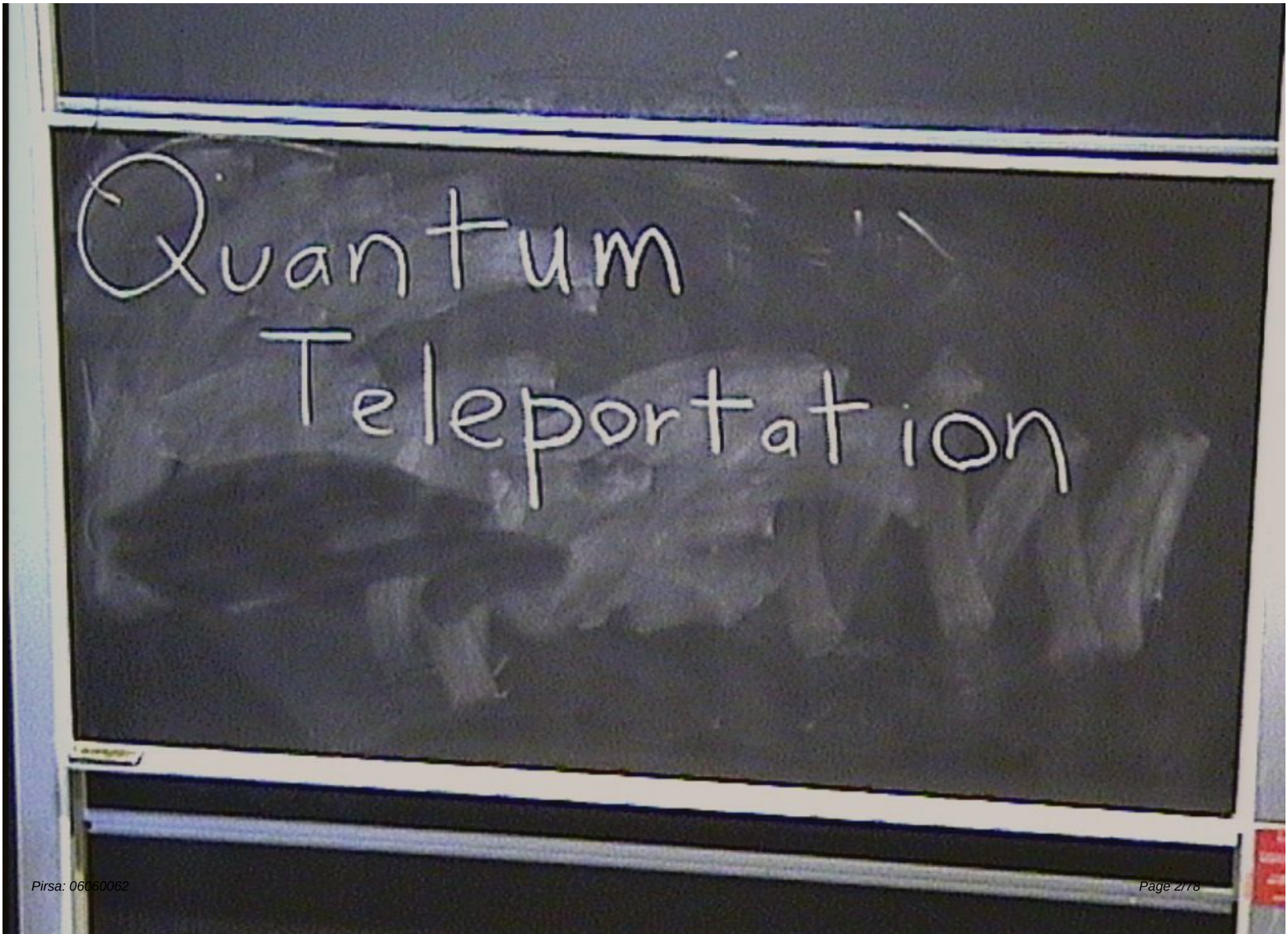
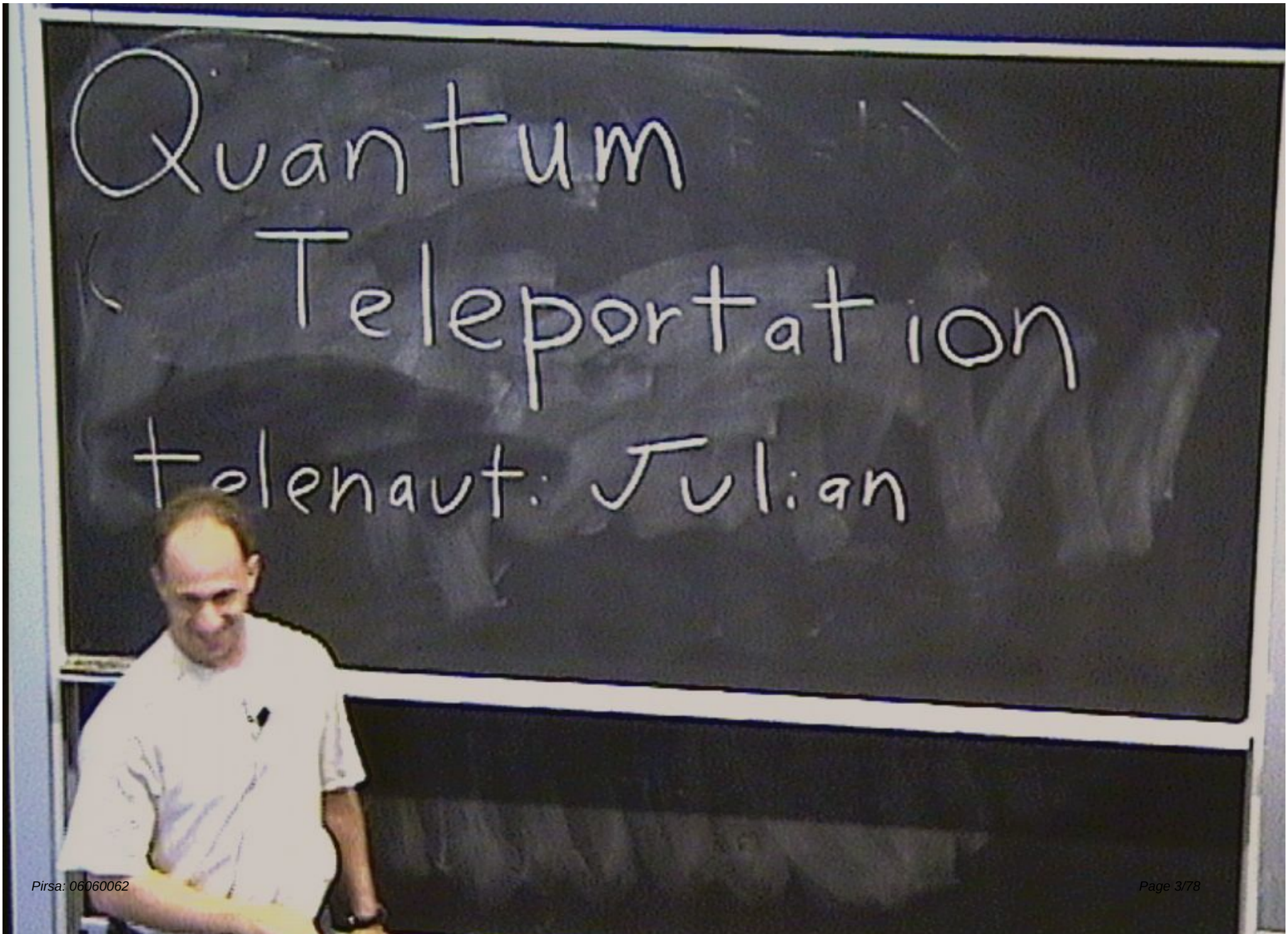
Title: Quantum Teleportation

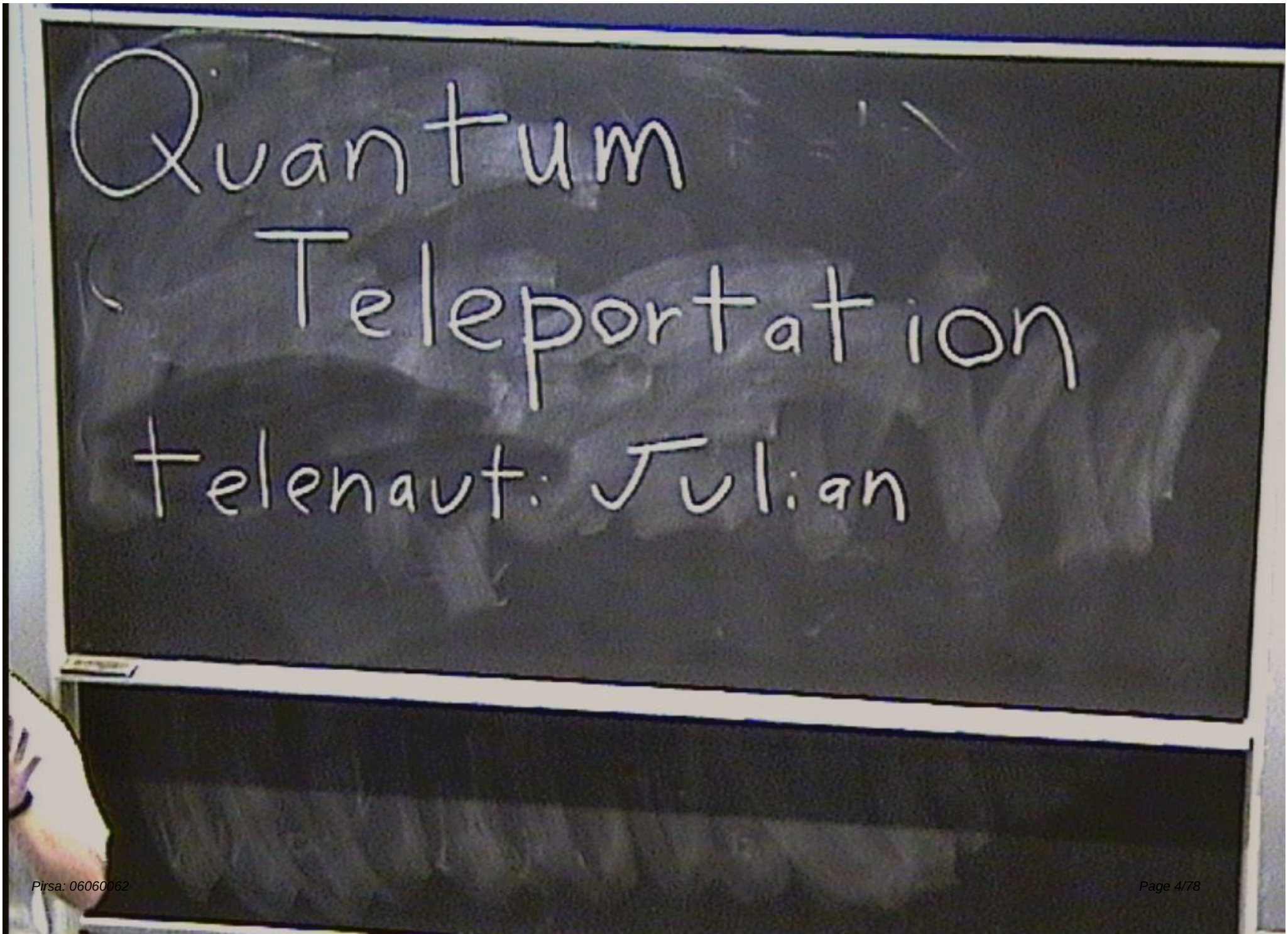
Date: Jun 28, 2006 03:00 PM

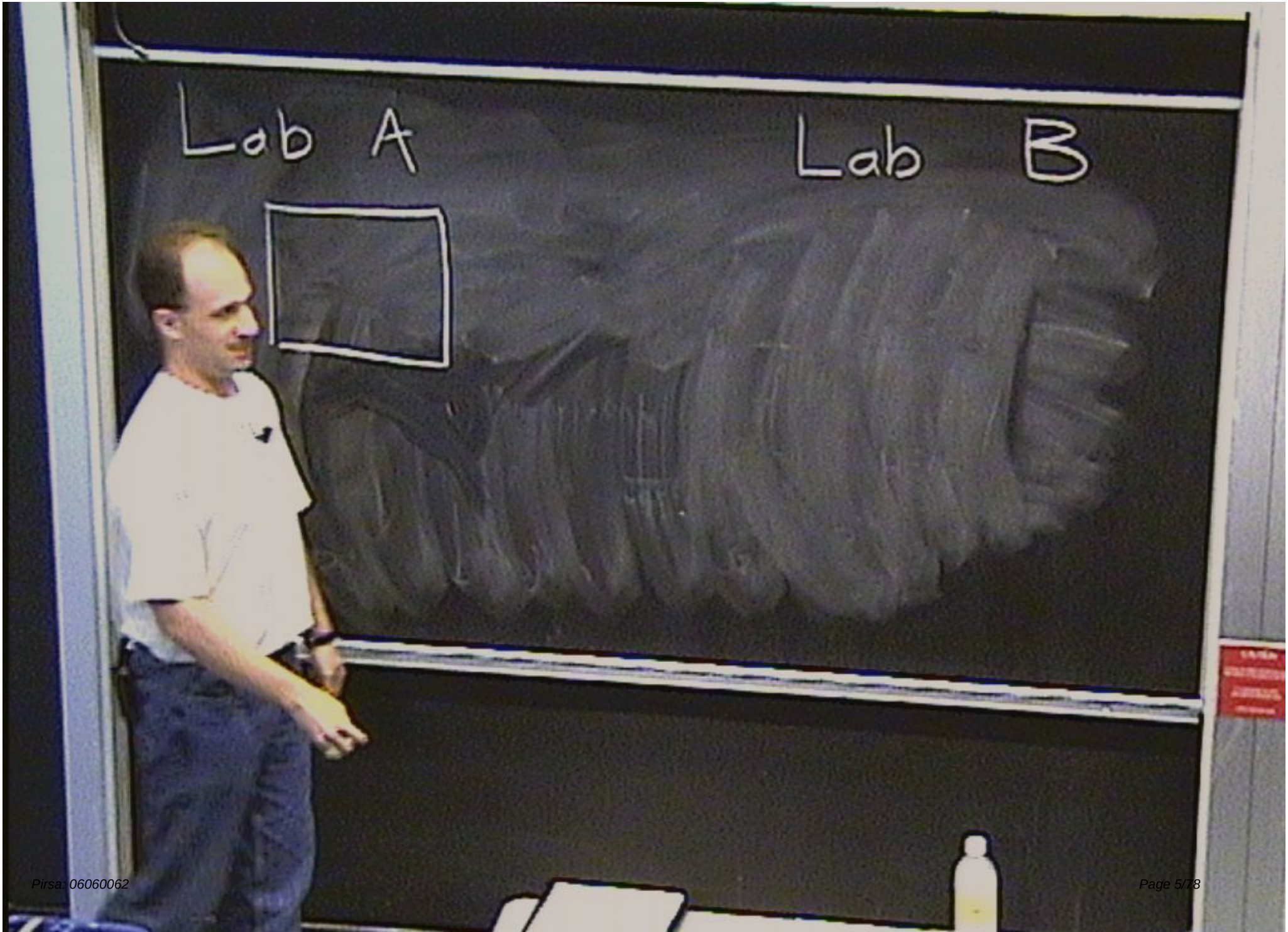
URL: http://pirsa.org/06060062

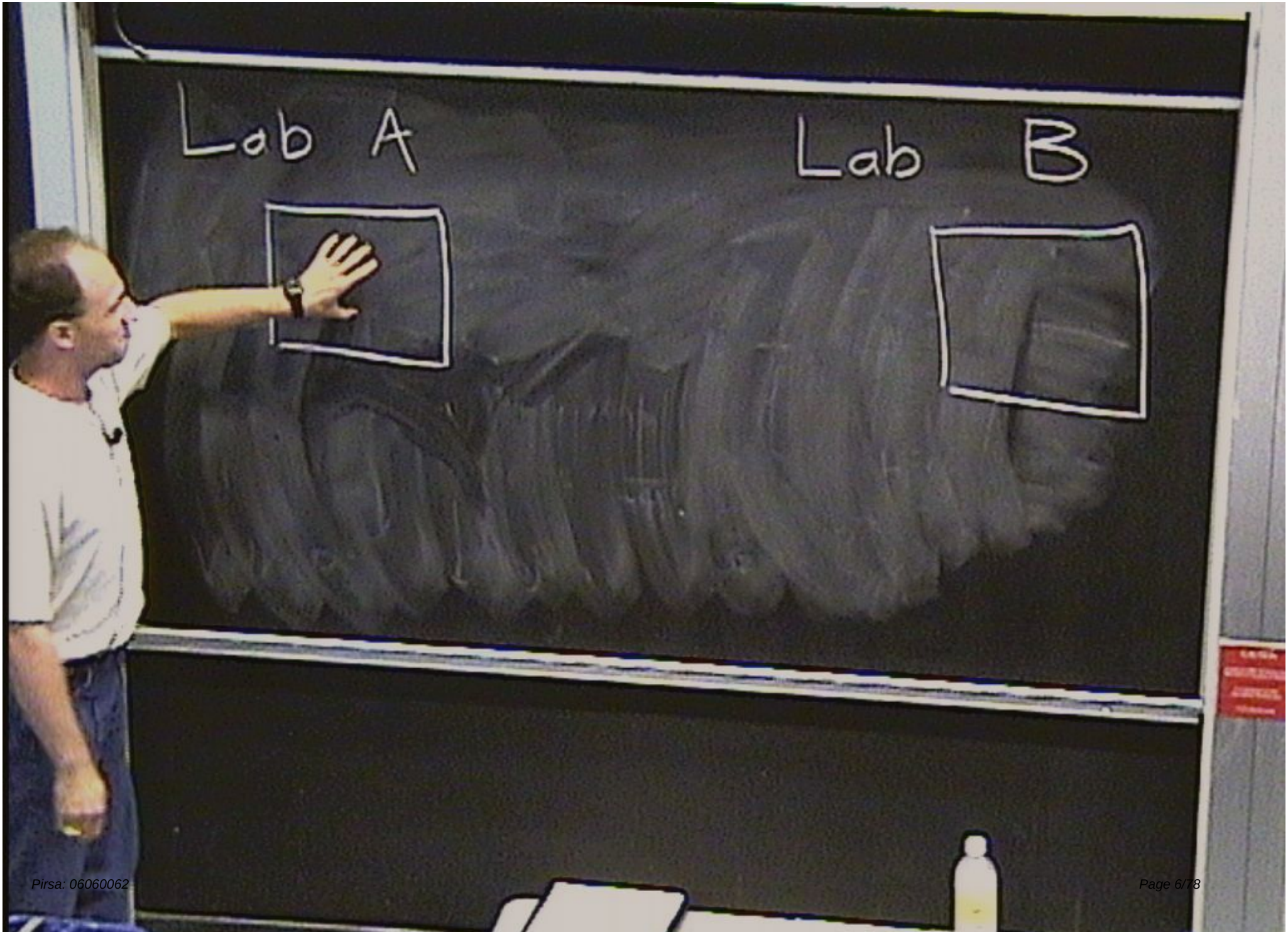
Abstract:

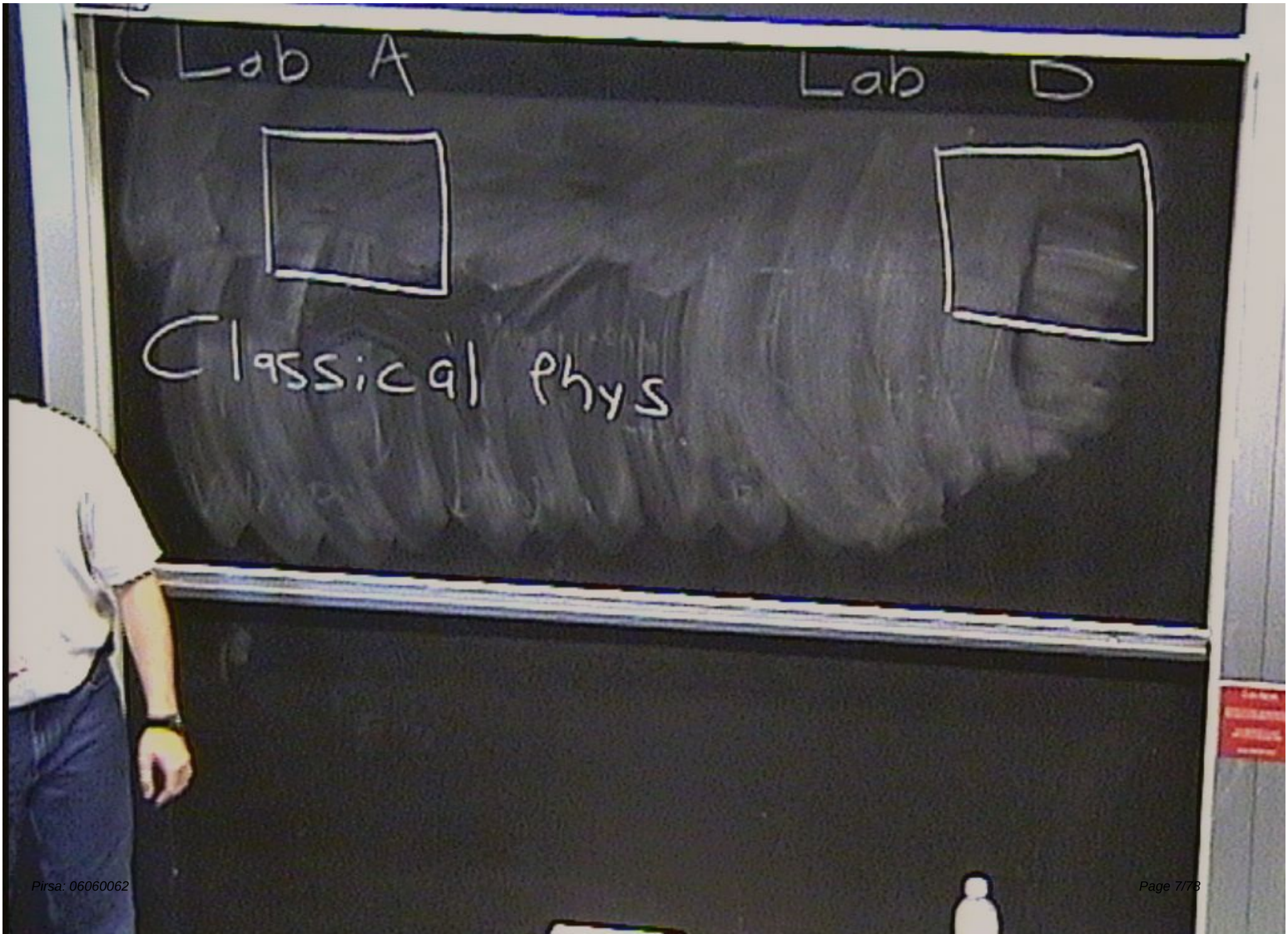

Quantum
Teleportation

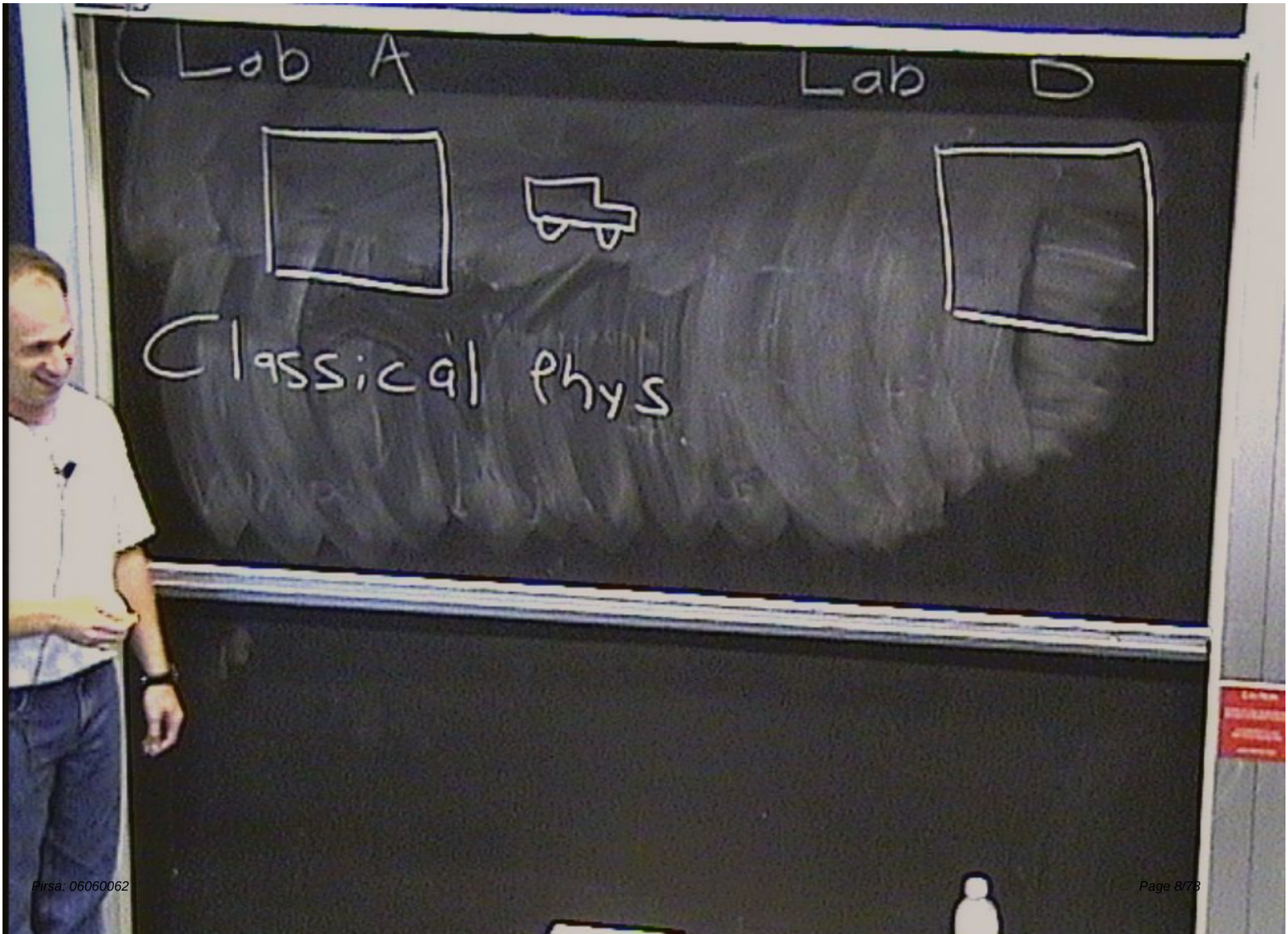

Quantum
Teleportation
telenaut: Julian

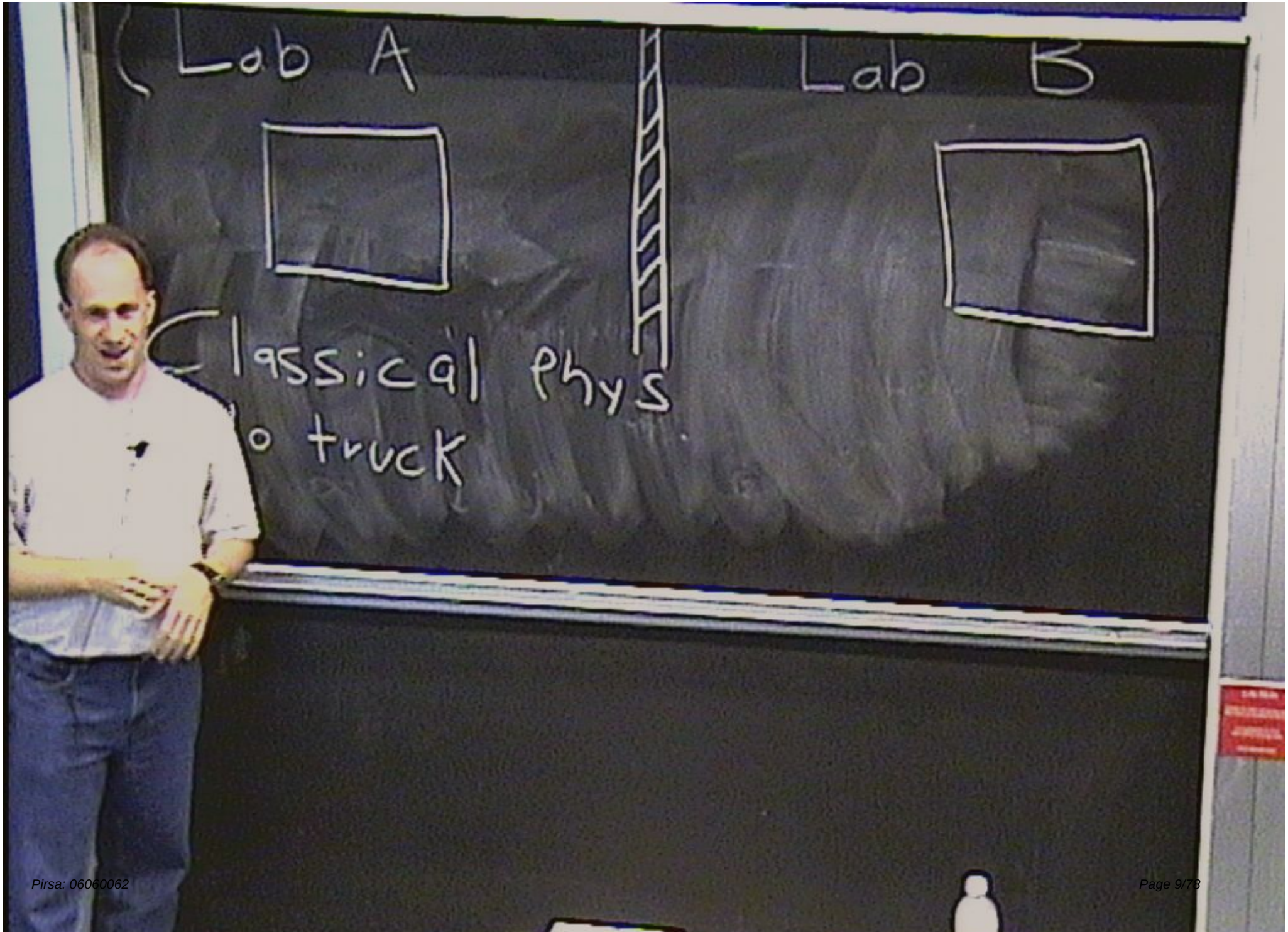

Quantum
Teleportation
telenaut: Julian

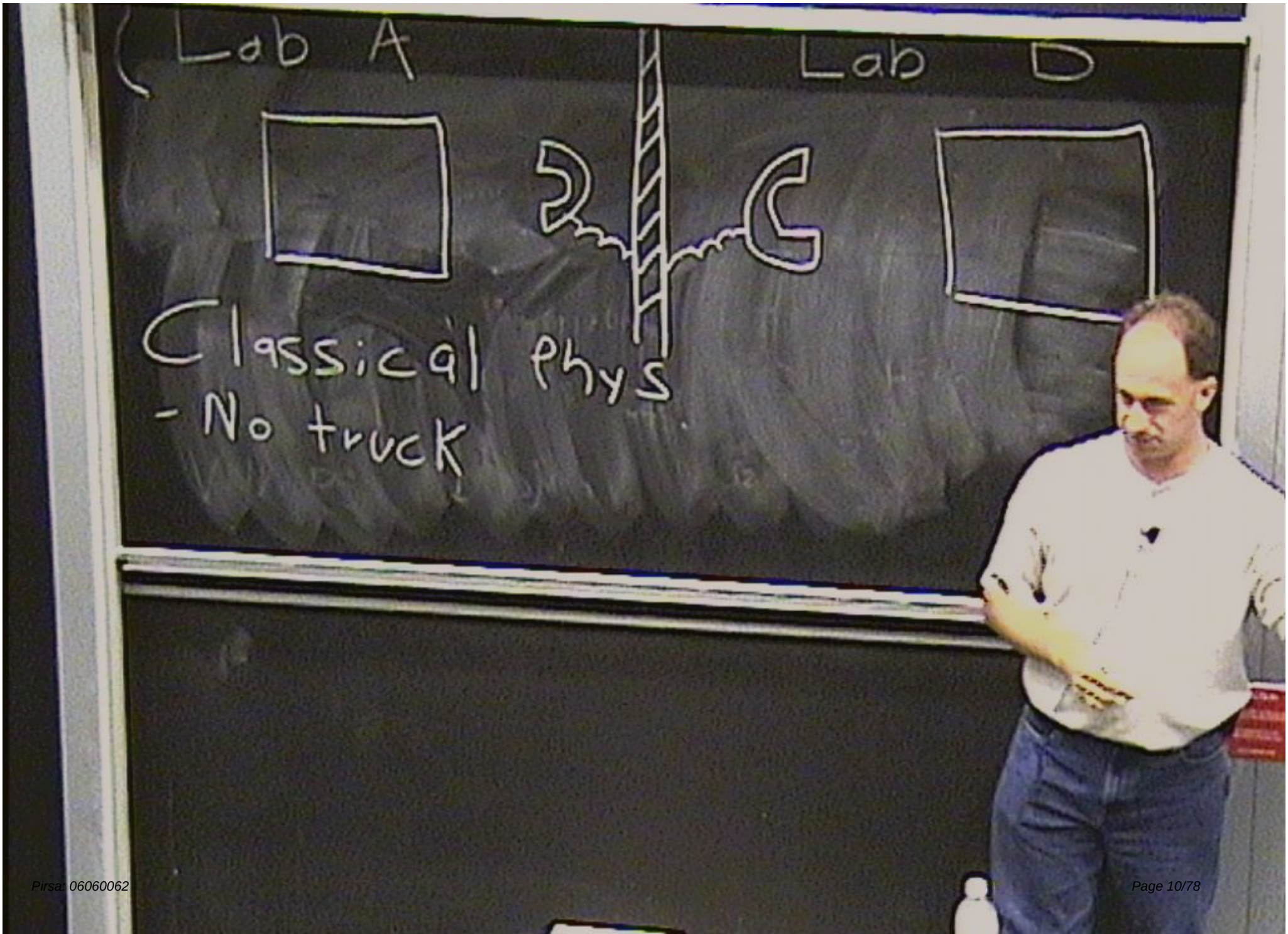

Lab A
Lab B

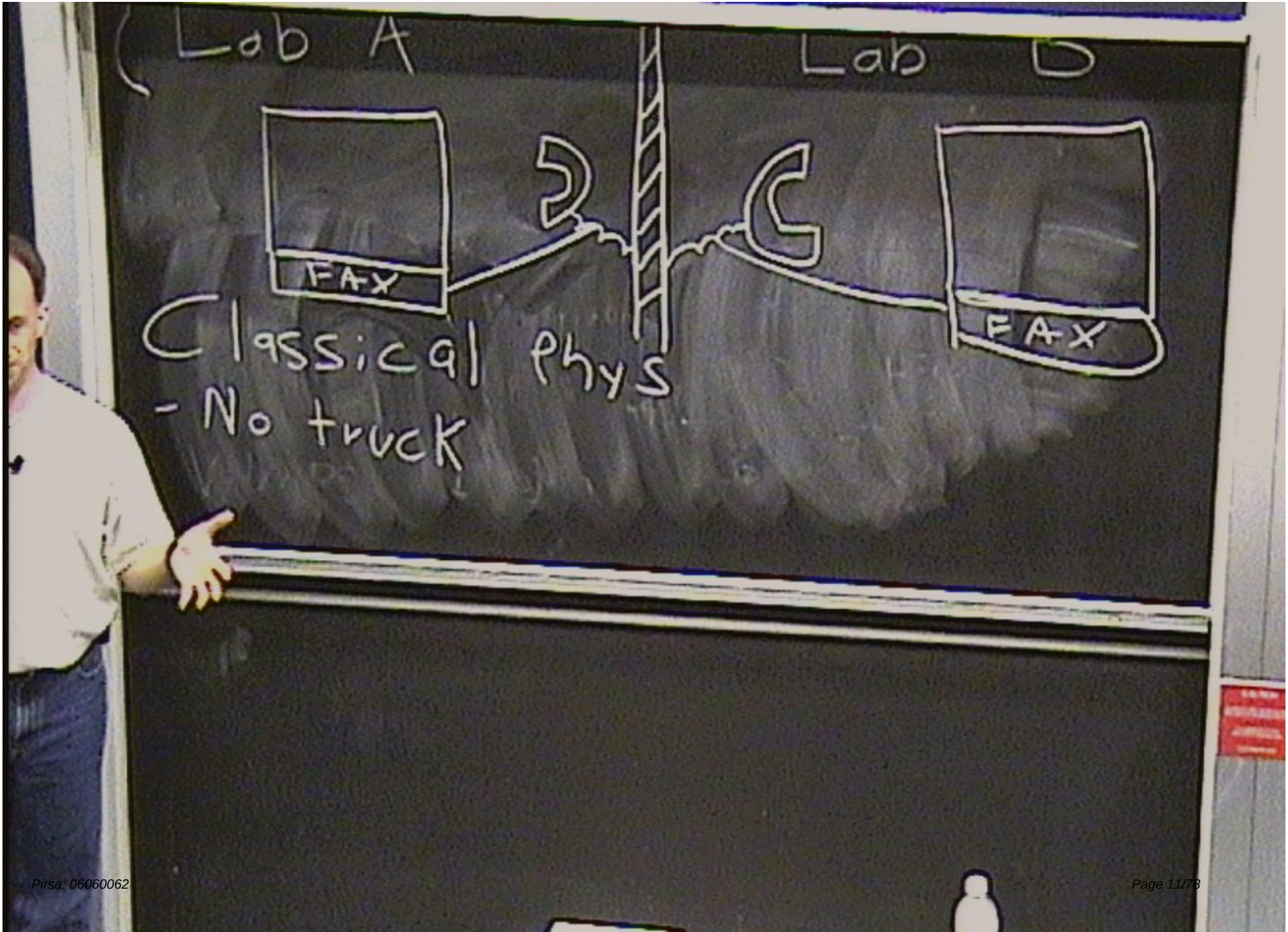

Lab A
Lab B

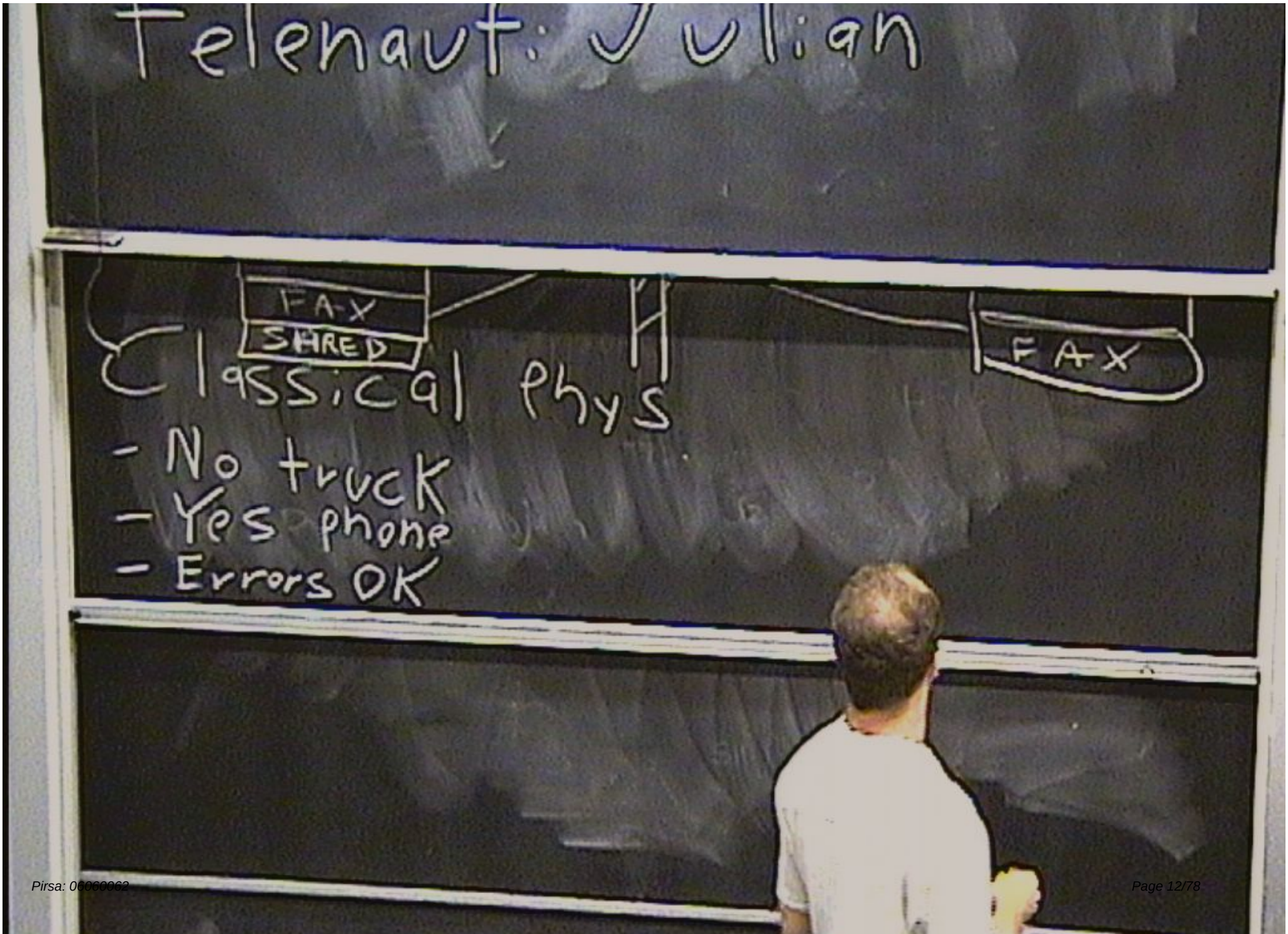

Lab A
Lab D
Classical Phys

