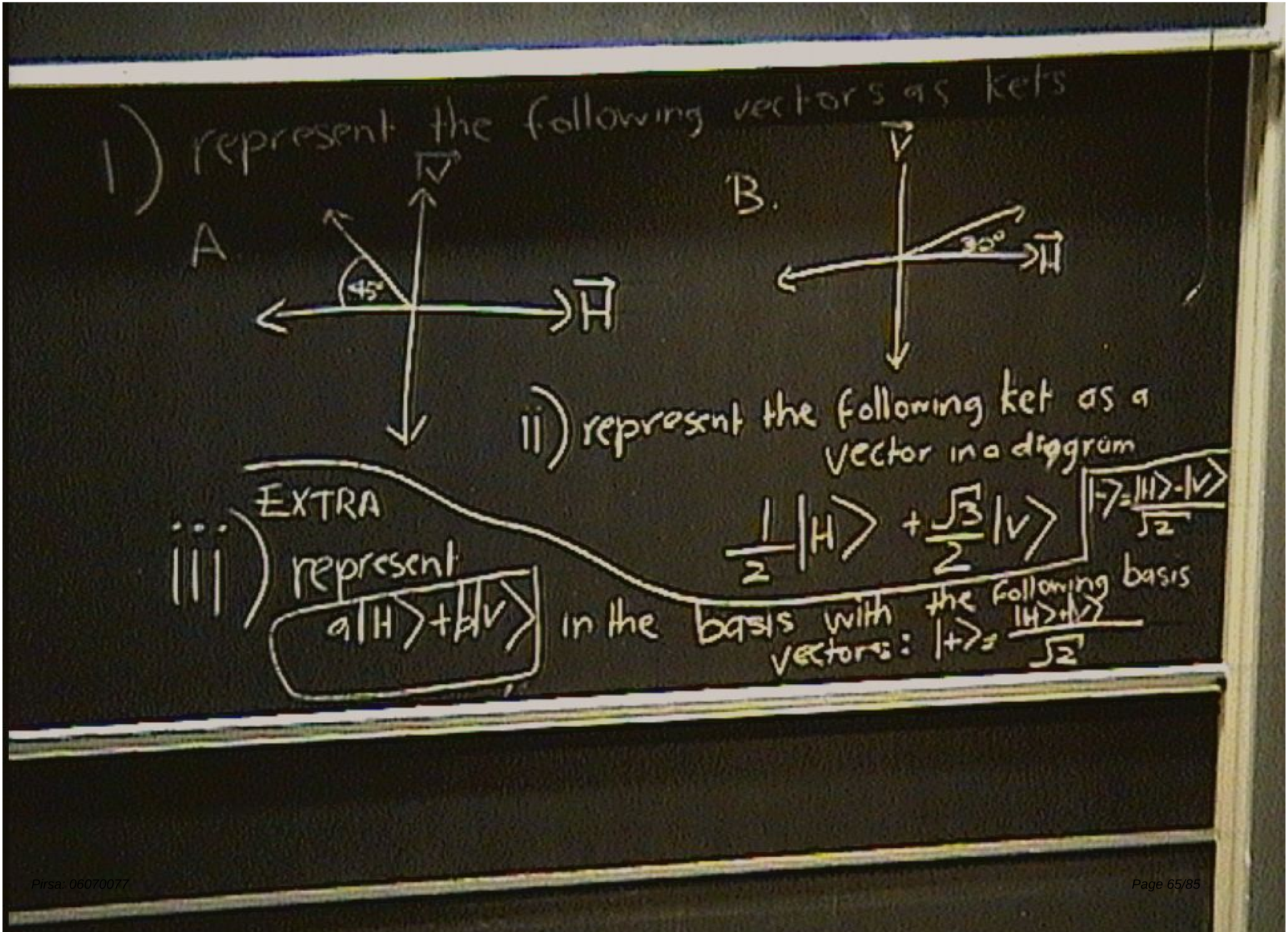

i) represent the following vectors as kets
A
45°
H
B.
V
30°
H
ii) represent the following ket as a
vector in a diagram
1/2 |H> + √3/2 |V>
EXTRA
iii) represent
a|H>+b|V> in the basis with the following basis
vectors |+>= (|H>+|V>)/√2
|−>= (|H>−|V>)/√2

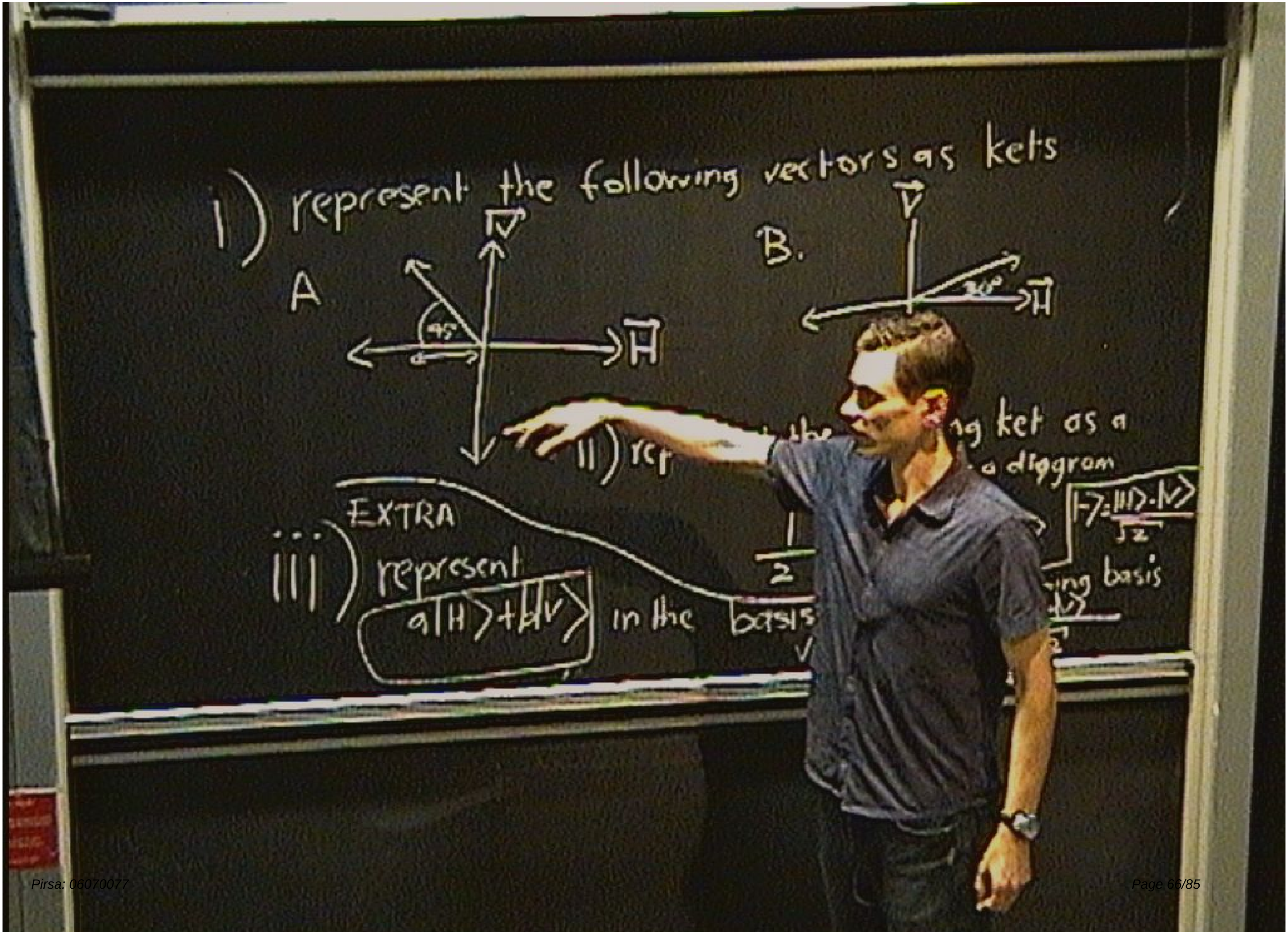

i) represent the following vectors as kets
A
45°
V
H
B.
30°
V
H
ii) represent the following ket as a vector in a diagram
$\frac{1}{2}|H\rangle + \frac{\sqrt{3}}{2}|V\rangle$
$|-\rangle = \frac{|H\rangle - |V\rangle}{\sqrt{2}}$
EXTRA
iii) represent
$a|H\rangle + b|V\rangle$ in the basis with the following basis vectors: $|+\rangle = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$