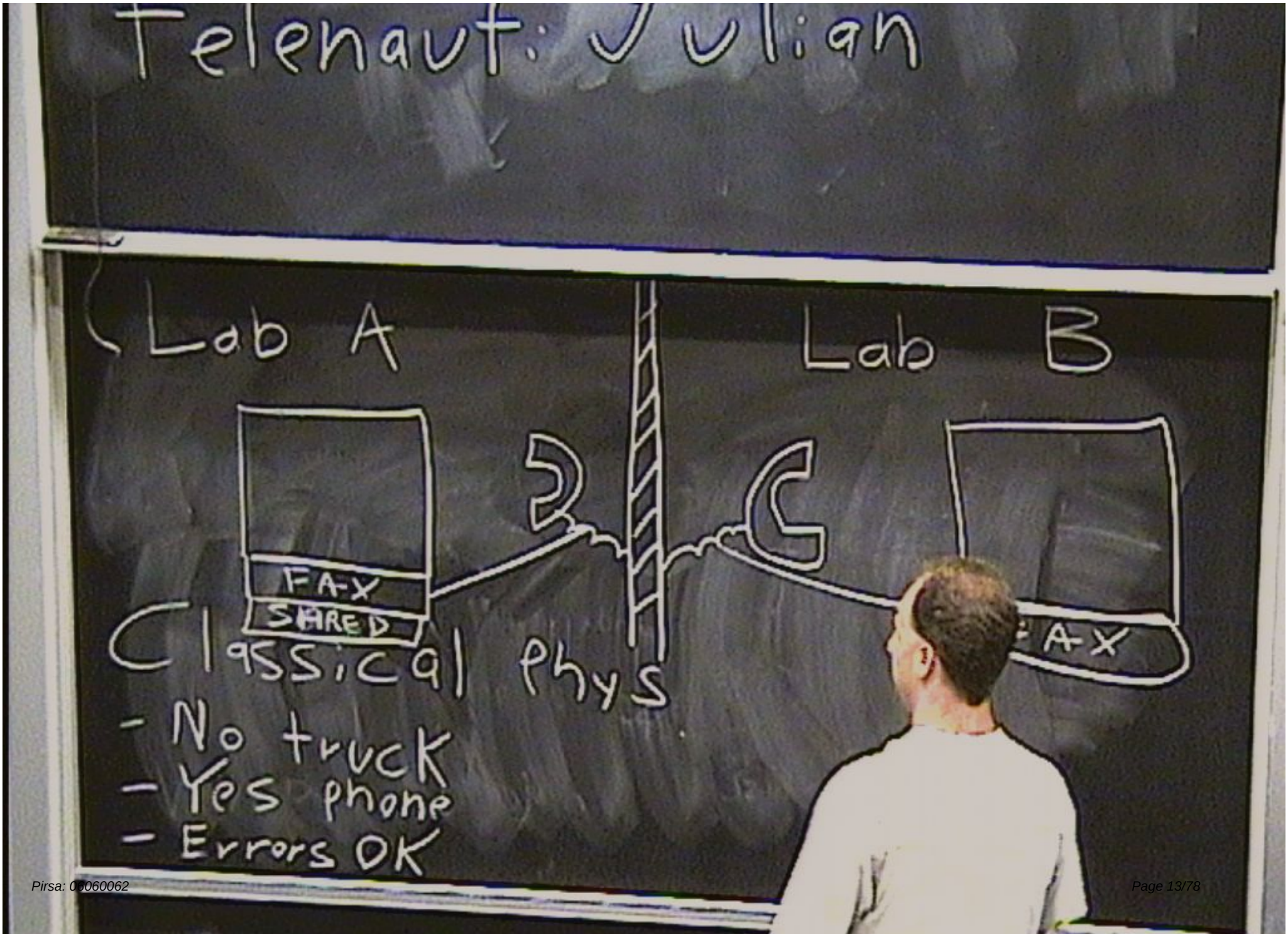

Lab A
Lab D
Classical Phys

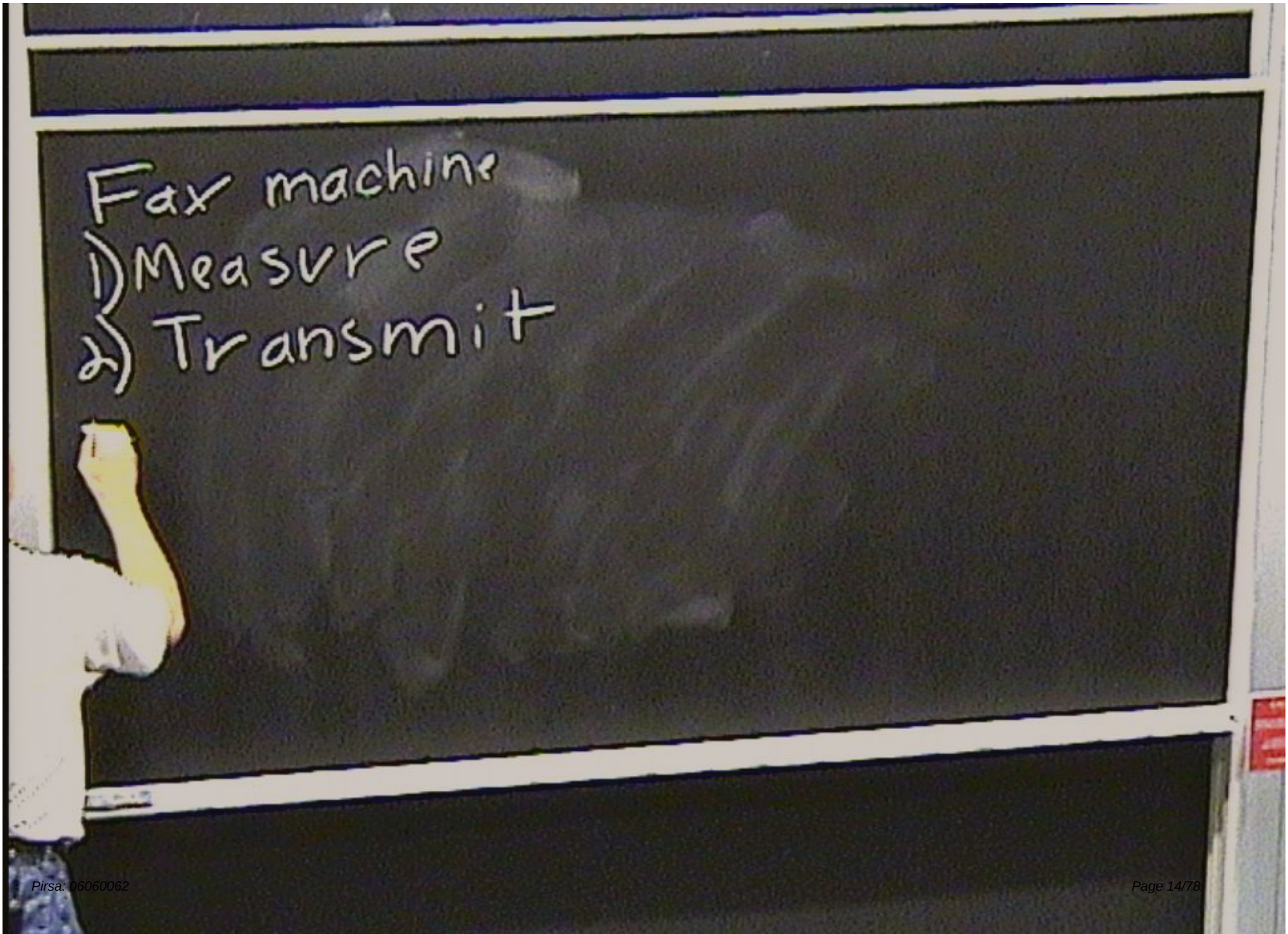

Lab A
Lab B
lassical phys
o truck

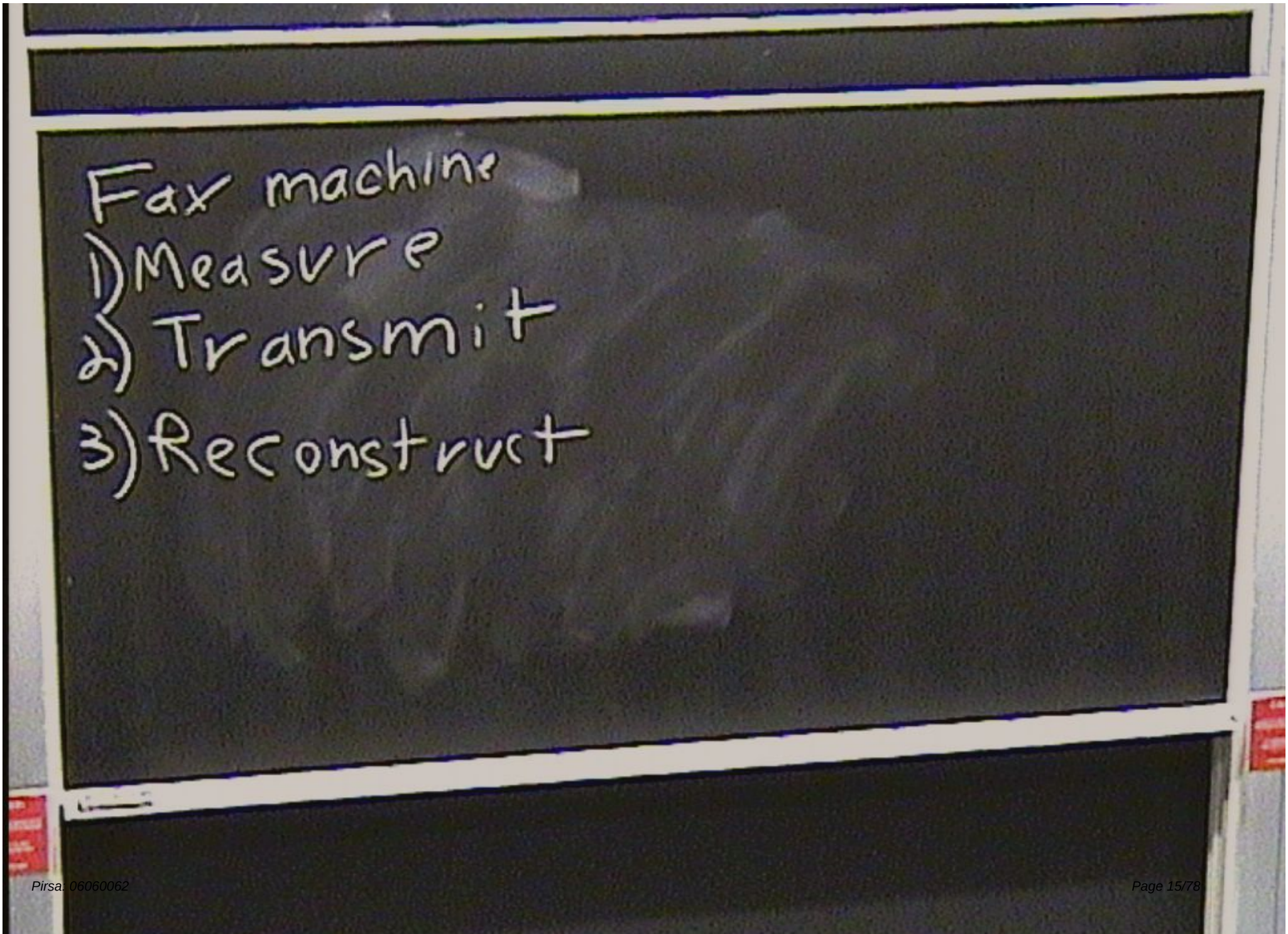

Lab A
Lab D
Classical Phys
- No truck

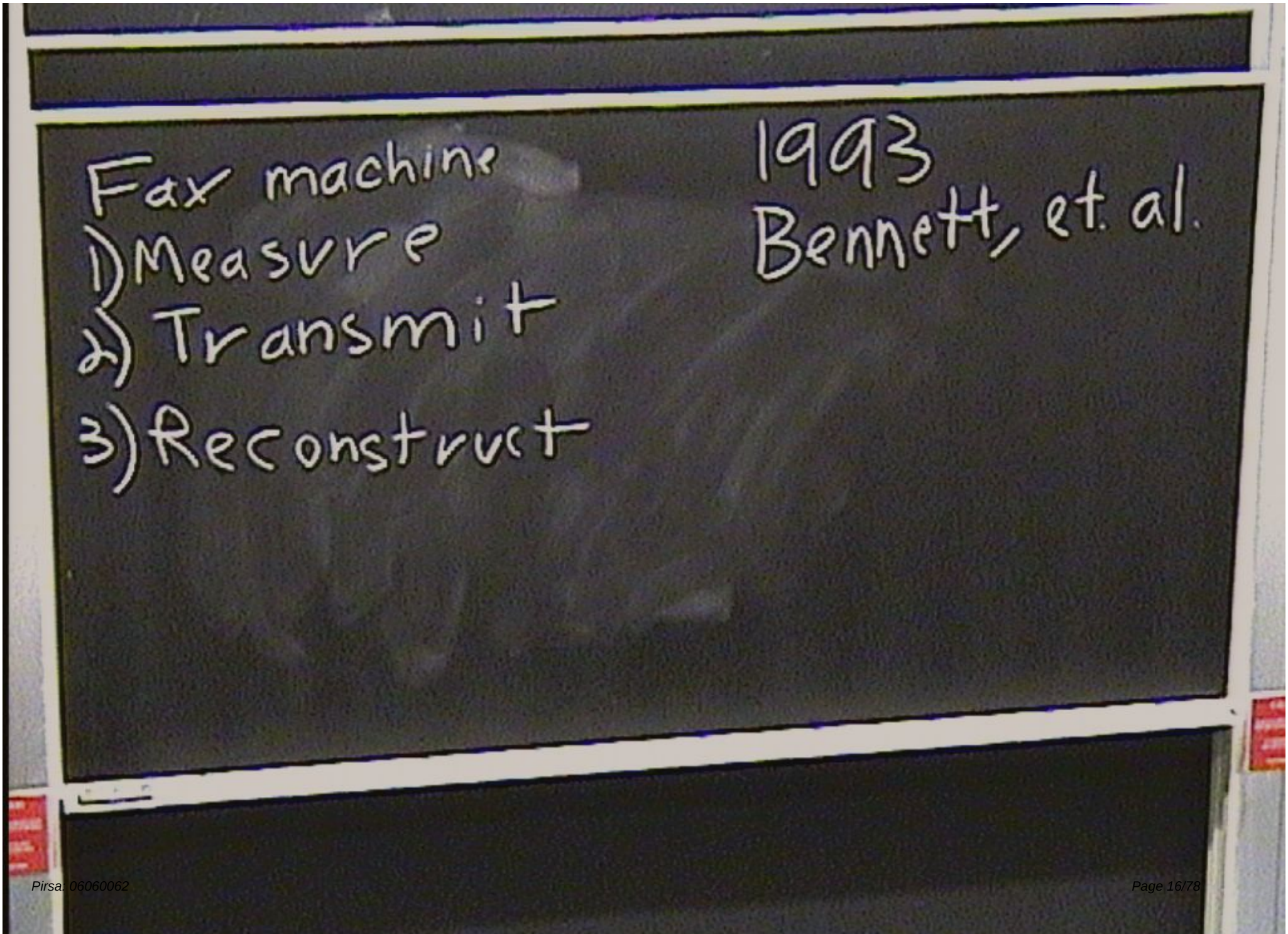

Lab A
Lab B
FAX
FAX
Classical phys
- No truck

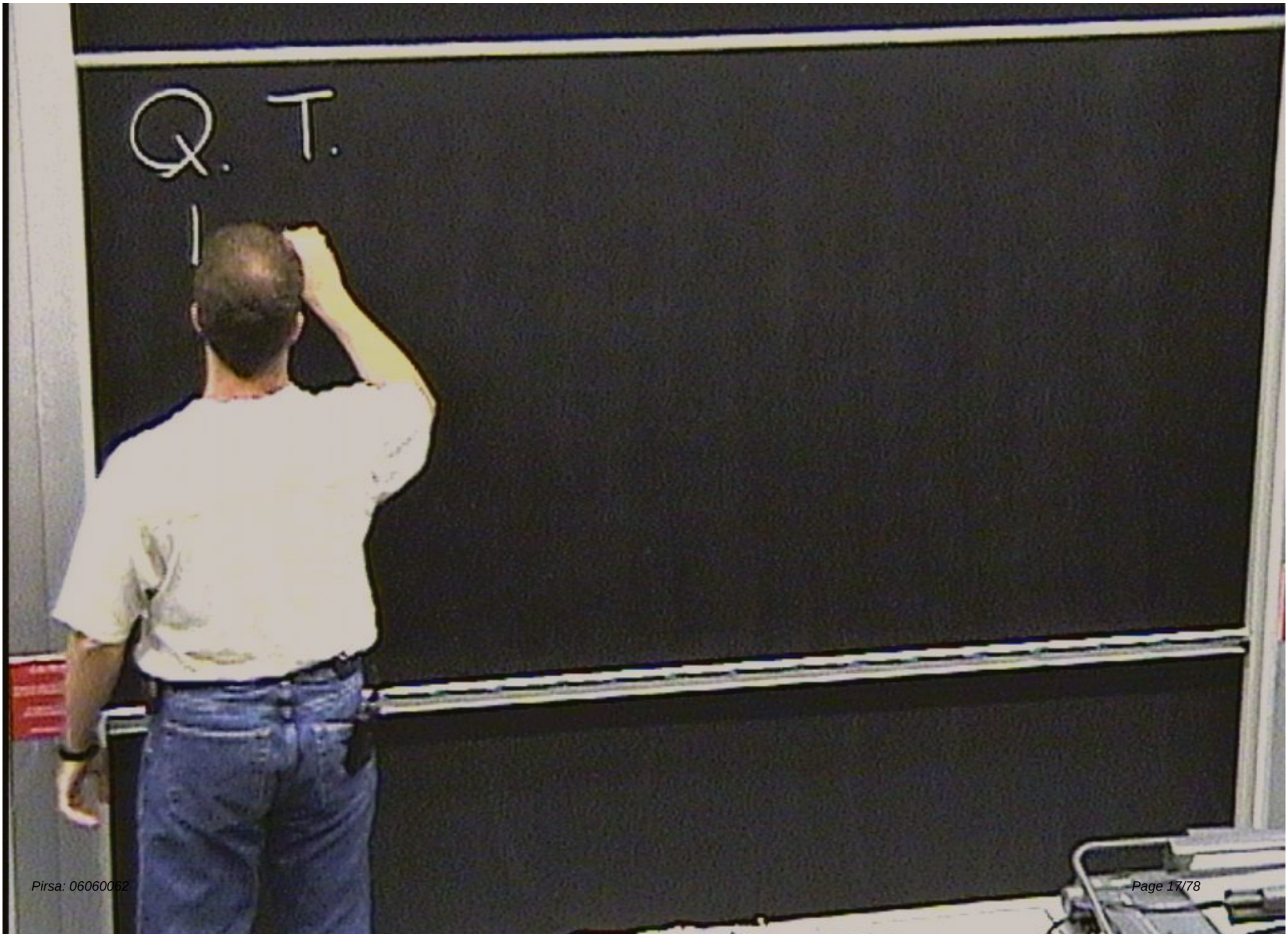

Telenaut: Julian
FAX
SHRED
FAX
Classical phys
- No truck
- Yes phone
- Errors OK

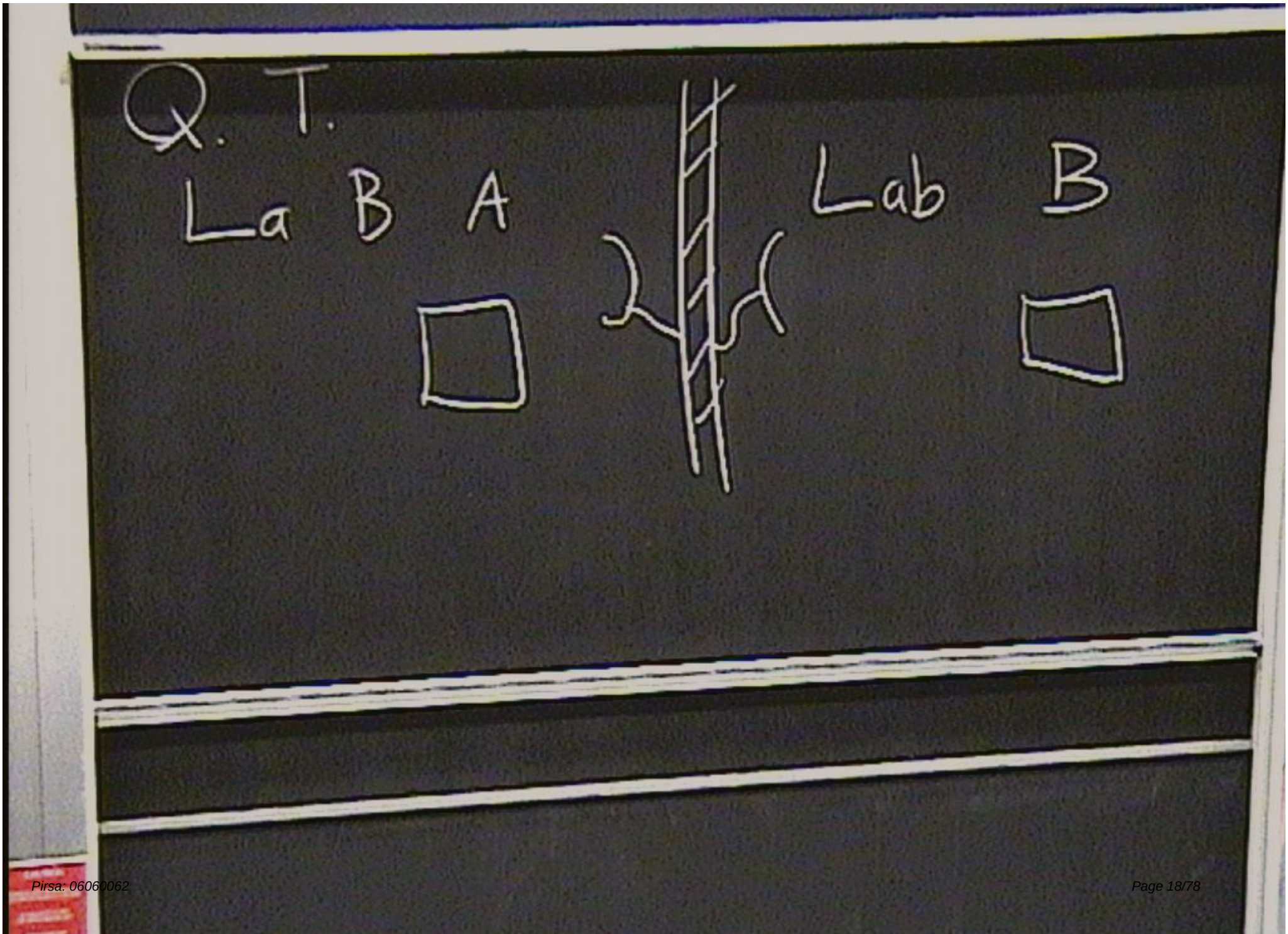

Telenaut: Julian
Lab A
Lab B
FAX
SHARED
Classical phys
- No truck
- Yes phone
- Errors OK

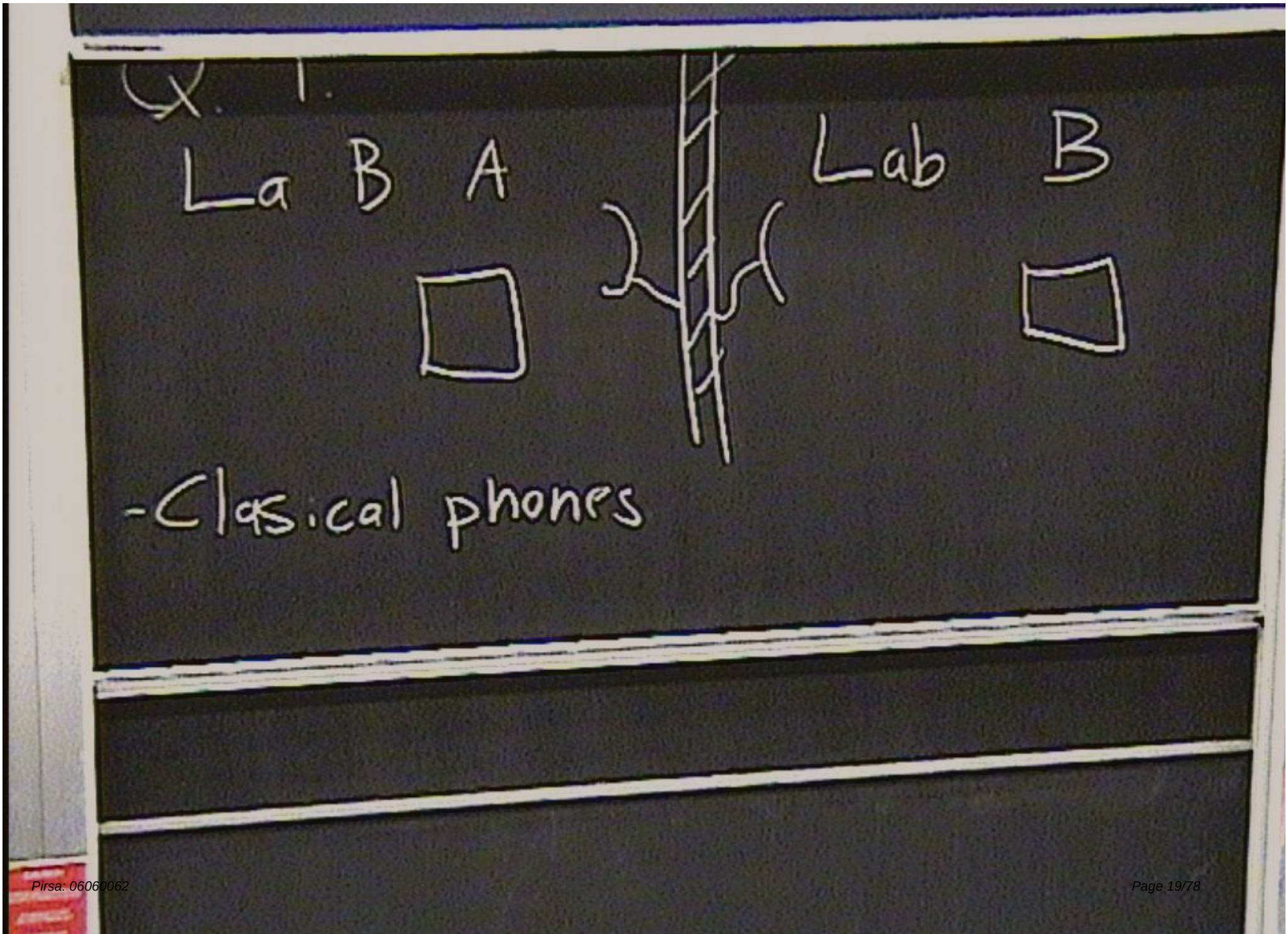

Fax machine
1) Measure
2) Transmit


Fax machine
1) Measure
2) Transmit
3) Reconstruct

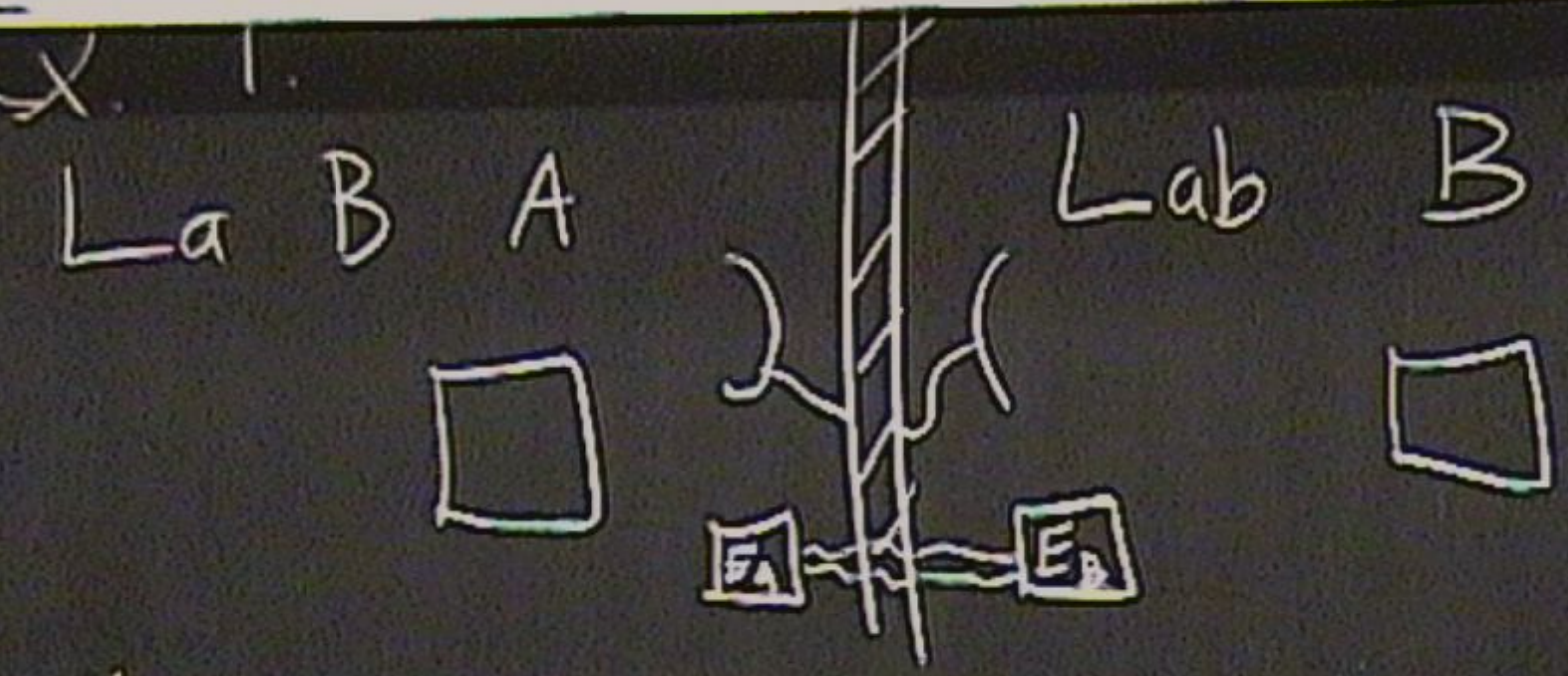

Fax machine
1) Measure
2) Transmit
3) Reconstruct
1993
Bennett, et. al.