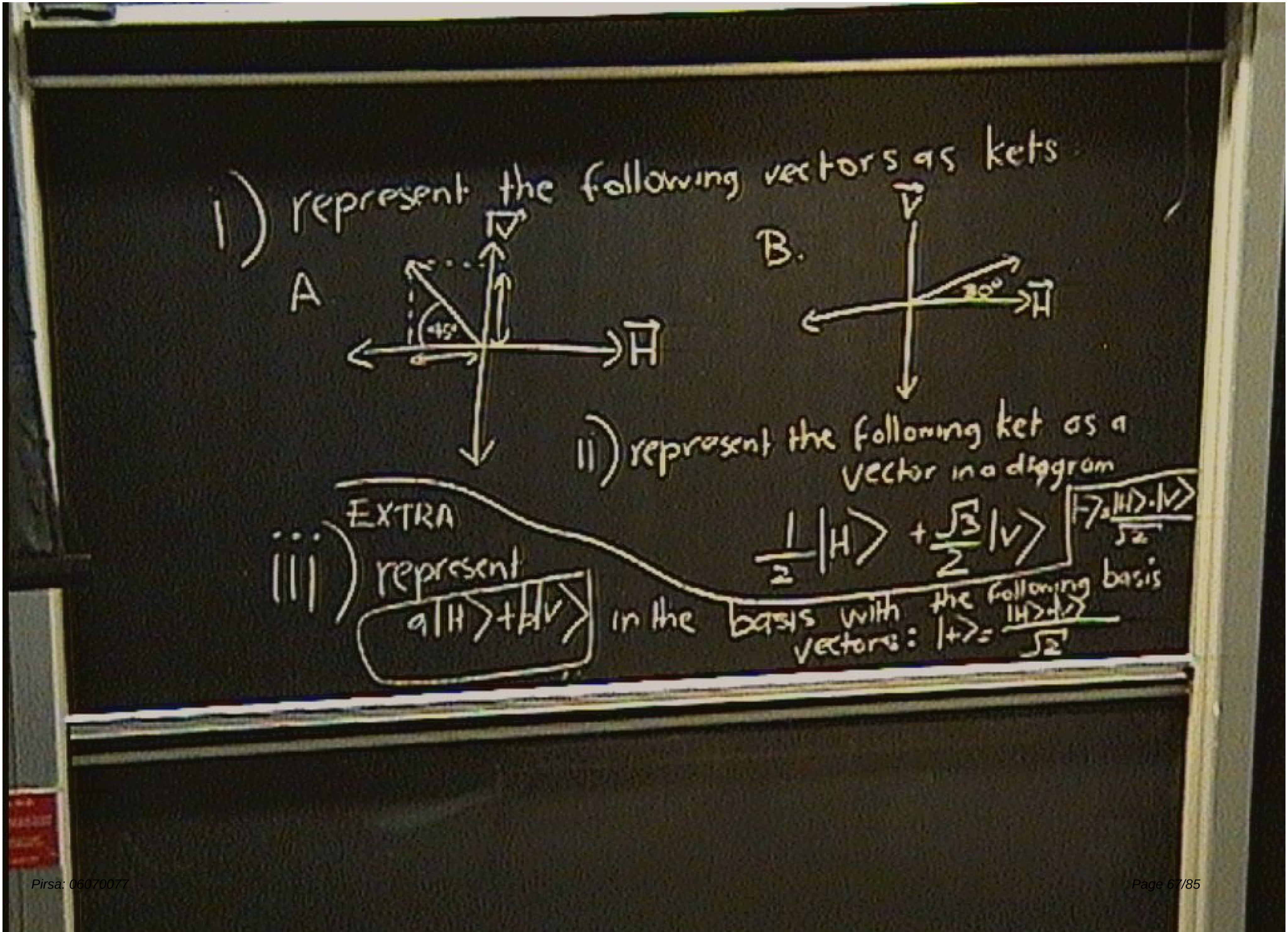


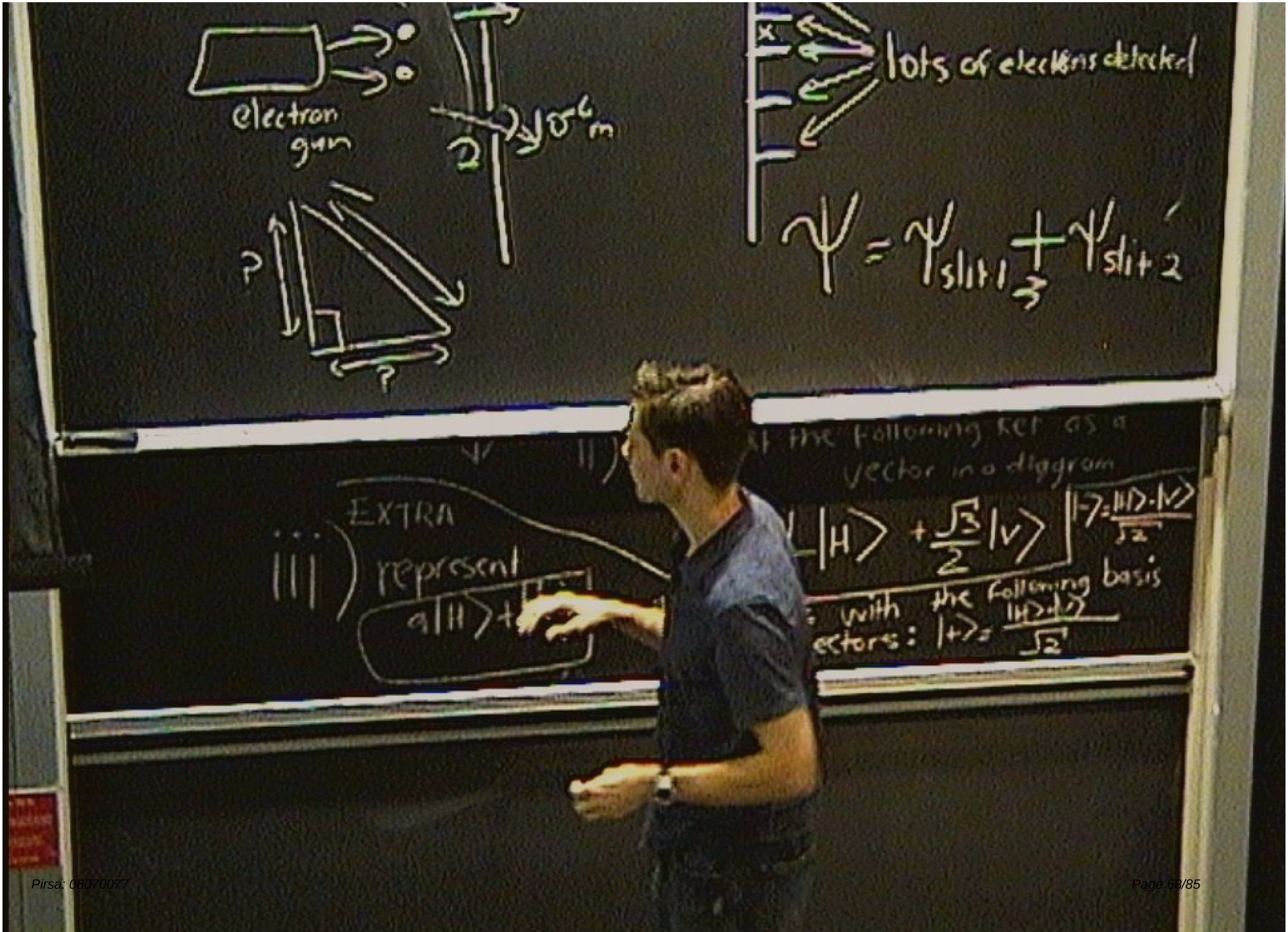
1) represent the following vectors as kets
A
45°
$\vec{V}$
$\vec{H}$
B.
30°
$\vec{V}$
$\vec{H}$
ii) represent the following ket as a vector in a diagram
$\frac{1}{2}|H\rangle + \frac{\sqrt{3}}{2}|V\rangle$
EXTRA
iii) represent $a|H\rangle + b|V\rangle$ in the basis with the following basis vectors: $|+\rangle = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$
$|-\rangle = \frac{|H\rangle - |V\rangle}{\sqrt{2}}$