Q. T.

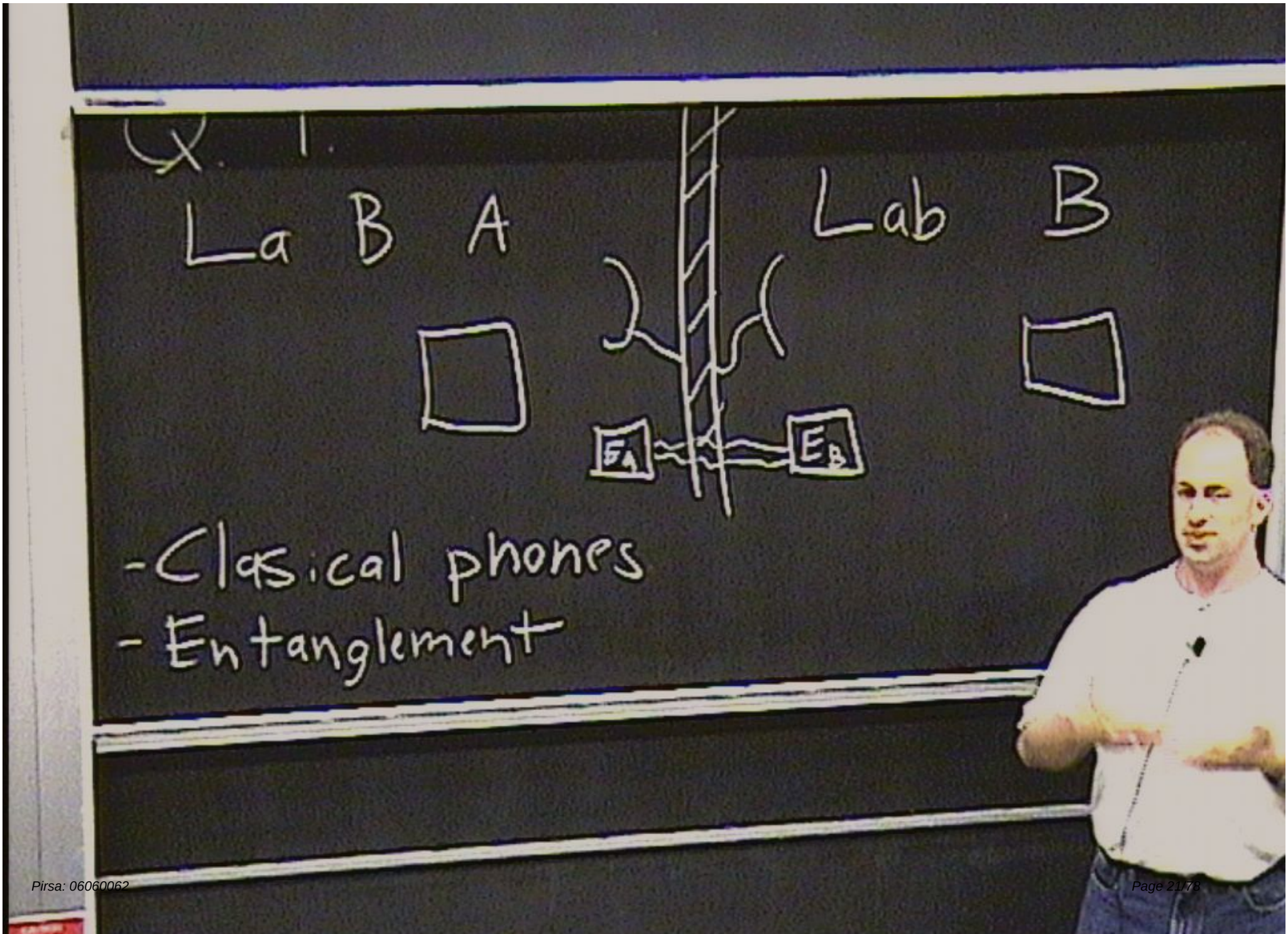

Q. T.
La B A
Lab B


Q. 1.
Lab A
Lab B
-Classical phones

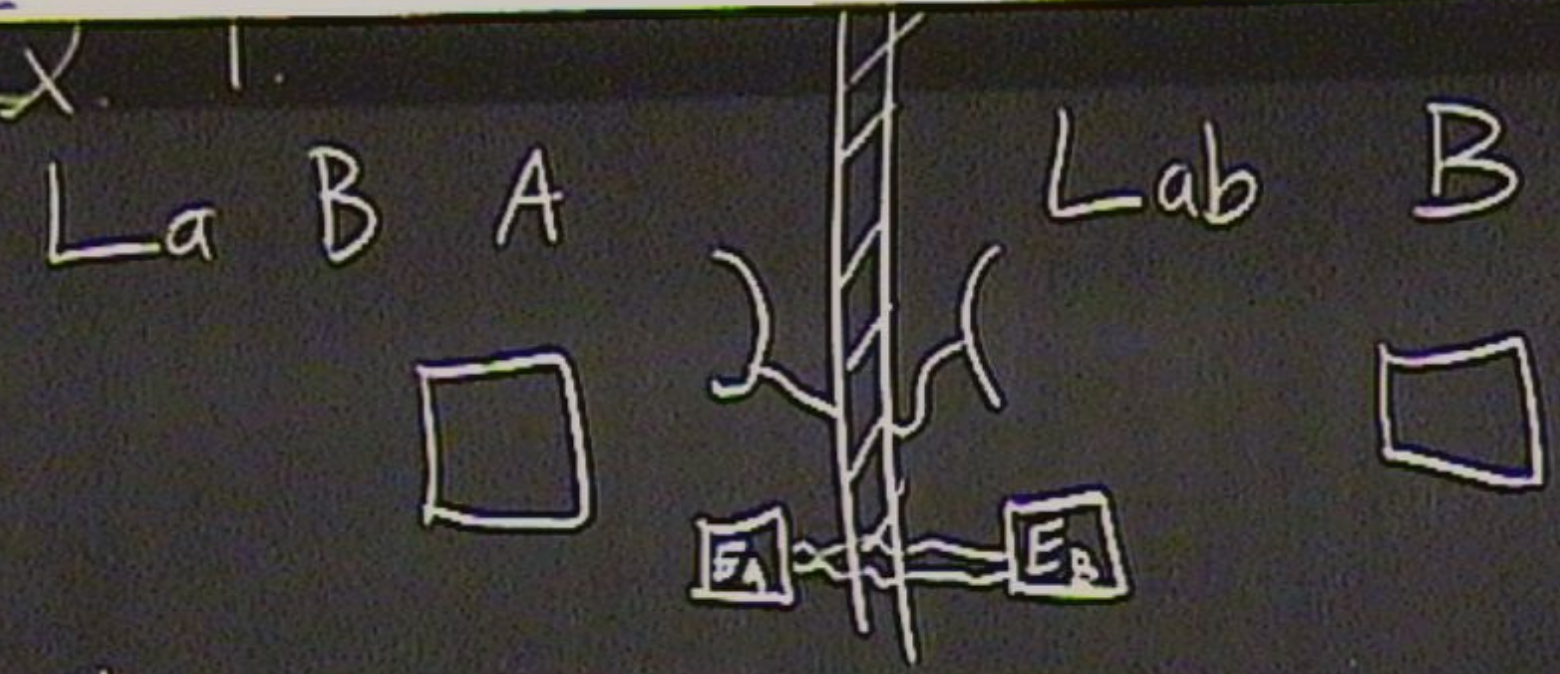
Q. 1.



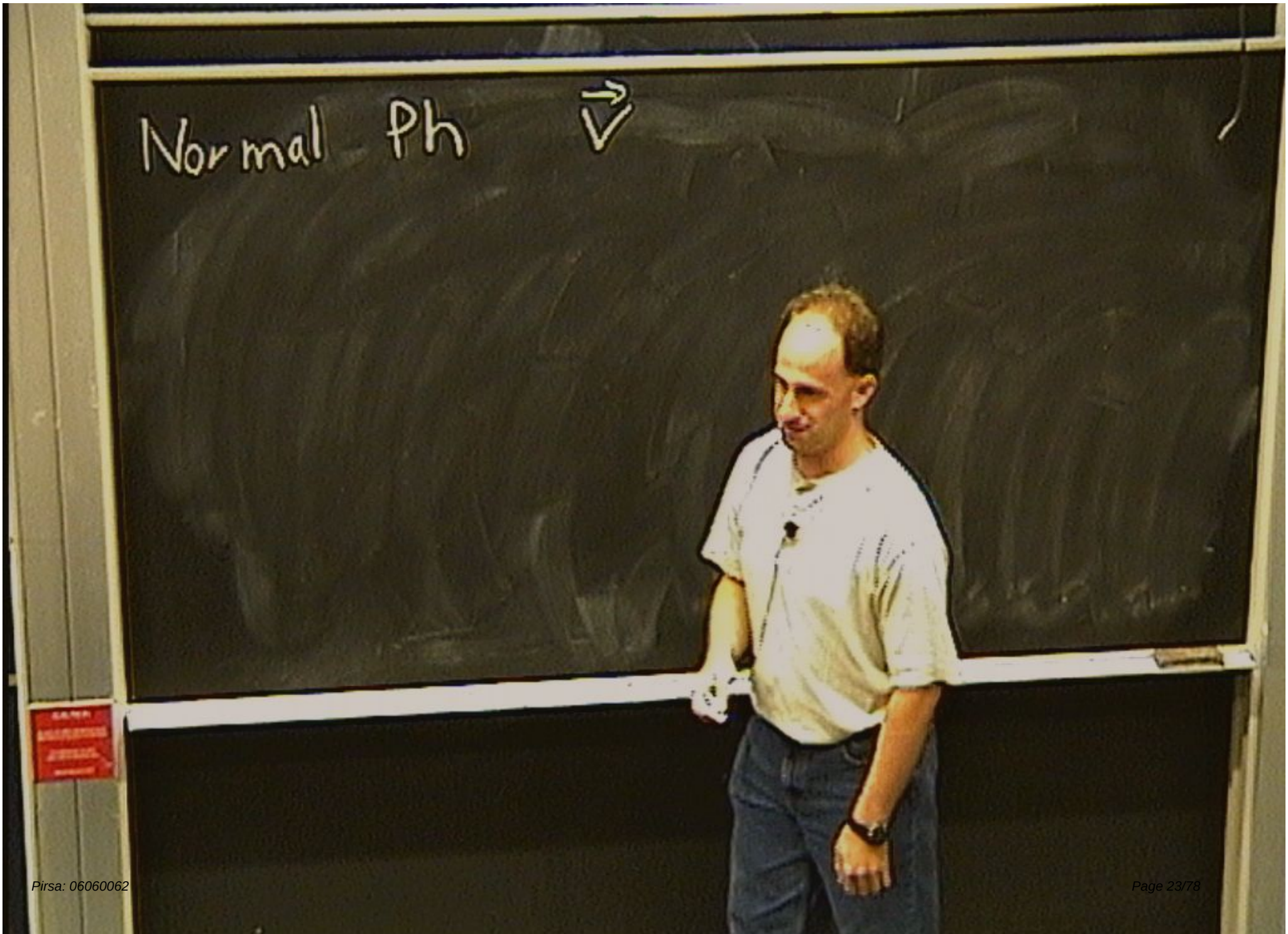
- Classical phones

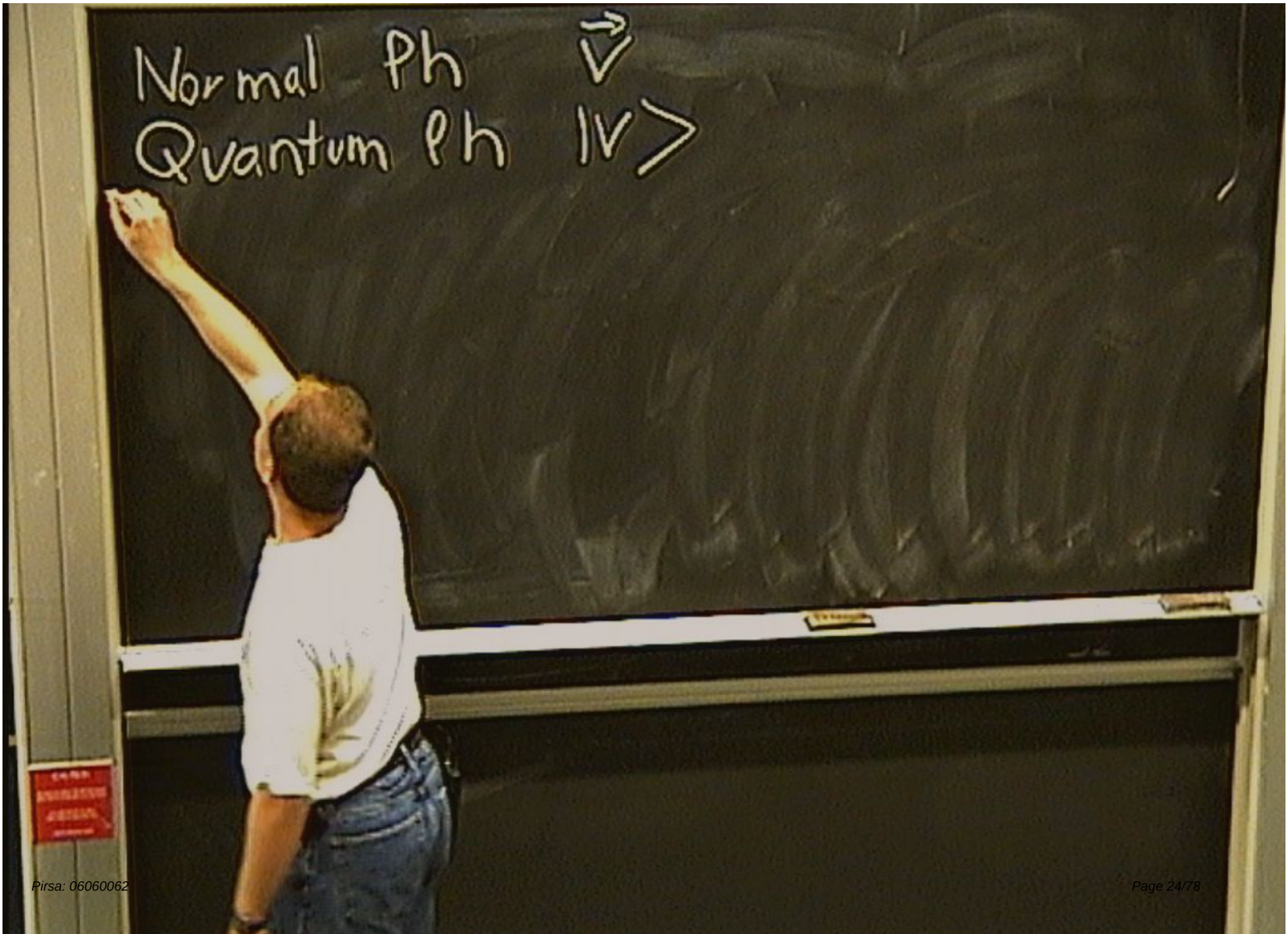

Q. 1.
Lab A
Lab B
E_A
E_B
- Classical phones
- Entanglement

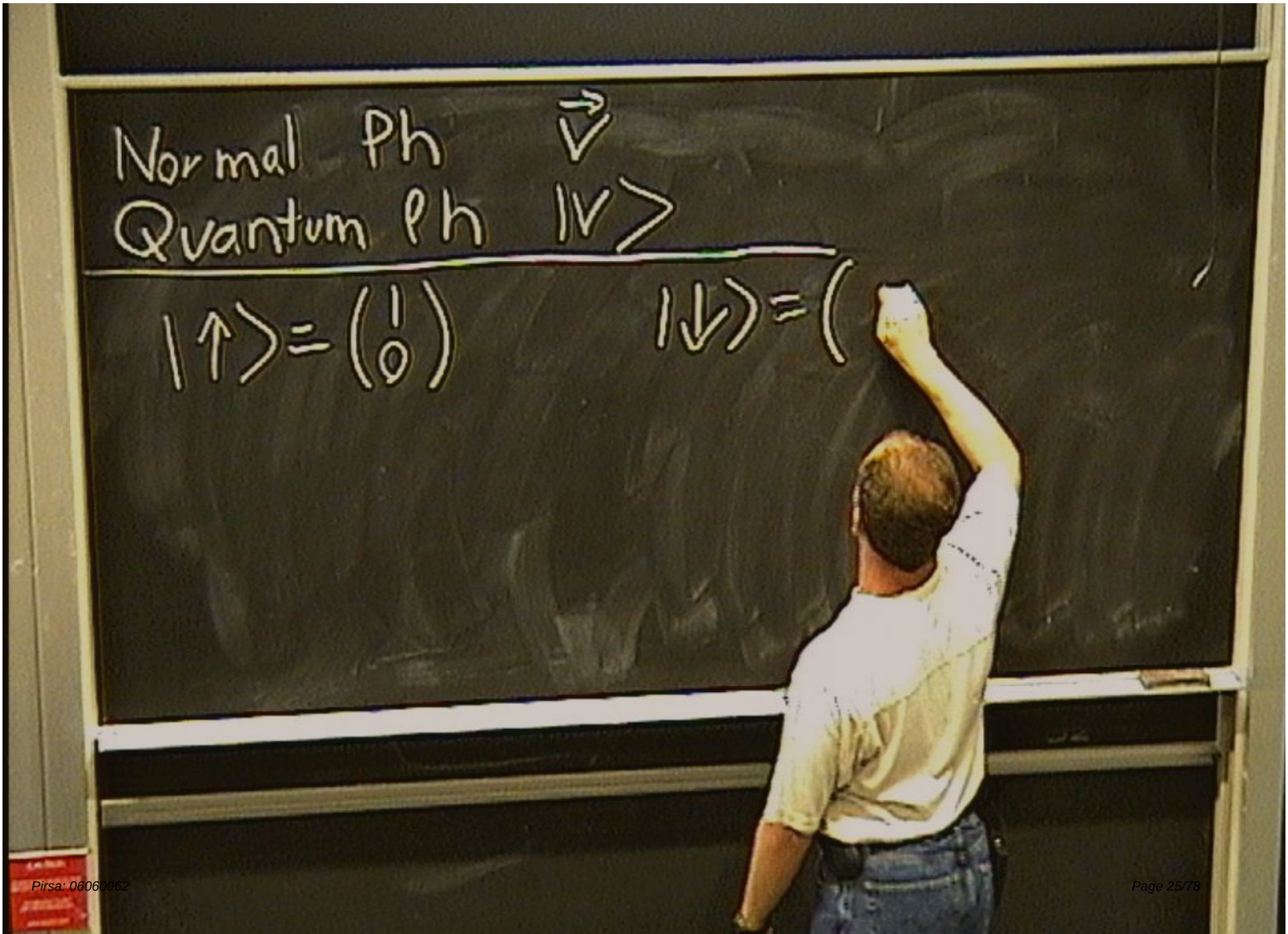
Q. 1.