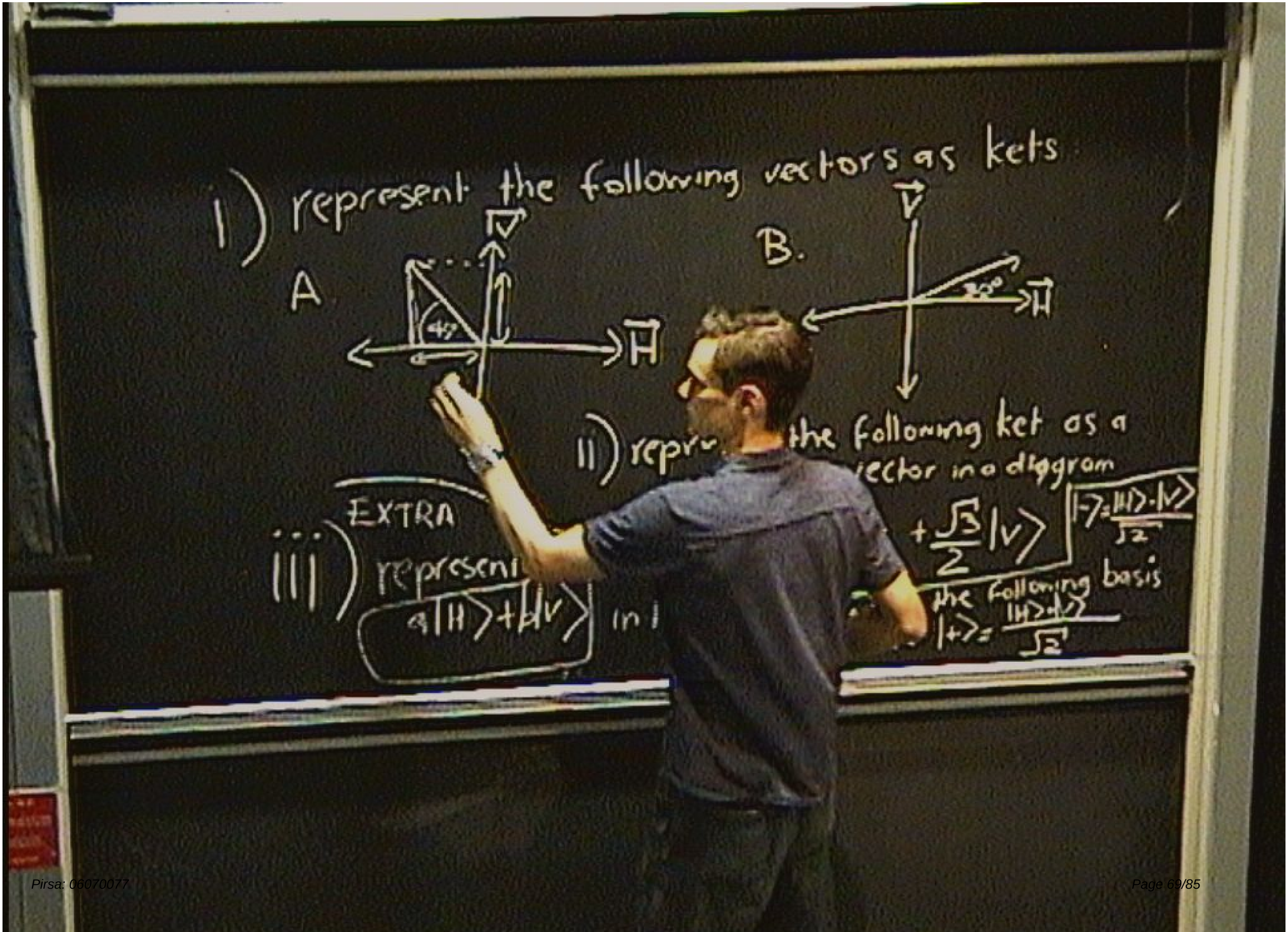

1) represent the following vectors as kets
A
45°
V
H
B.
V
30°
H
ii) represent the following ket as a vector in a diagram
1/2 |H> + √3/2 |V>
EXTRA
iii) represent a|H>+b|V> in the basis with the following basis vectors: |+> = (|H>+|V>)/√2
|-> = (|H>-|V>)/√2

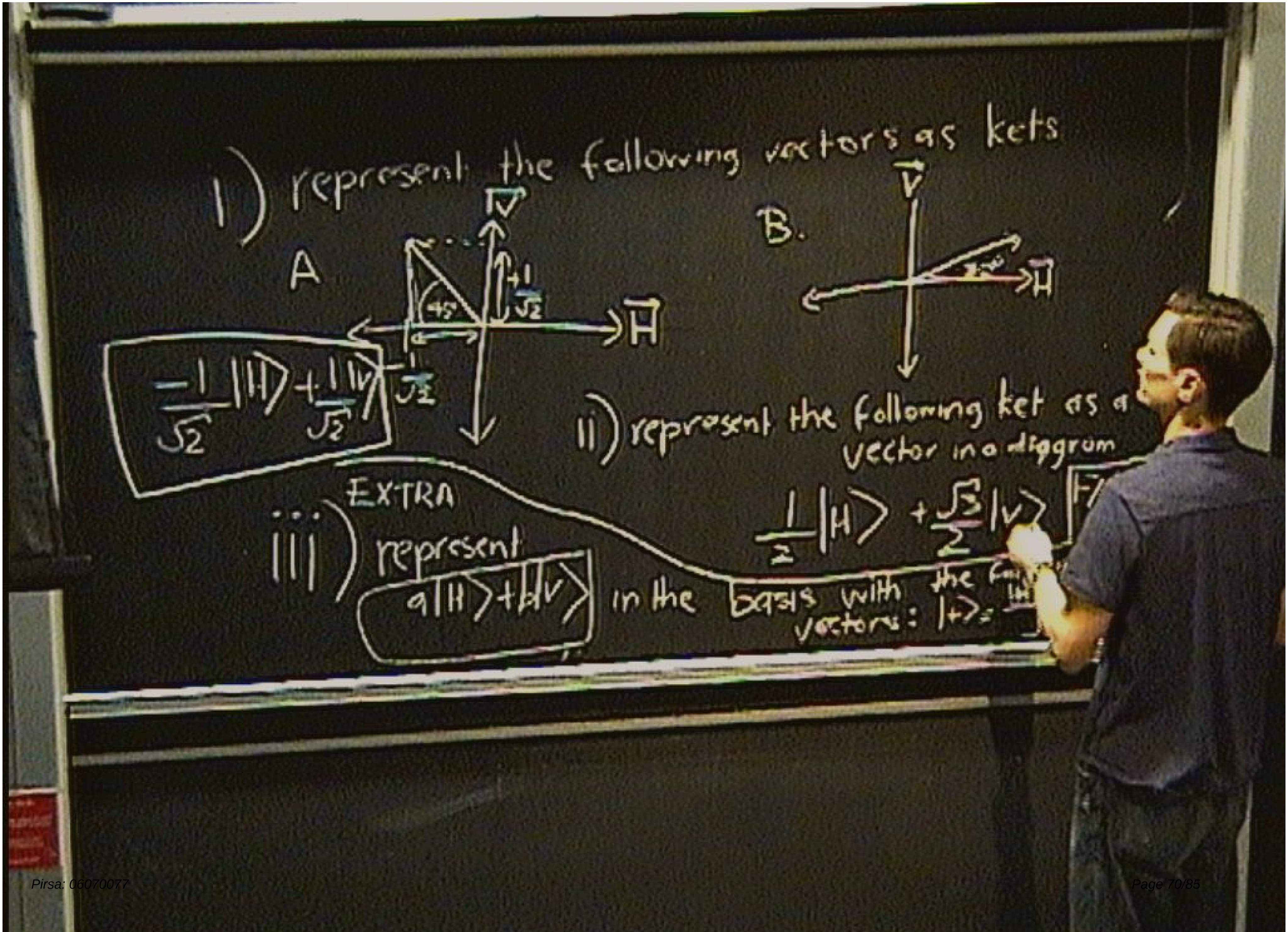

1) represent the following vectors as kets
A.
V
45°
H
B.
V
30°
H
ii) represent the following ket as a vector in a diagram
1/2 |H> + √3/2 |V>
|-> = (|H> - |V>)/√2
EXTRA
iii) represent
a|H>+b|V> in the basis with the following basis vectors: |+> = (|H>+|V>)/√2

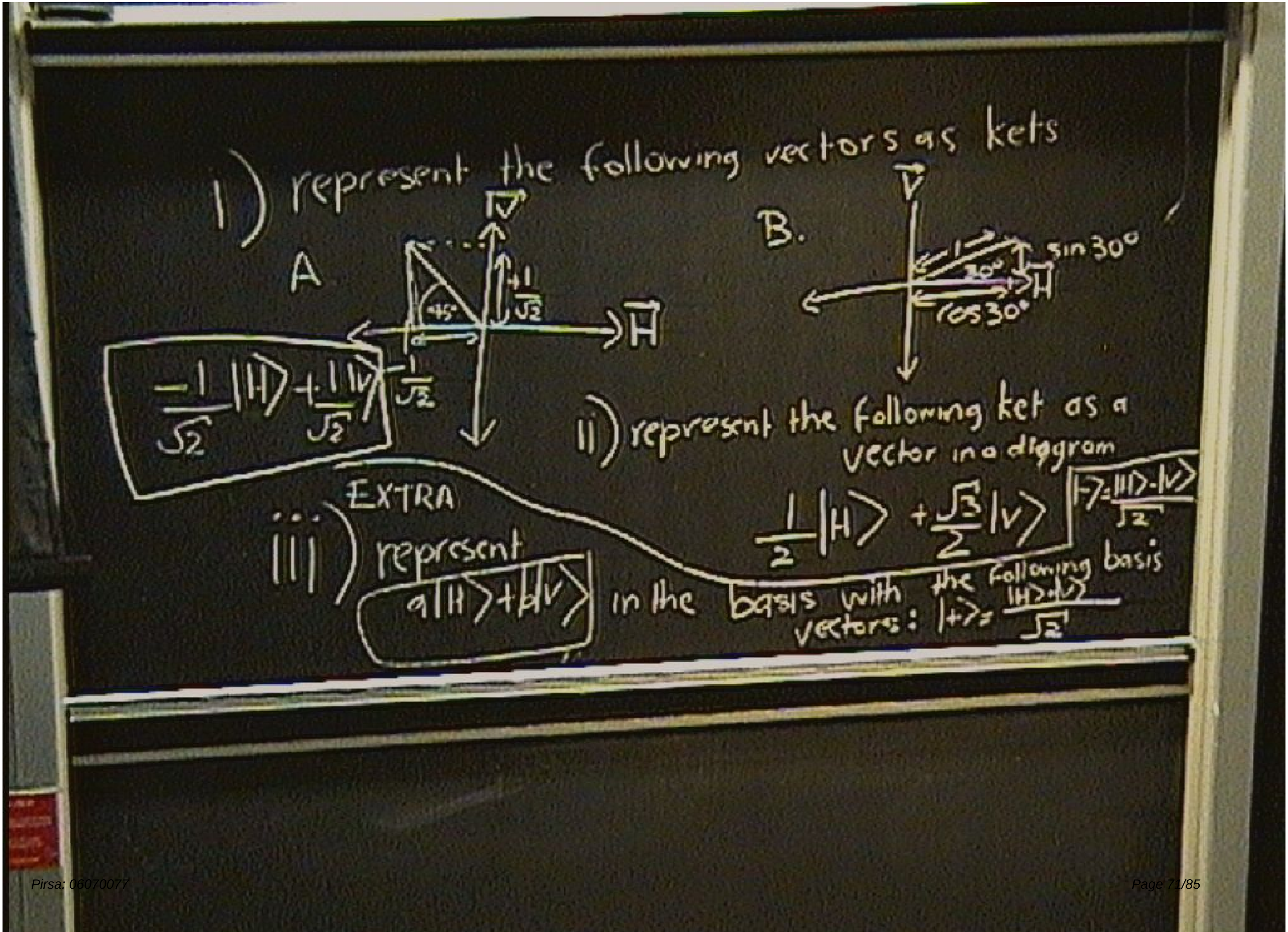

i) represent the following vectors as kets
A
B.
EXTRA
iii) represent
a|H>+b|V> in the basis
ket as a
diagram
basis