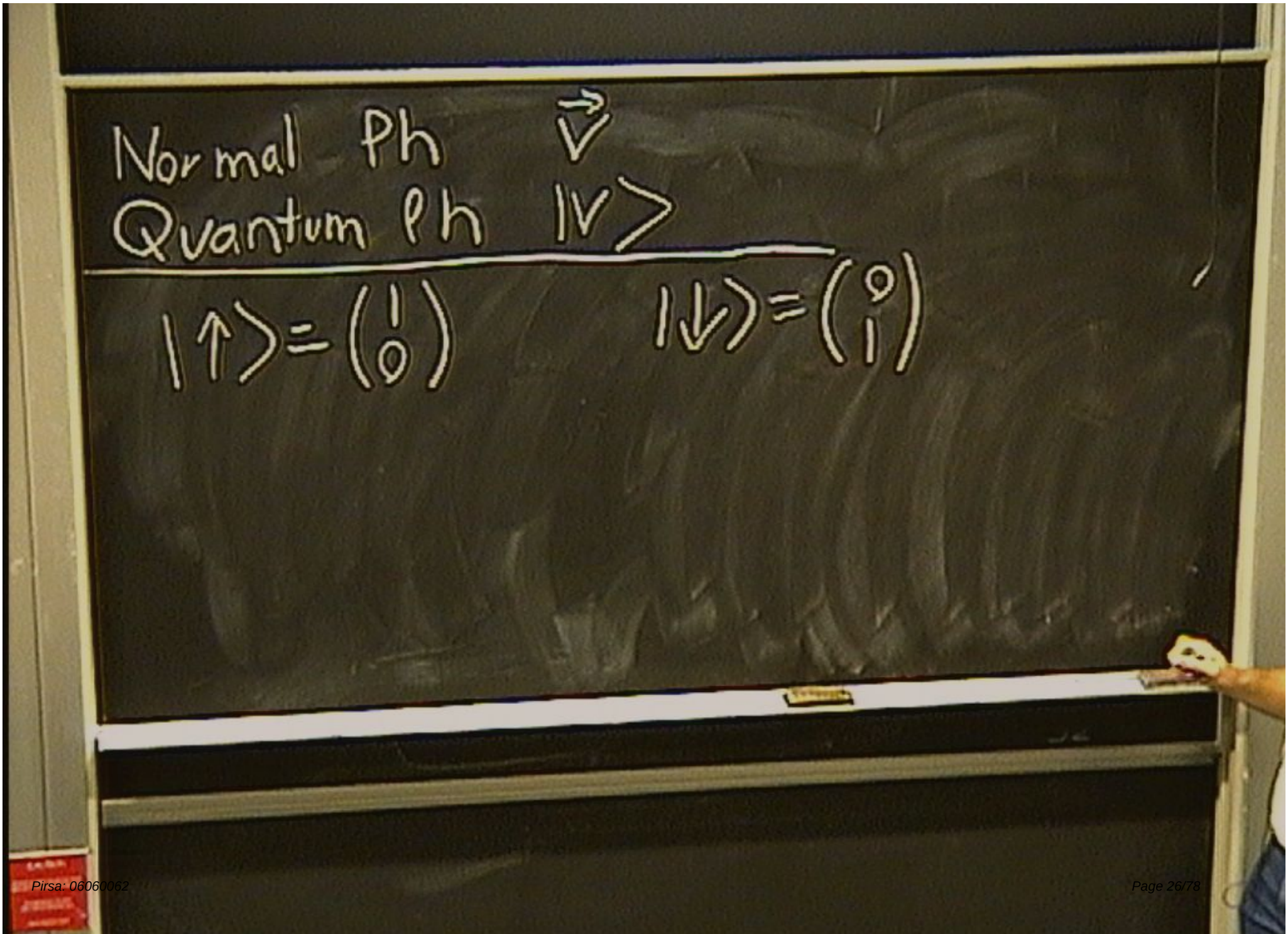


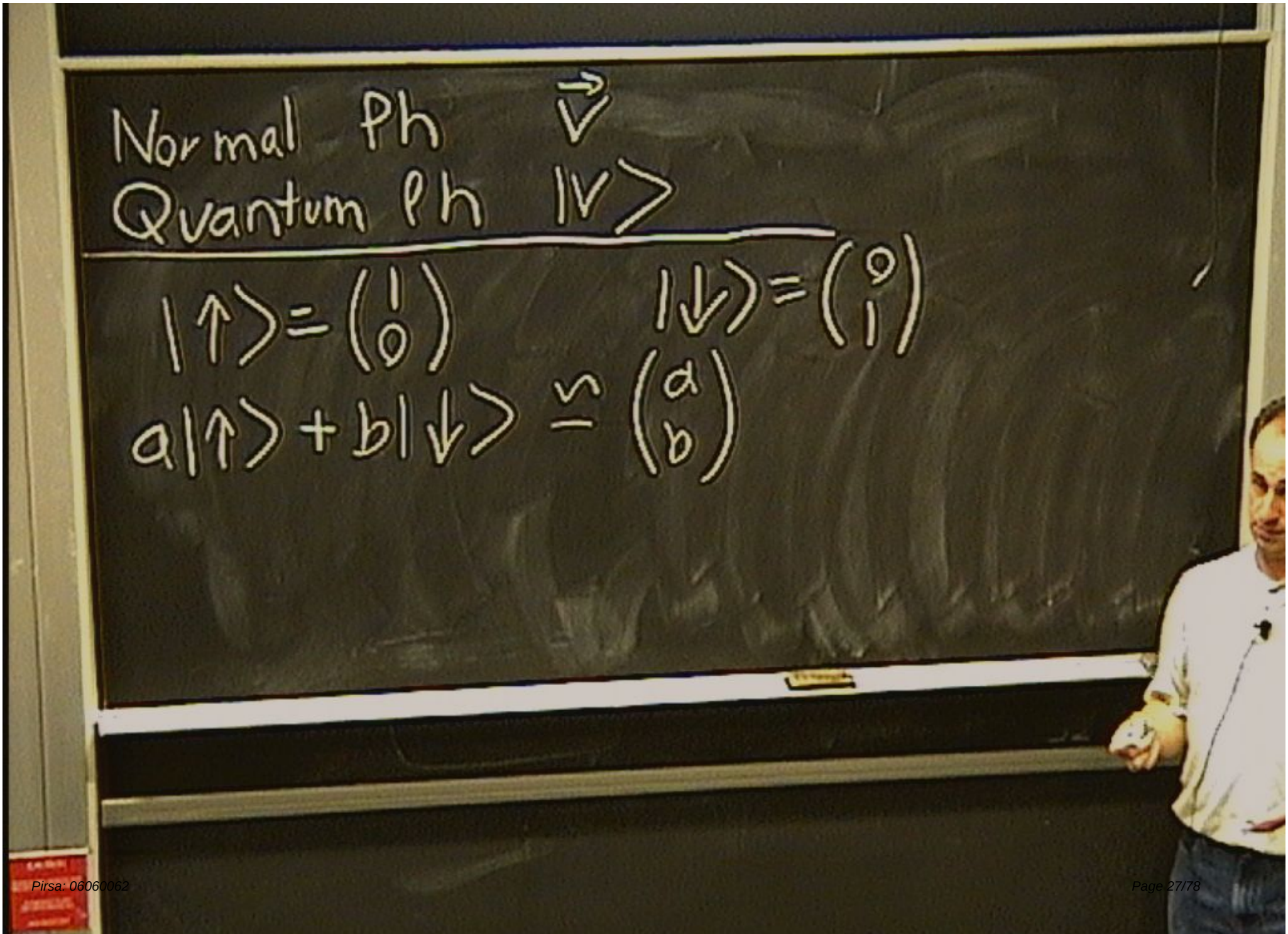
- Classical phones
- Entanglement

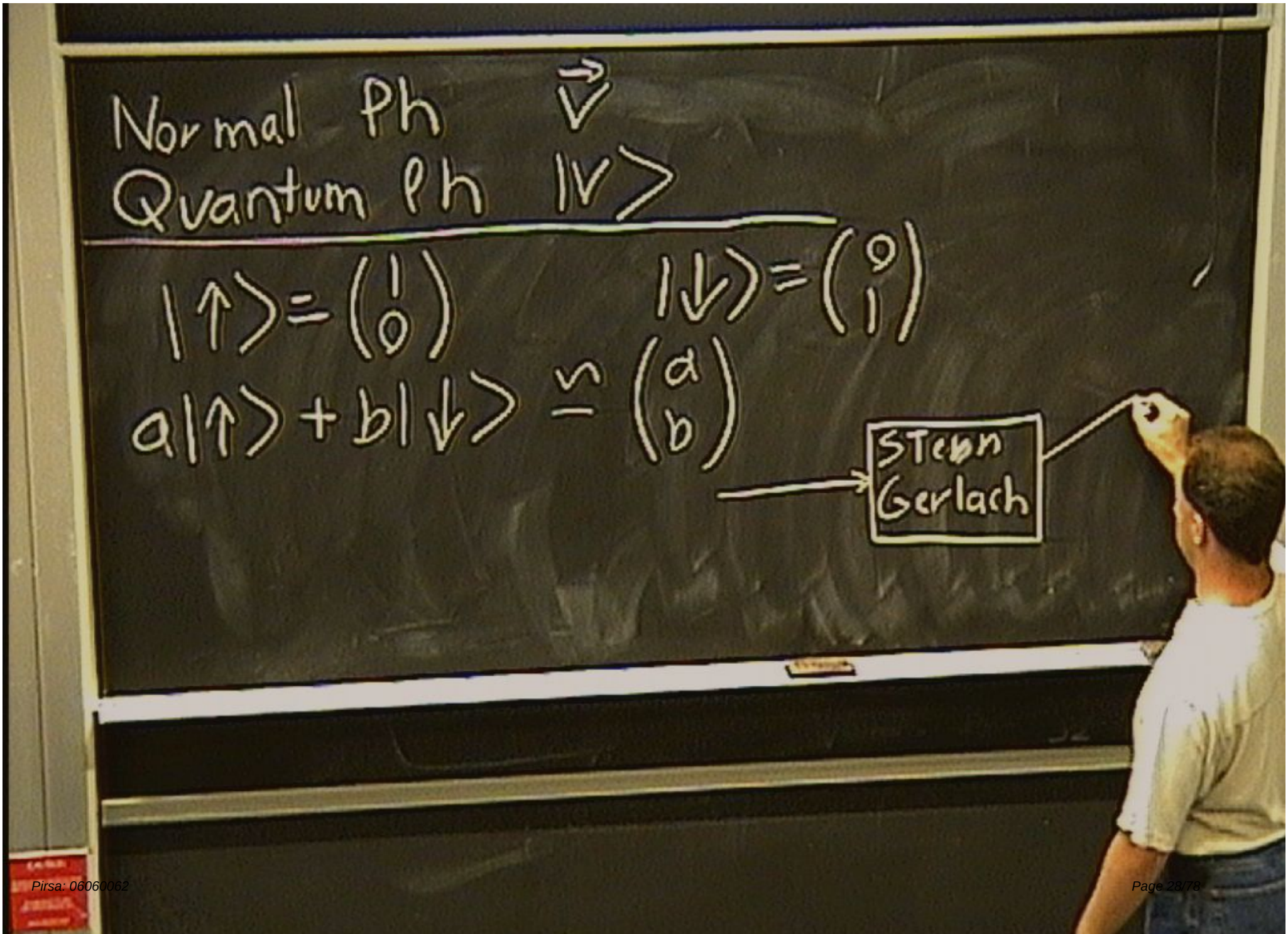

Normal ph
$\vec{v}$


Normal ph $\vec{v}$
Quantum ph $|v\rangle$


Normal Ph $\vec{v}$
Quantum Ph $|v\rangle$
$|\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$
$|\downarrow\rangle = ($


Normal Ph $\vec{v}$
Quantum Ph $|v\rangle$
$|\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$
$|\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$


Normal Ph $\vec{v}$
Quantum Ph $|v\rangle$
$|\uparrow\rangle = \begin{pmatrix}1\\0\end{pmatrix}$
$|\downarrow\rangle = \begin{pmatrix}0\\1\end{pmatrix}$
$a|\uparrow\rangle + b|\downarrow\rangle \doteq \begin{pmatrix}a\\b\end{pmatrix}$

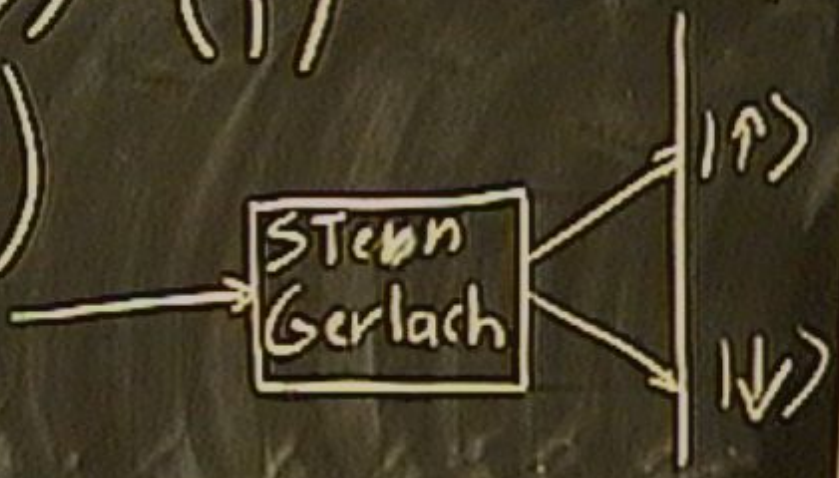

Normal ph $\vec{v}$
Quantum ph $|v\rangle$
$|\uparrow\rangle = \begin{pmatrix}1\\0\end{pmatrix}$
$|\downarrow\rangle = \begin{pmatrix}0\\1\end{pmatrix}$
$a|\uparrow\rangle + b|\downarrow\rangle \stackrel{n}{=} \begin{pmatrix}a\\b\end{pmatrix}$
Stern Gerlach

Normal Ph $\vec{v}$

Quantum Ph $|v\rangle$

$|\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $|\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

$a|\uparrow\rangle + b|\downarrow\rangle \doteq \begin{pmatrix} a \\ b \end{pmatrix}$