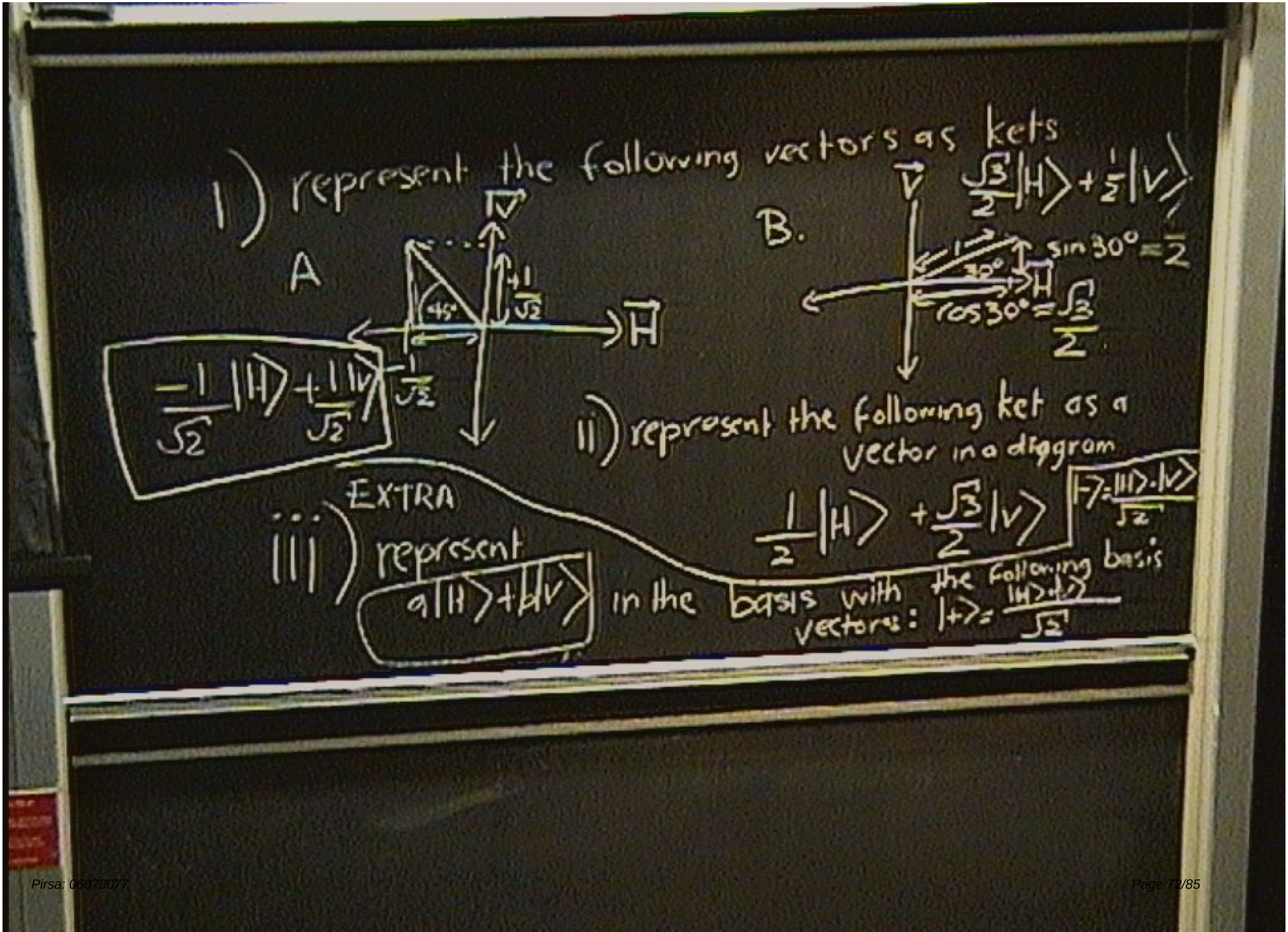

i) represent the following vectors as kets
$\vec{V}$
$\vec{V}$
B.
A
30°
$\vec{H}$
45°
$\vec{H}$
ii) represent the following ket as a vector in a diagram
EXTRA
$\frac{1}{2}|H\rangle + \frac{\sqrt{3}}{2}|V\rangle$
$|-\rangle = \frac{|H\rangle - |V\rangle}{\sqrt{2}}$
iii) represent
$a|H\rangle + b|V\rangle$ in the basis with the following basis vectors: $|+\rangle = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$

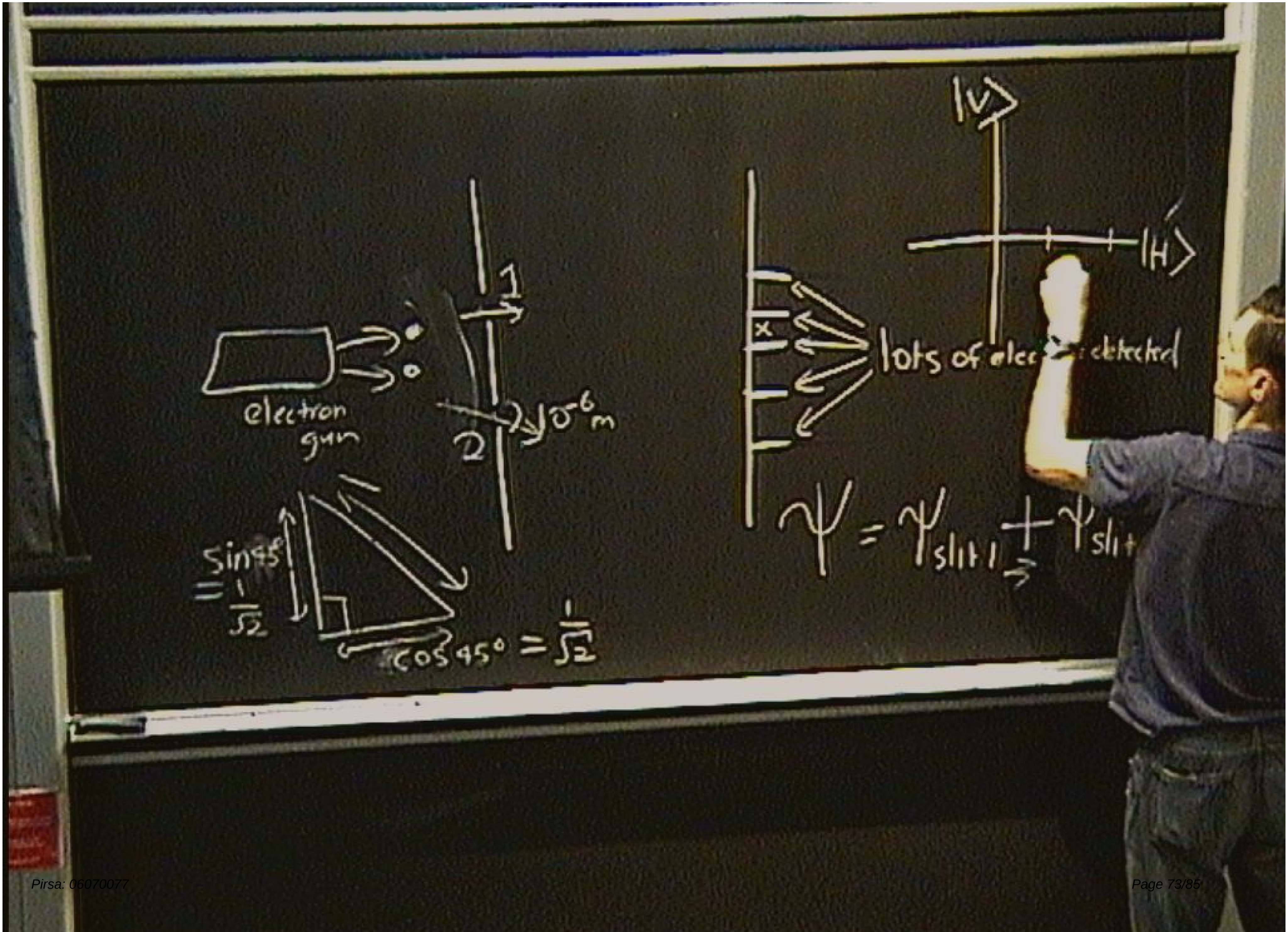

electron gun
lots of electrons detected
EXTRA
iii) represent
vector in a diagram
with the following basis
vectors:

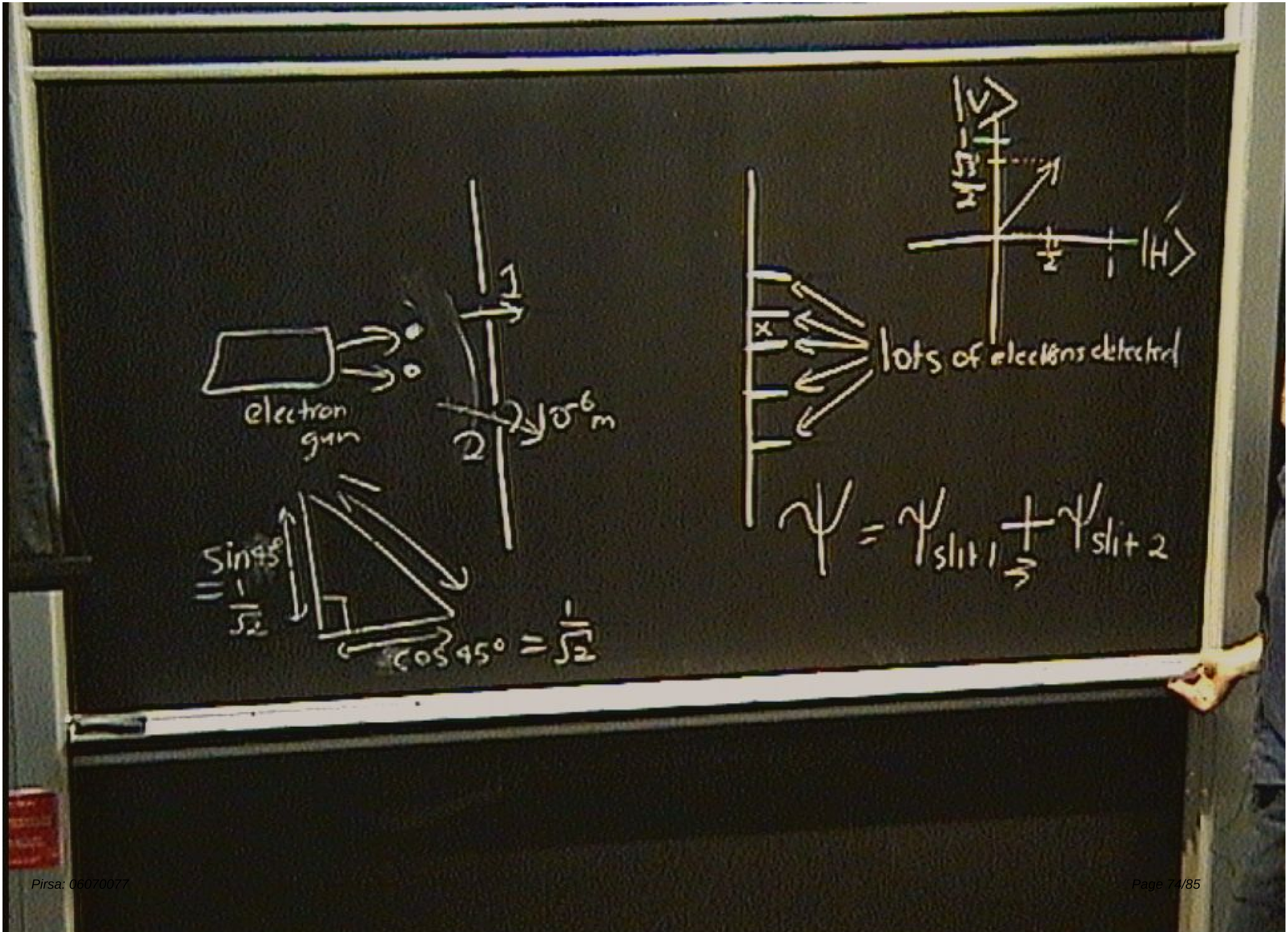

i) represent the following vectors as kets
A.
B.
45°
30°
ii) repr the following ket as a
vector in a diagram
EXTRA
iii) represent
a|H⟩+b|V⟩ in
the following basis

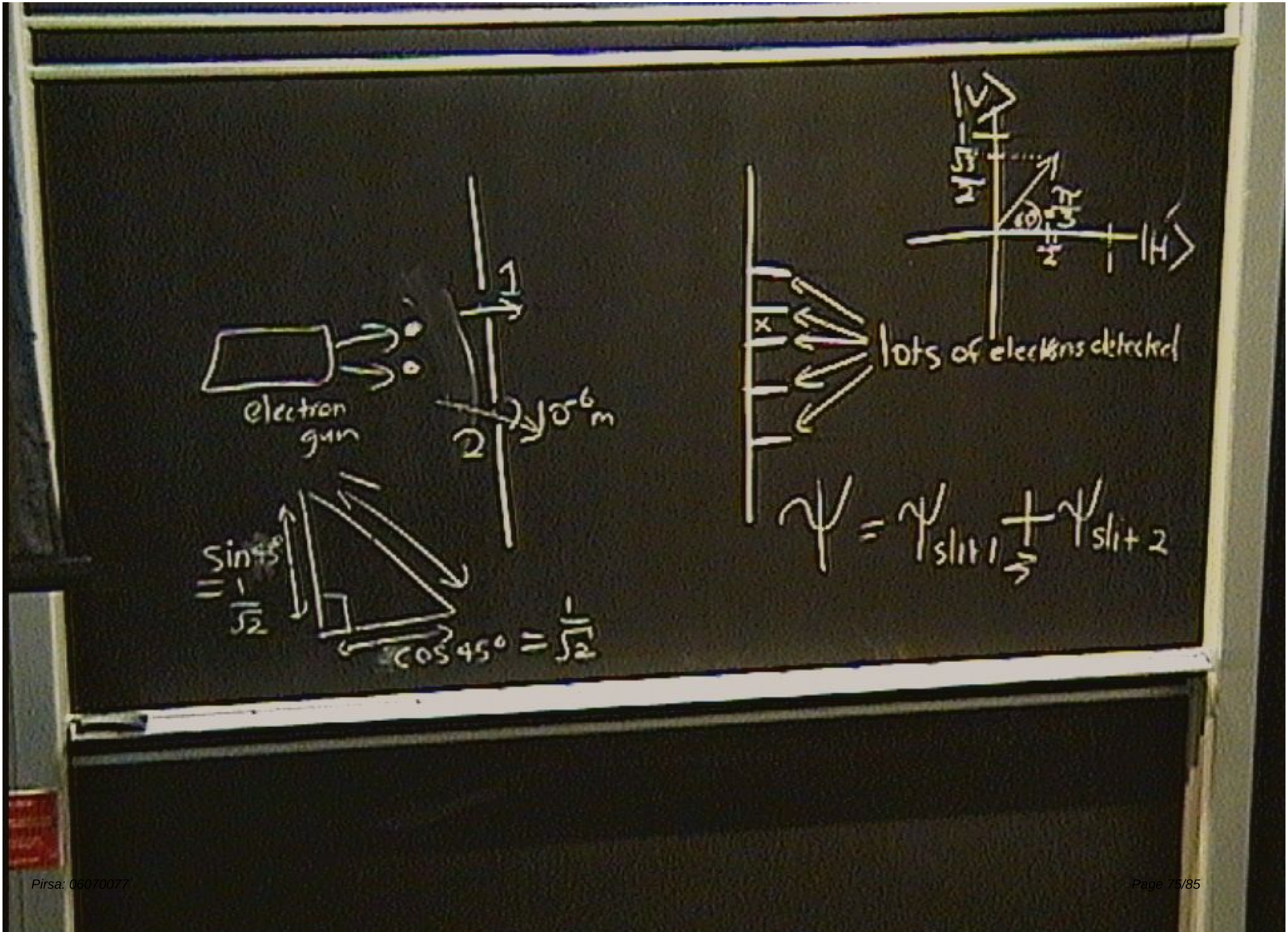

1) represent the following vectors as kets
A
B.
V
H
45°
+1/√2
-1/√2
-1/√2 |H> + 1/√2 |V>
ii) represent the following ket as a vector in a diagram
1/2 |H> + √3/2 |V>
EXTRA
iii) represent
a|H> + b|V> in the basis with the
vectors: |+> =


1) represent the following vectors as kets
A
B.
sin 30°
30°
cos 30°
1
V
H
45°
+1/√2
-1/√2
-1/√2 |H> + 1/√2 |V>
ii) represent the following ket as a vector in a diagram
1/2 |H> + √3/2 |V>
|-> = (|H> - |V>)/√2
EXTRA
iii) represent
a|H> + b|V> in the basis with the following basis vectors: |+> = (|H> + |V>)/√2


i) represent the following vectors as kets
A
B.
sin 30° = 1/2
cos 30° = √3/2
30°
45°
+1/√2
-1/√2
-1/√2 |H⟩ + 1/√2 |V⟩
√3/2 |H⟩ + 1/2 |V⟩
ii) represent the following ket as a vector in a diagram
1/2 |H⟩ + √3/2 |V⟩
EXTRA
iii) represent a|H⟩ + b|V⟩ in the basis with the following basis vectors: |+⟩ = (|H⟩ + |V⟩)/√2
|-⟩ = (|H⟩ - |V⟩)/√2

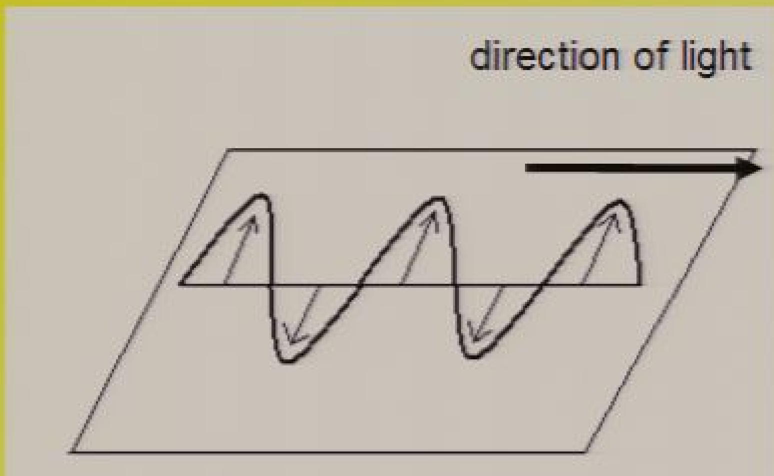

electron gun
1
2
10^{-6} m
$\sin 45° = \frac{1}{\sqrt{2}}$
$\cos 45° = \frac{1}{\sqrt{2}}$
x
lots of elec detected
$|V\rangle$
$|H\rangle$
$\psi = \psi_{slit\,1} + \psi_{slit}$


electron gun
1
2
~10^-6 m
x
lots of electrons detected
|V>
|H>
1/√2
1
Ψ = Ψslit 1 ± Ψslit 2
Sin45° = 1/√2
cos45° = 1/√2

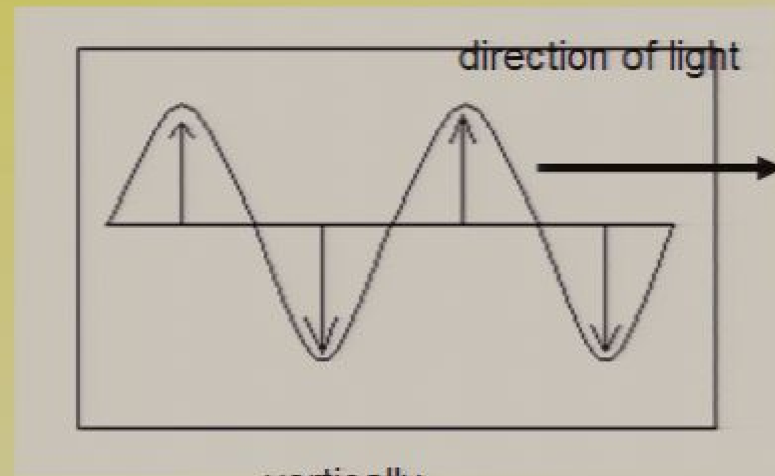


electron gun
1
2
10^{-6} m
$\sin 45° = \frac{1}{\sqrt{2}}$
$\cos 45° = \frac{1}{\sqrt{2}}$
lots of electrons detected
$\psi = \psi_{slit\,1} \pm \psi_{slit\,2}$
$|V\rangle$
$|H\rangle$

Some examples

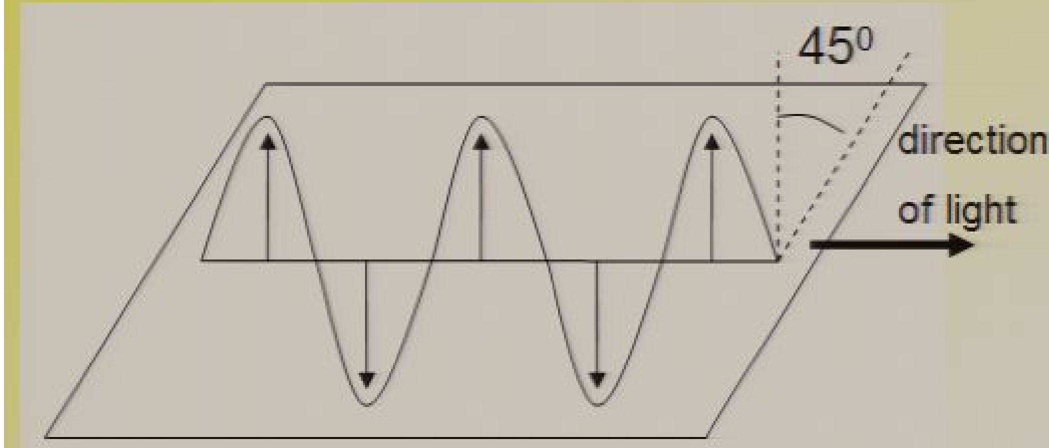


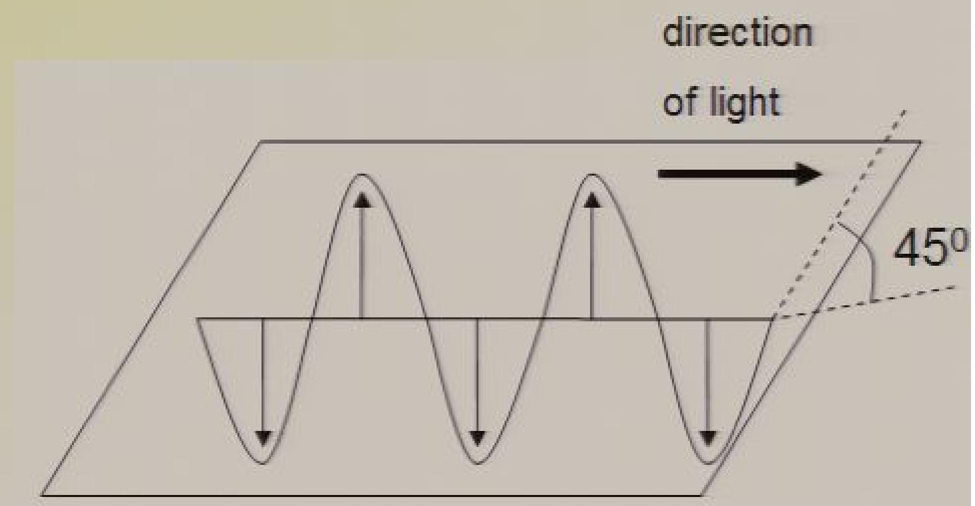
horizontally
polarized light



vertically

polarized light





light polarized at a 45 degree
angle to the horizontal ($+45^0$)

light polarized at another 45 degree
angle to the horizontal (-45^0)

Application of superposition: The quantum game

- A simple game with a coin.

- Ali: Heads

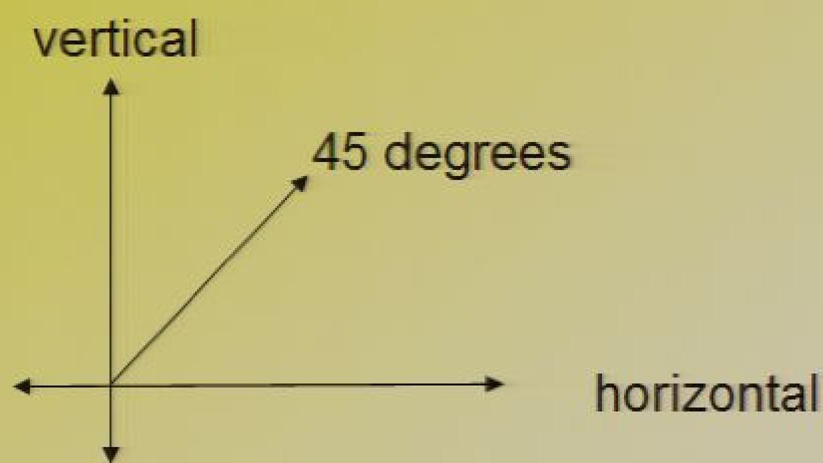
↓

- Brenda (can choose to flip the coin or not).