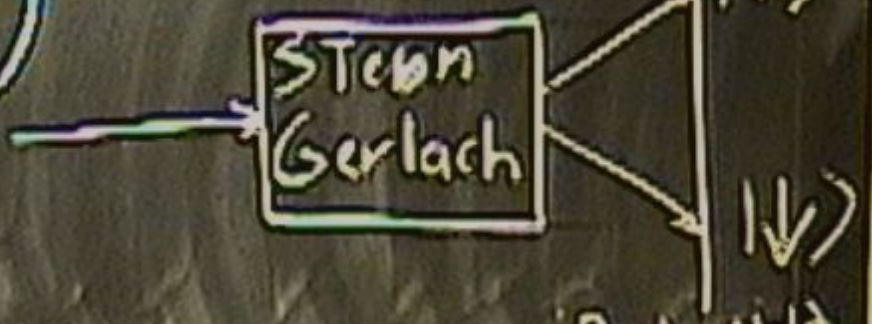


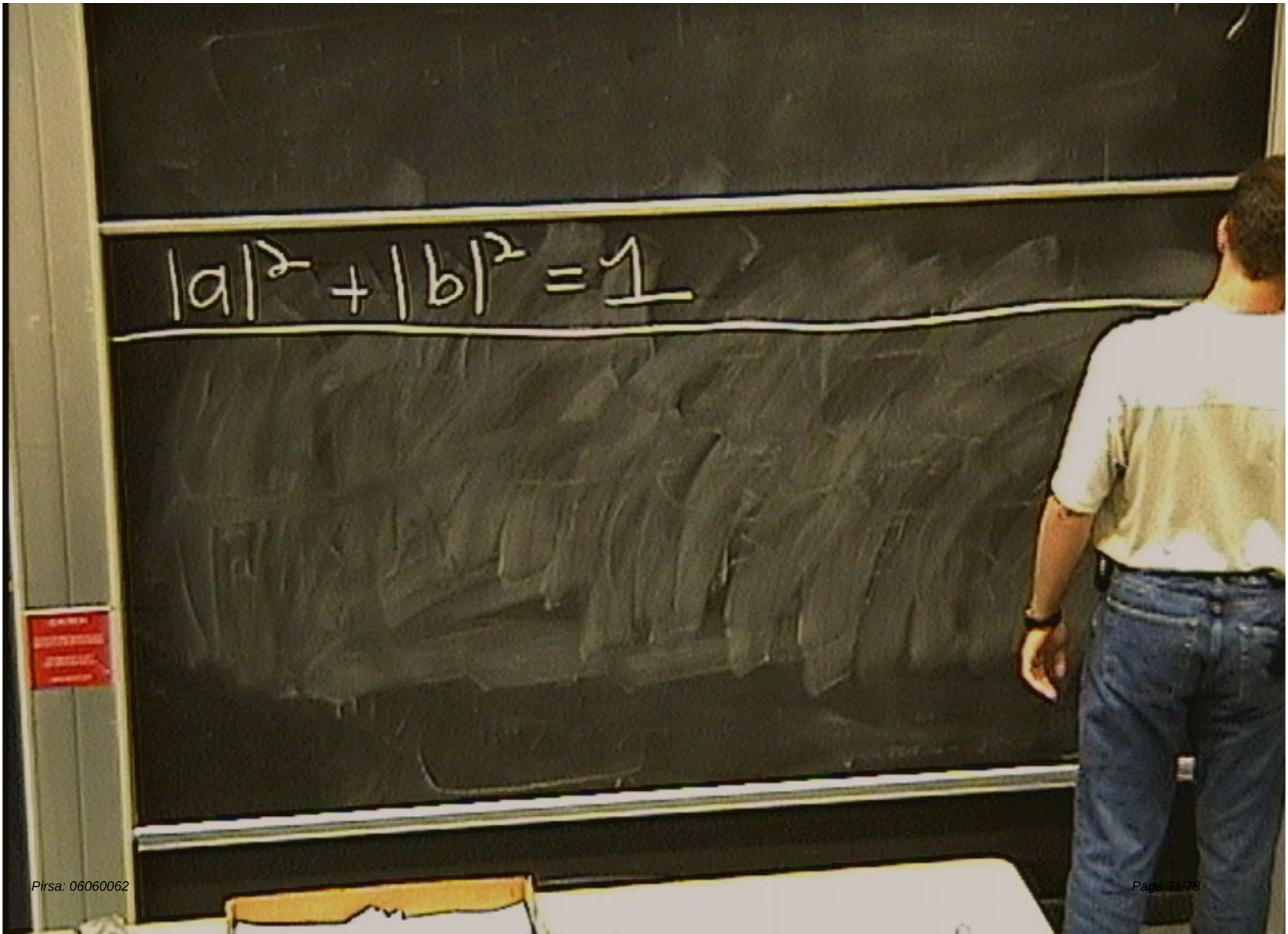
Normal Ph V

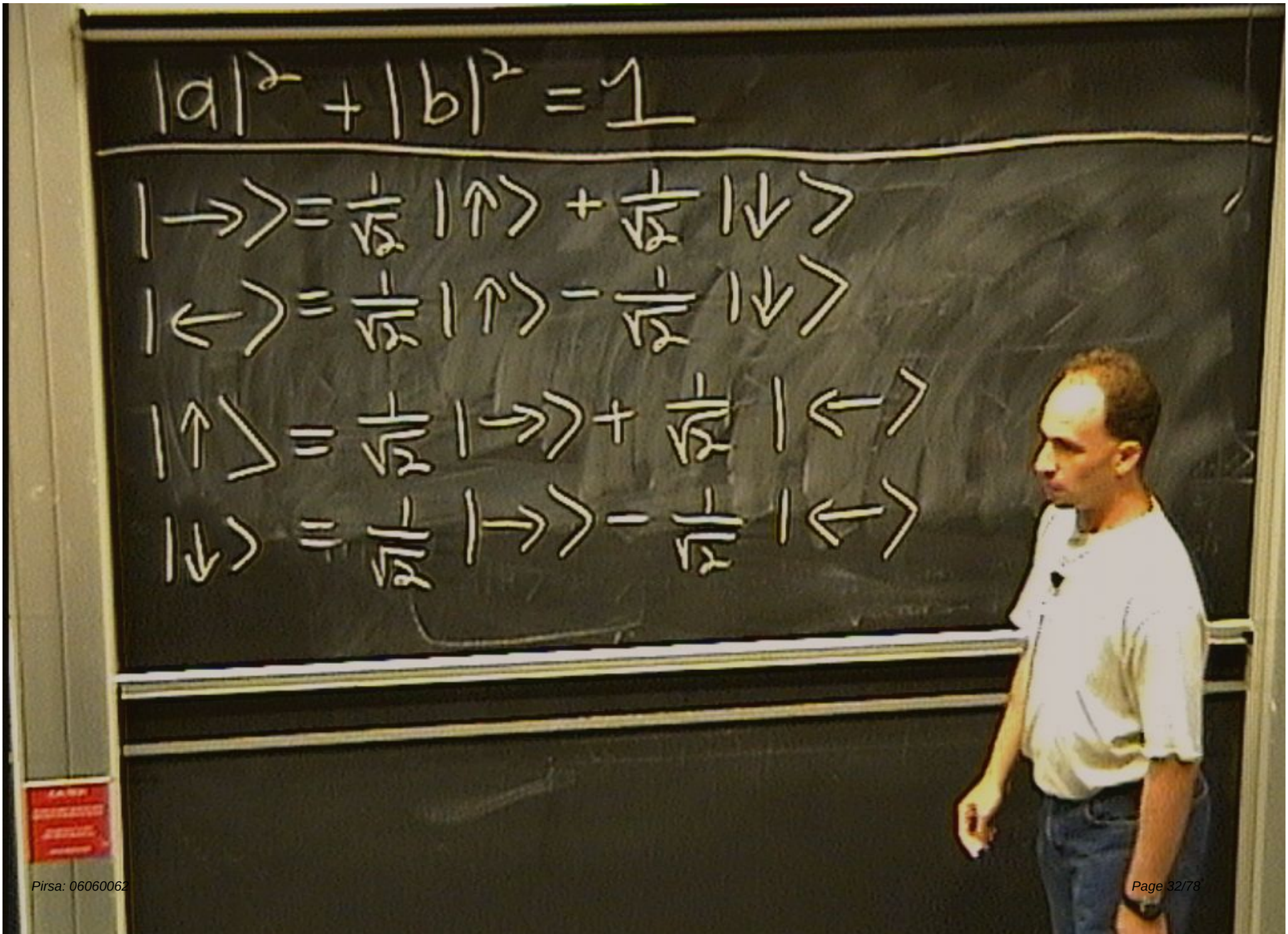
Quantum Ph $|V\rangle$

$|\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $|\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

$a|\uparrow\rangle + b|\downarrow\rangle \stackrel{n}{=} \begin{pmatrix} a \\ b \end{pmatrix}$




$|a|^2 + |b|^2 = 1$


$|a|^2 + |b|^2 = 1$
$|\rightarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle$
$|\leftarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle$
$|\uparrow\rangle = \frac{1}{\sqrt{2}}|\rightarrow\rangle + \frac{1}{\sqrt{2}}|\leftarrow\rangle$
$|\downarrow\rangle = \frac{1}{\sqrt{2}}|\rightarrow\rangle - \frac{1}{\sqrt{2}}|\leftarrow\rangle$

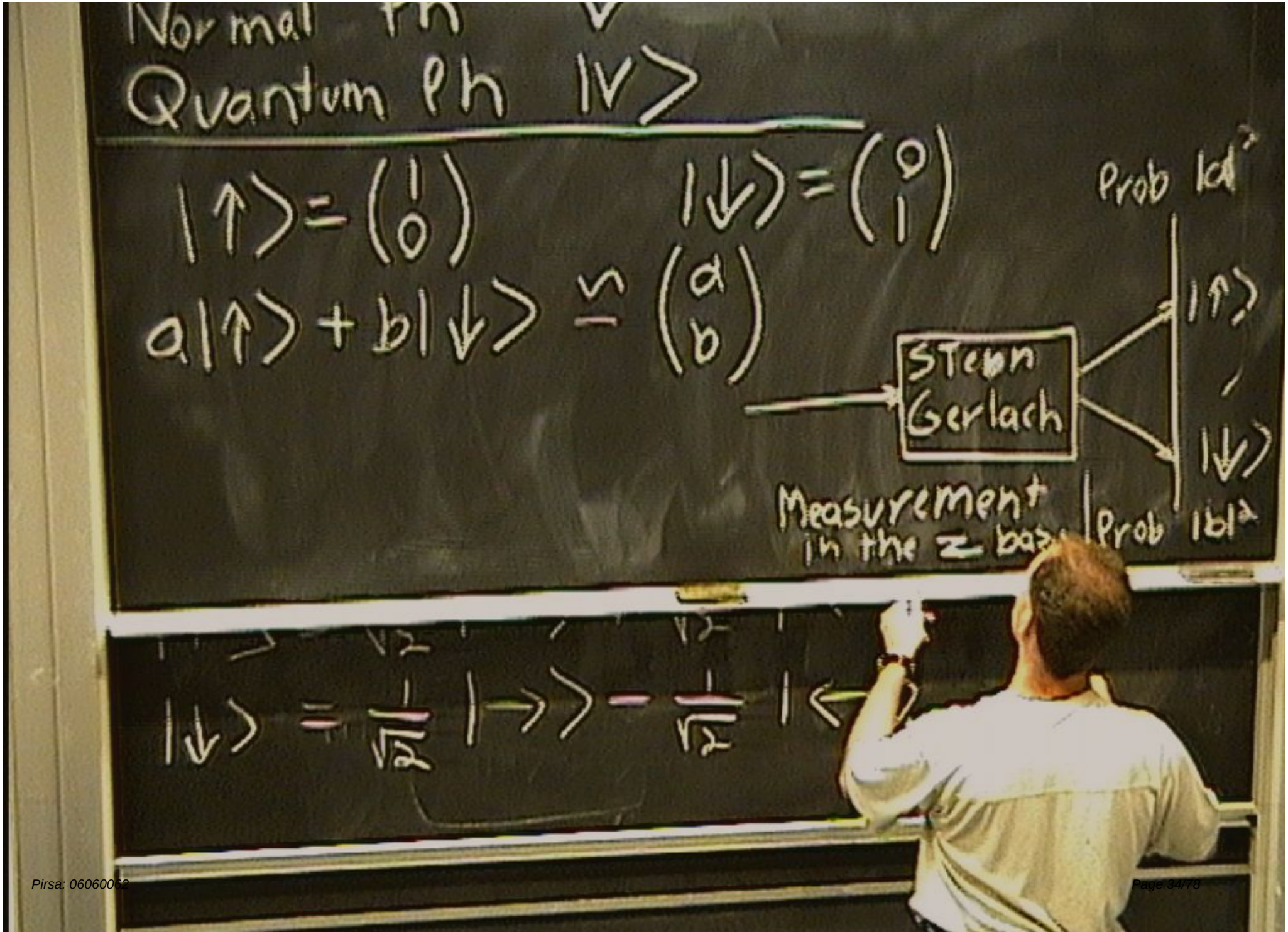
$$|a|^2 + |b|^2 = 1$$

$$|\rightarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle$$

$$|\leftarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle$$

$$|\uparrow\rangle = \frac{1}{\sqrt{2}}|\rightarrow\rangle + \frac{1}{\sqrt{2}}|\leftarrow\rangle$$

$$|\downarrow\rangle = \frac{1}{\sqrt{2}}|\rightarrow\rangle - \frac{1}{\sqrt{2}}|\leftarrow\rangle$$

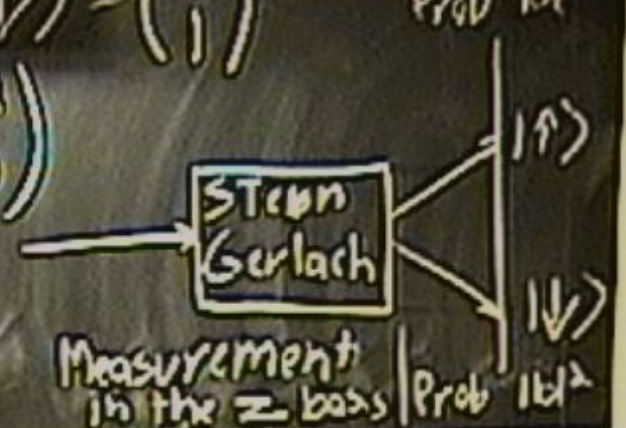

Normal ph
Quantum ph |v⟩
|↑⟩ = (1 0)
|↓⟩ = (0 1)
a|↑⟩ + b|↓⟩ ≐ (a b)
Prob |a|²
Stern Gerlach
|↑⟩
|↓⟩
Measurement in the z basis
Prob |b|²
|↓⟩ = 1/√2 |→⟩ − 1/√2 |←⟩

et. al

Quantum Ph

$|\uparrow\rangle = \begin{pmatrix}1\\0\end{pmatrix}$ $|\downarrow\rangle = \begin{pmatrix}0\\1\end{pmatrix}$

$a|\uparrow\rangle + b|\downarrow\rangle \leftrightarrow \begin{pmatrix}a\\b\end{pmatrix}$



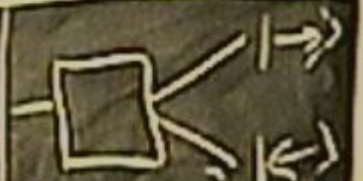
$|a|^2 + |b|^2 = 1$

$|\rightarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle$

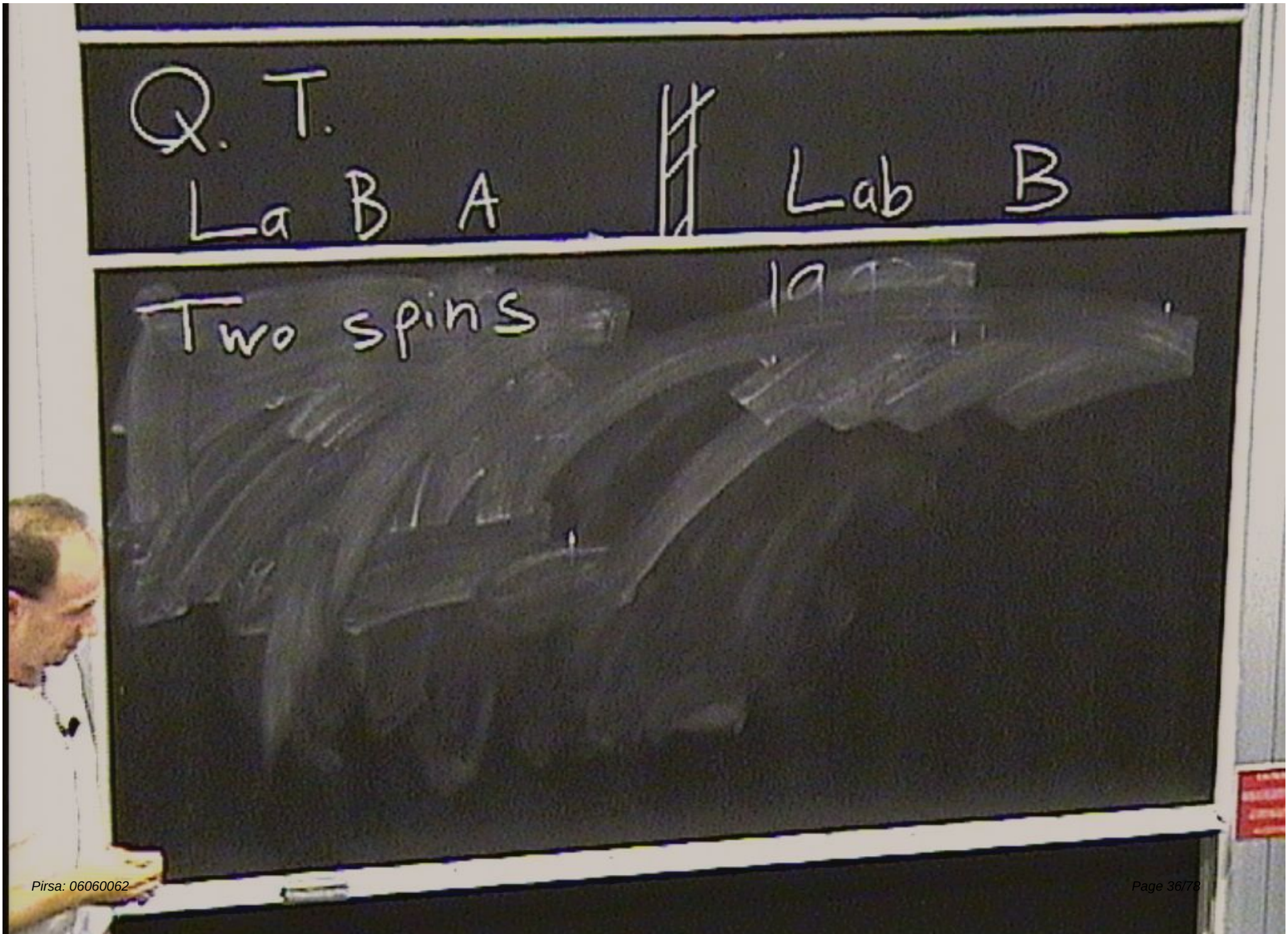
$|\leftarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle$