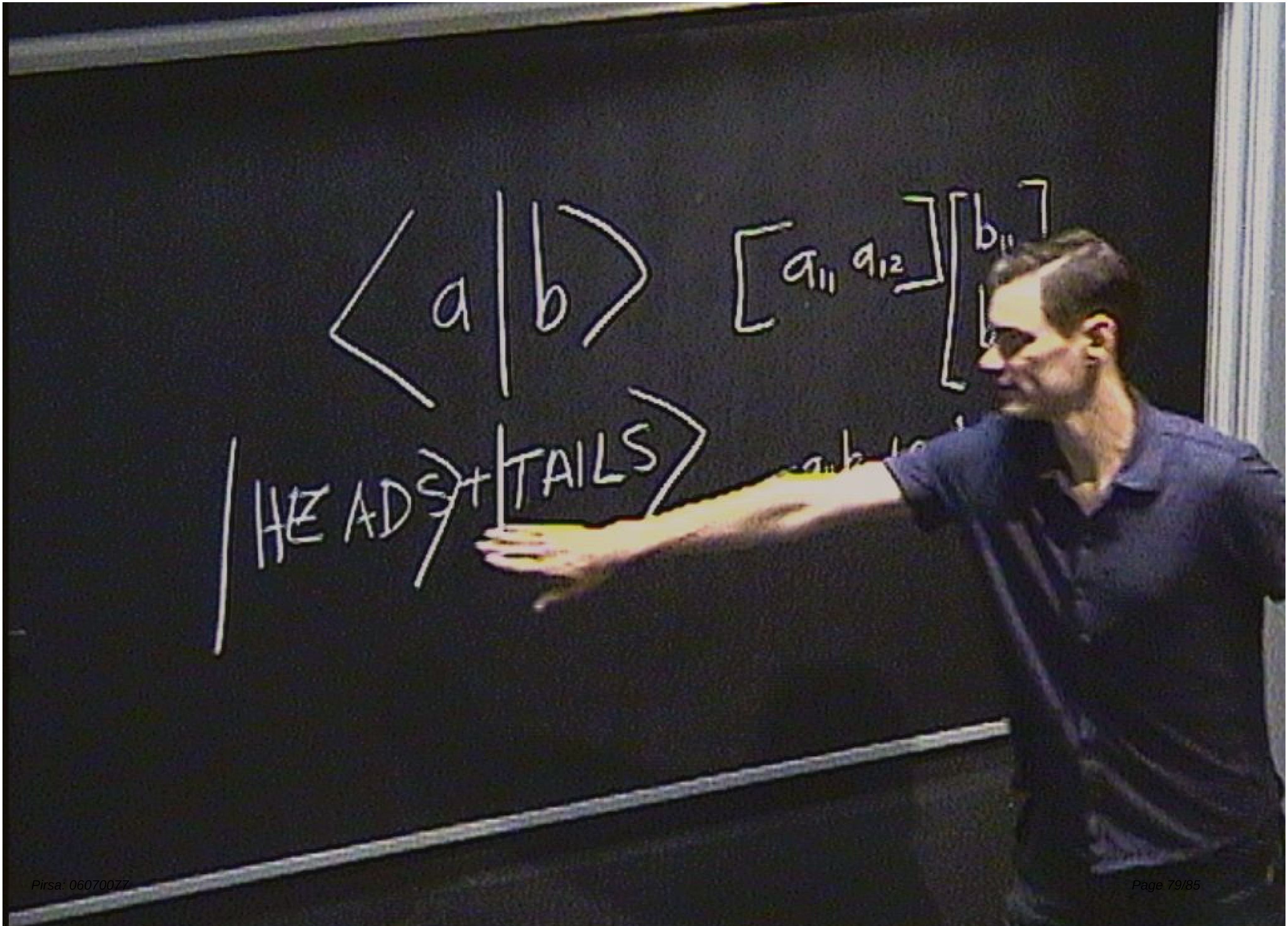
↓

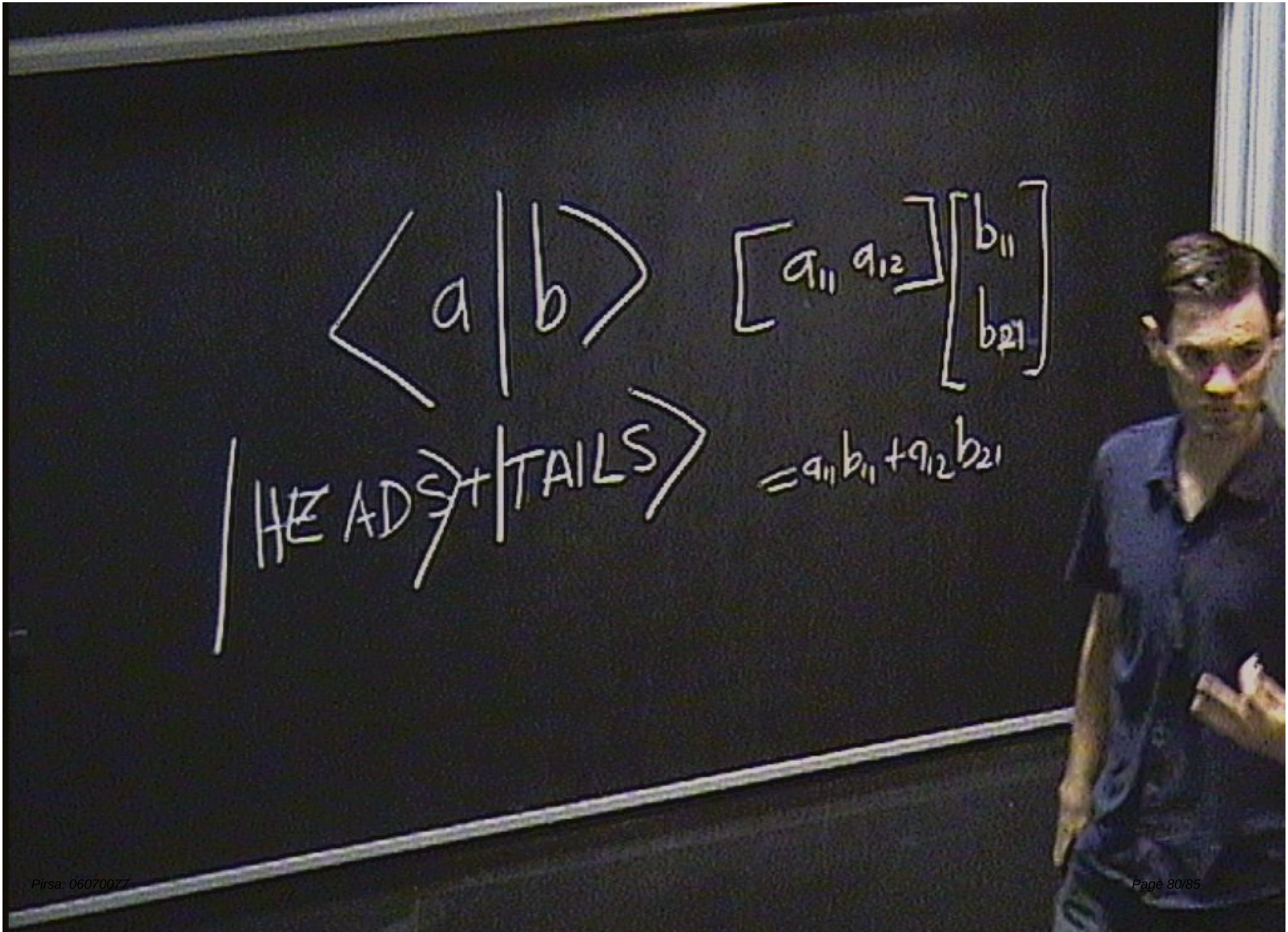
- Ali (Goal is to make the coin heads all of the time.)

Using superposition you can always win. How?

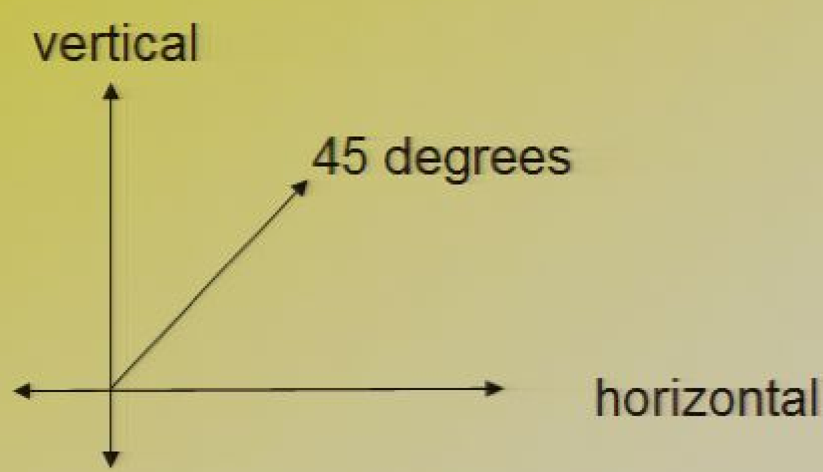


- flip takes H to V and V to H
- Acts on the superposition state a H + b V as follows:
- a H + b V $\rightarrow$ a V + b H


⟨a|b⟩
[a11 a12]
|HEADS⟩+|TAILS⟩

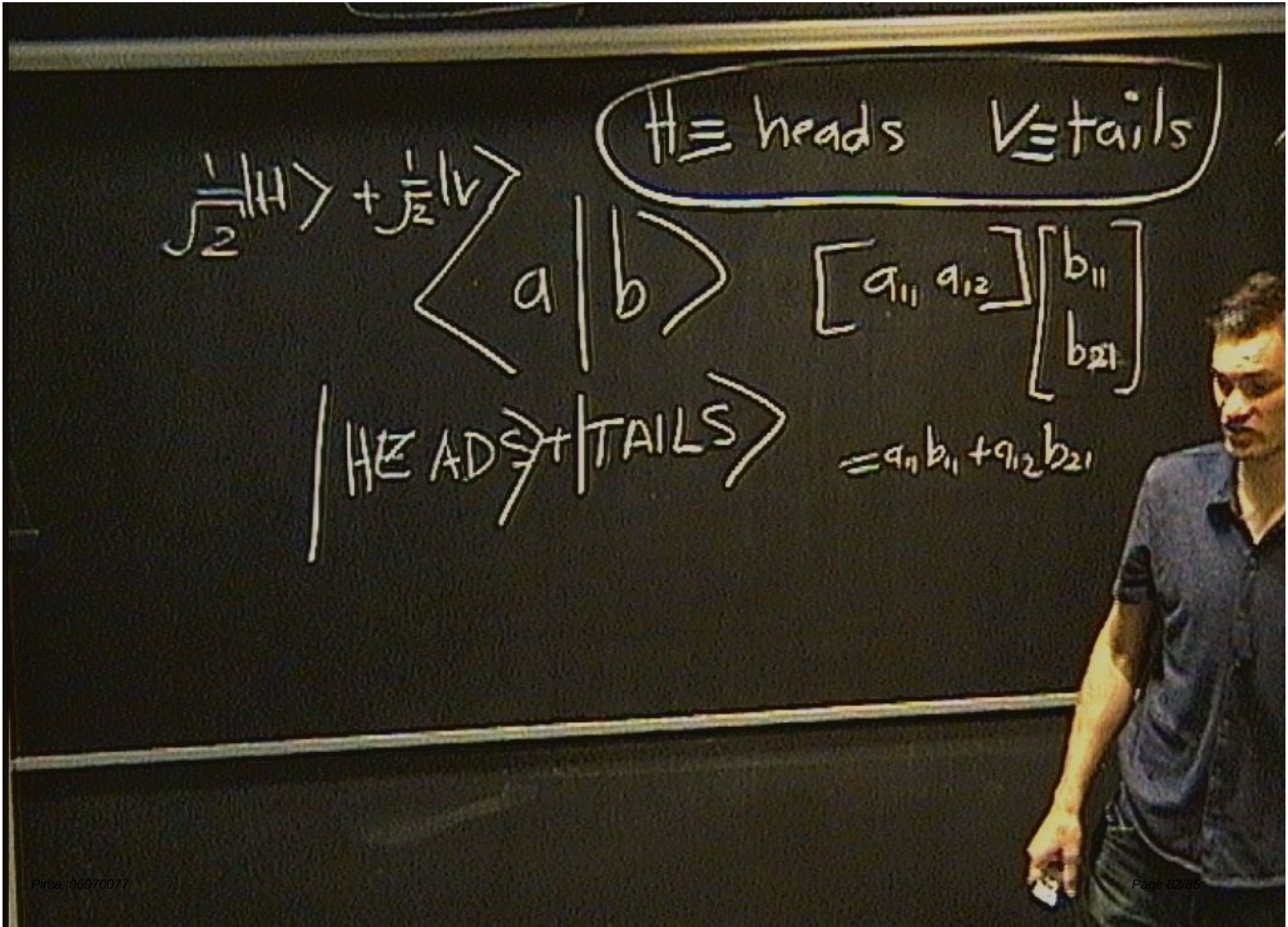

⟨a|b⟩
[a11 a12] [b11 b21]
= a11 b11 + a12 b21
|HEADS⟩ + |TAILS⟩

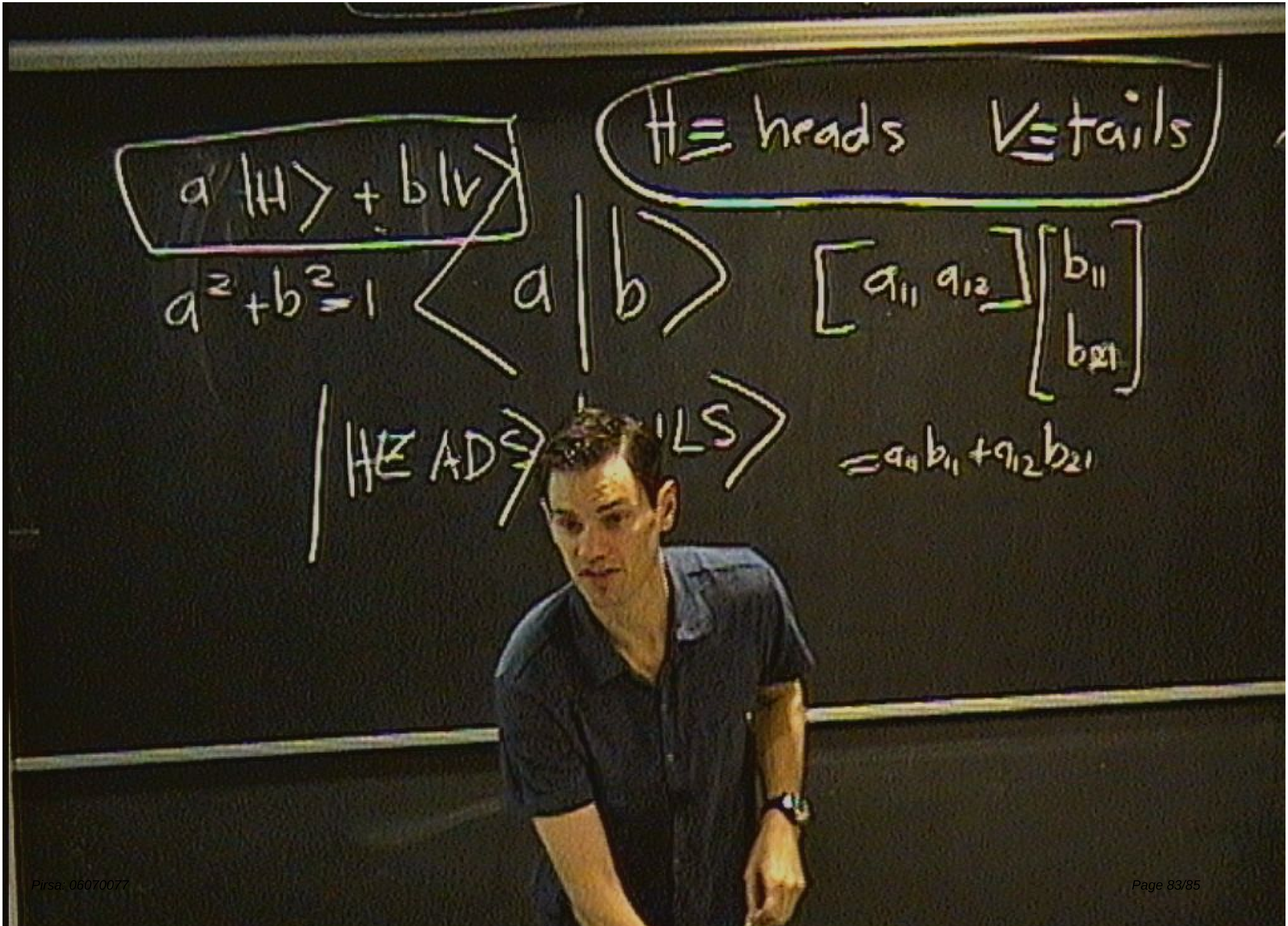
Using superposition you can always win. How?



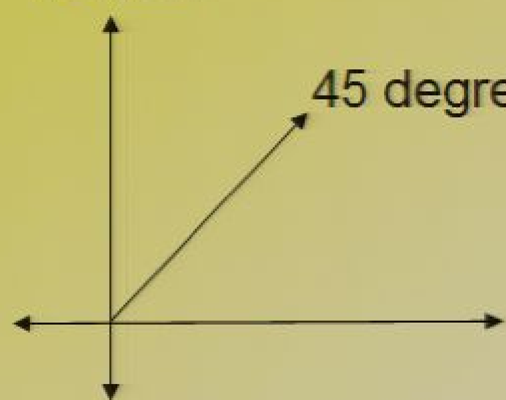
- flip takes H to V and V to H

- Acts on the superposition state a H + b V as follows:
- $a H + b V \rightarrow a V + b H$


H ≡ heads V ≡ tails
1/√2 |H⟩ + 1/√2 |V⟩
⟨a|b⟩
[a11 a12] [b11 b21]
|HEADS⟩ + |TAILS⟩
= a11 b11 + a12 b21

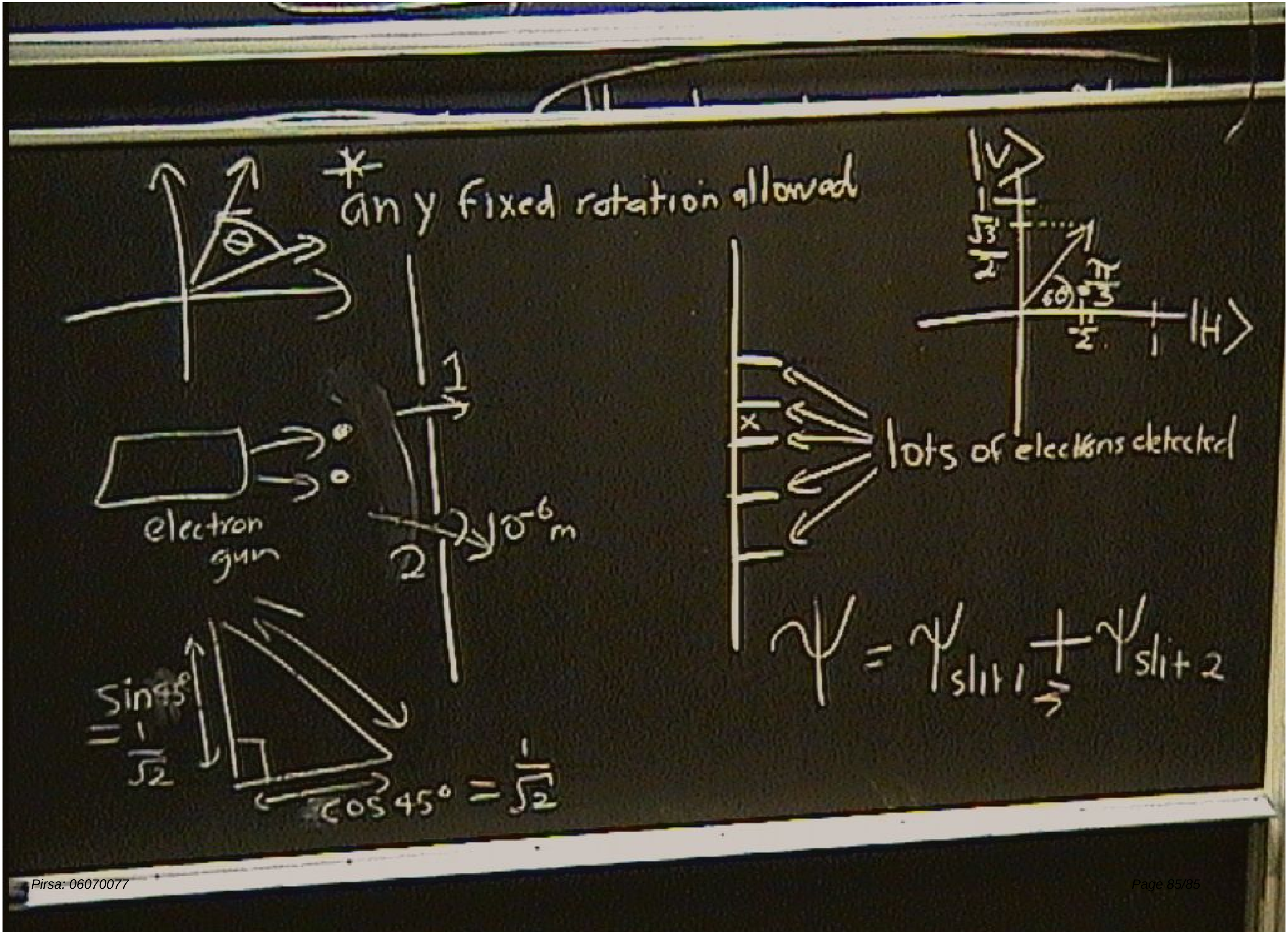

H = heads V = tails
a|H> + b|V>
a2+b2=1
<a|b>
[a11 a12] [b11 b21]
=a11b11+a12b21

Using superposition you can always win. How?



- flip takes H to V and V to H

- Acts on the superposition state a H + b V as follows:
- a H + b V → a V + b H


* any fixed rotation allowed
electron gun
1
2
10^-6 m
lots of electrons detected
|V>
|H>
sin 45° = 1/√2
cos 45° = 1/√2
ψ = ψslit 1 + ψslit 2