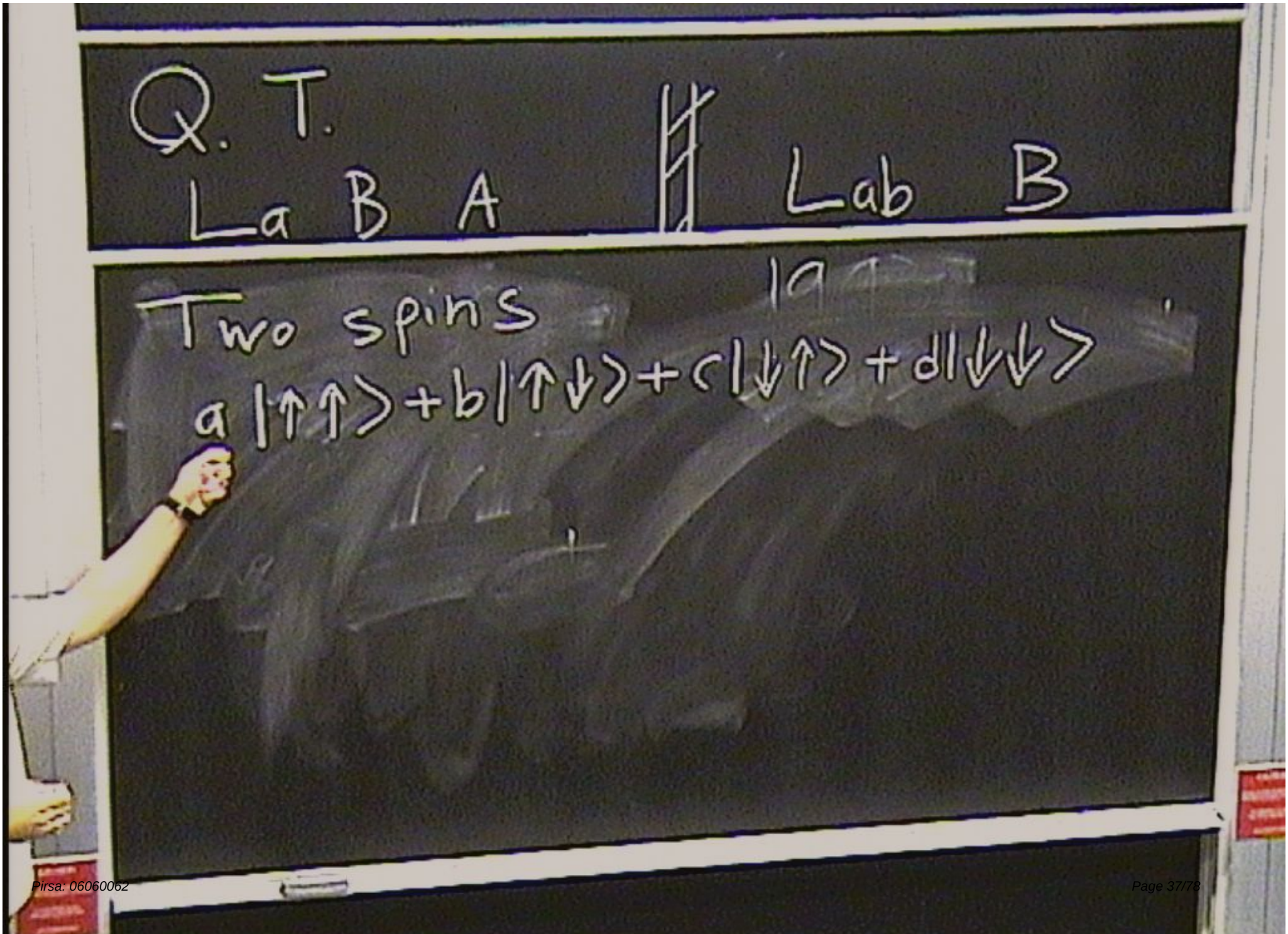
$|\uparrow\rangle = \frac{1}{\sqrt{2}}|\rightarrow\rangle + \frac{1}{\sqrt{2}}|\leftarrow\rangle$

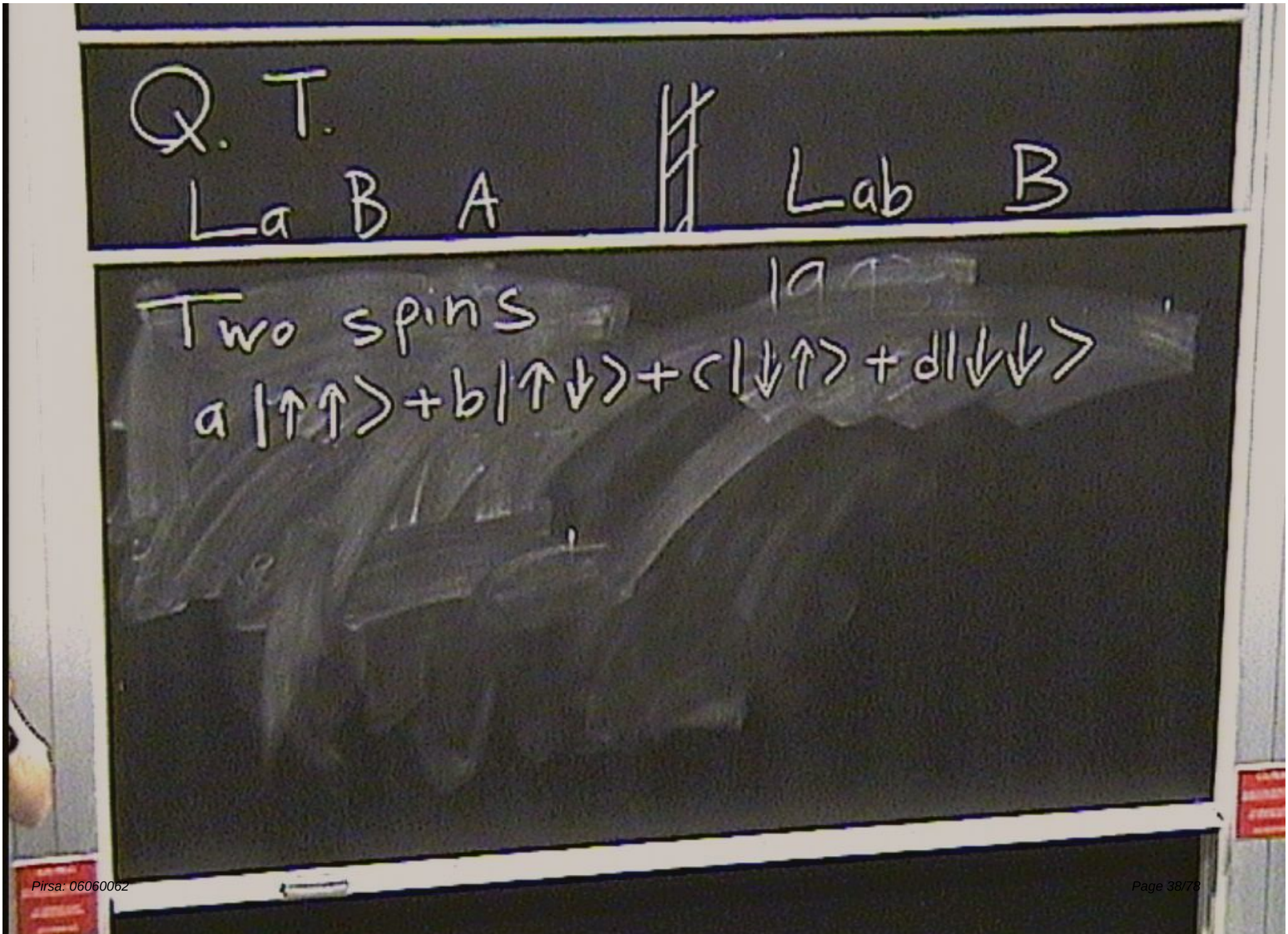
$|\downarrow\rangle = \frac{1}{\sqrt{2}}|\rightarrow\rangle - \frac{1}{\sqrt{2}}|\leftarrow\rangle$

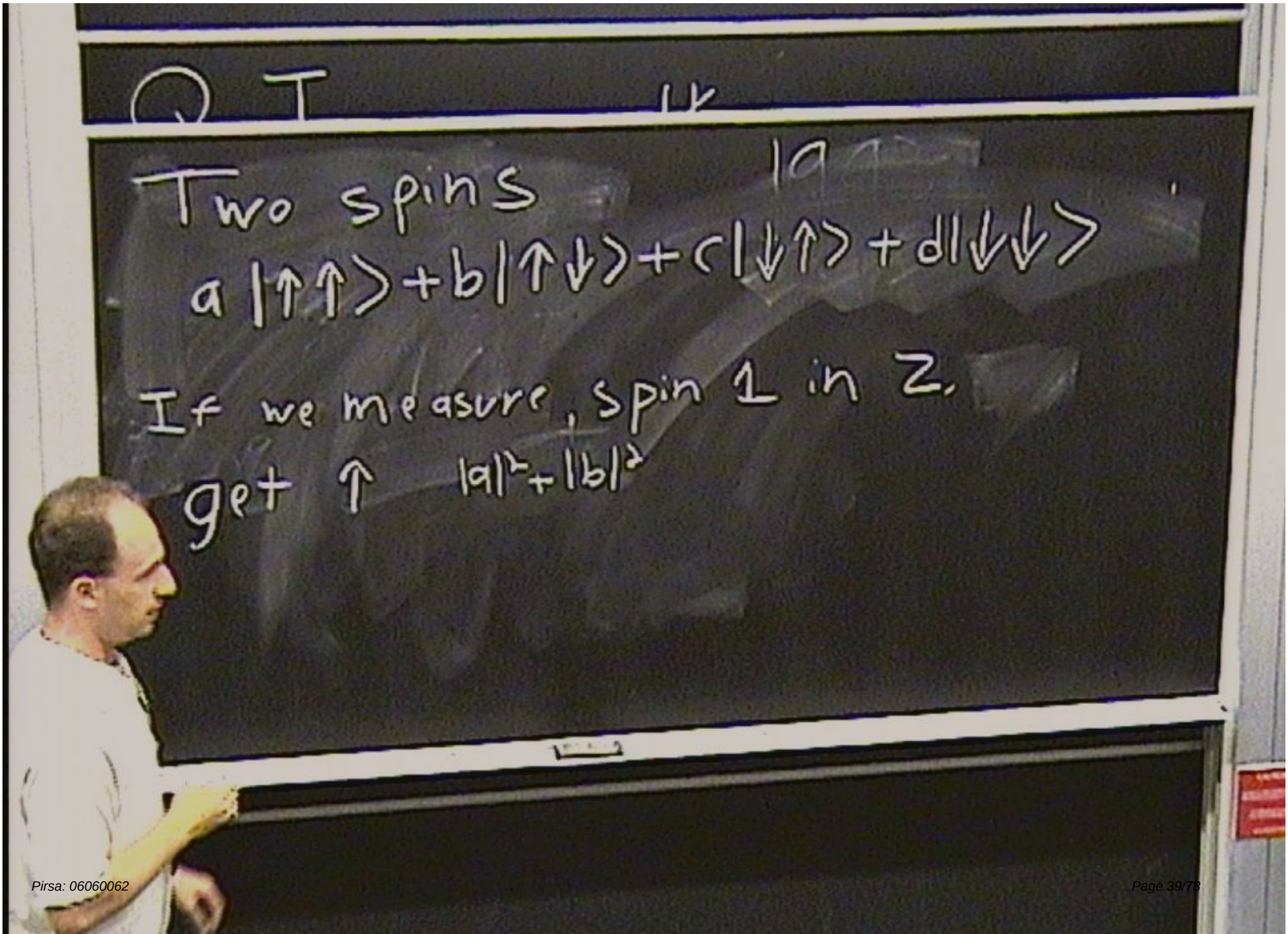


B


Q. T.
La B A
Lab B
Two spins


Q. T.
La B A
Lab B
Two spins
a|↑↑⟩+b|↑↓⟩+c|↓↑⟩+d|↓↓⟩


Q. T.
La B A
Lab B
Two spins
a|↑↑⟩+b|↑↓⟩+c|↓↑⟩+d|↓↓⟩


Two spins
$a|\uparrow\uparrow\rangle + b|\uparrow\downarrow\rangle + c|\downarrow\uparrow\rangle + d|\downarrow\downarrow\rangle$
If we measure, spin 1 in Z.
get ↑ $|a|^2 + |b|^2$

Two spins

$a|\uparrow\uparrow\rangle + b|\uparrow\downarrow\rangle + c|\downarrow\uparrow\rangle + d|\downarrow\downarrow\rangle$

If we measure, spin 1 in Z.

get $\uparrow$ $|a|^2 + |b|^2$

$\downarrow$ $|c|^2 + |d|^2$

Two spins

$a|\uparrow\uparrow\rangle + b|\uparrow\downarrow\rangle + c|\downarrow\uparrow\rangle + d|\downarrow\downarrow\rangle$

If we measure, spin 1 in Z.

get $\uparrow$ $|a|^2 + |b|^2$

$\downarrow$ $|c|^2 + |d|^2$

Two spins

$a|\uparrow\uparrow\rangle + b|\uparrow\downarrow\rangle + c|\downarrow\uparrow\rangle + d|\downarrow\downarrow\rangle$

If we measure, spin 1 in Z.

get $\uparrow$ $|a|^2+|b|^2 \Rightarrow a|\uparrow\uparrow\rangle + b|\uparrow\downarrow\rangle$

$\downarrow$ $|c|^2+|d|^2$

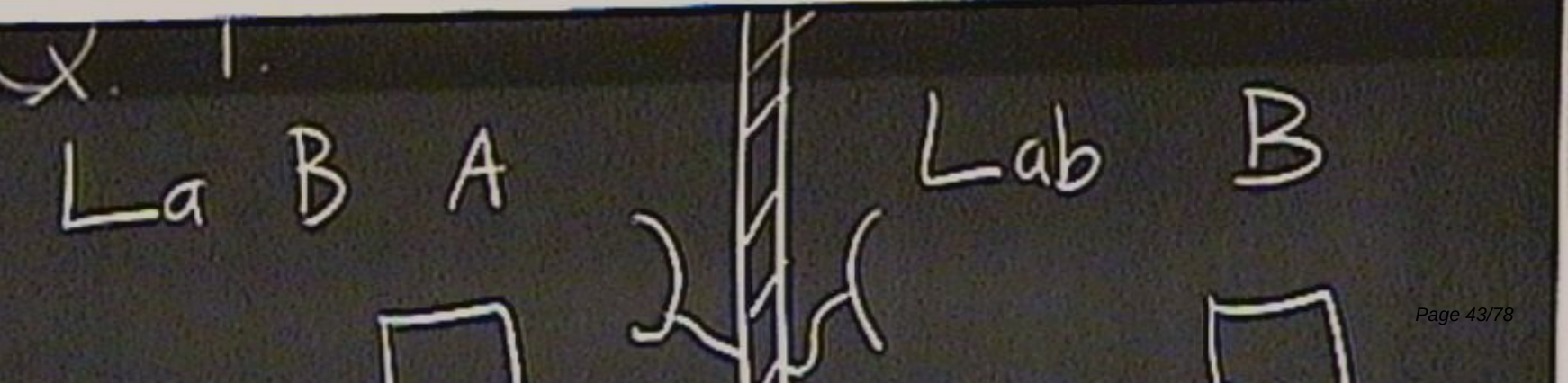
$a|\uparrow\uparrow\rangle + b|\uparrow\downarrow\rangle + c|\downarrow\uparrow\rangle + d|\downarrow\downarrow\rangle$

If we measure spin 1 in Z.

get $\uparrow$ $|a|^2+|b|^2$ $\Rightarrow$ $\frac{a|\uparrow\uparrow\rangle + b|\uparrow\downarrow\rangle}{\sqrt{|a|^2+|b|^2}}$

$\downarrow$ $|c|^2+|d|^2$ $\frac{}{\sqrt{|a|^2+|b|^2}}$

Q. 1.



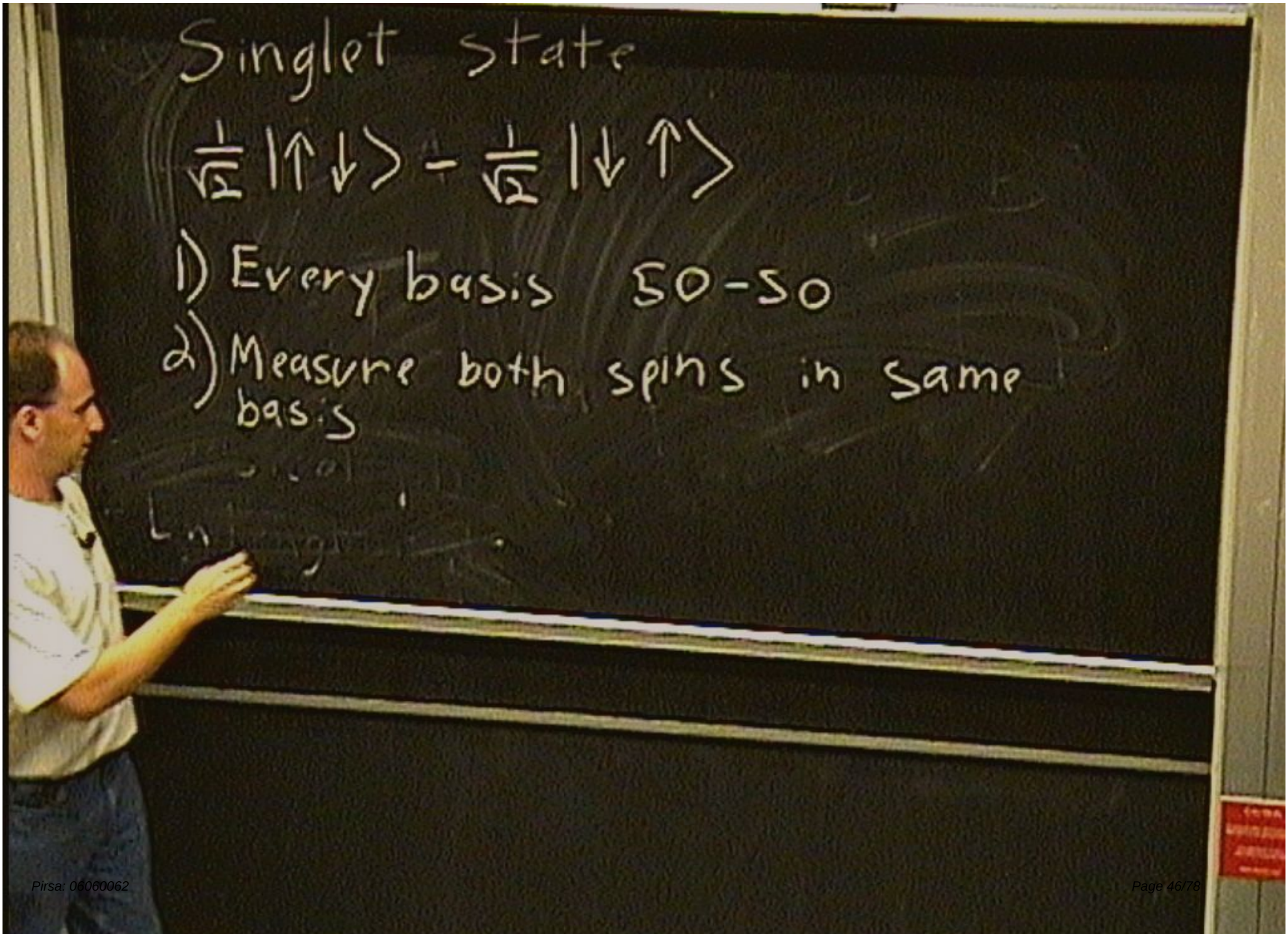
Singlet state

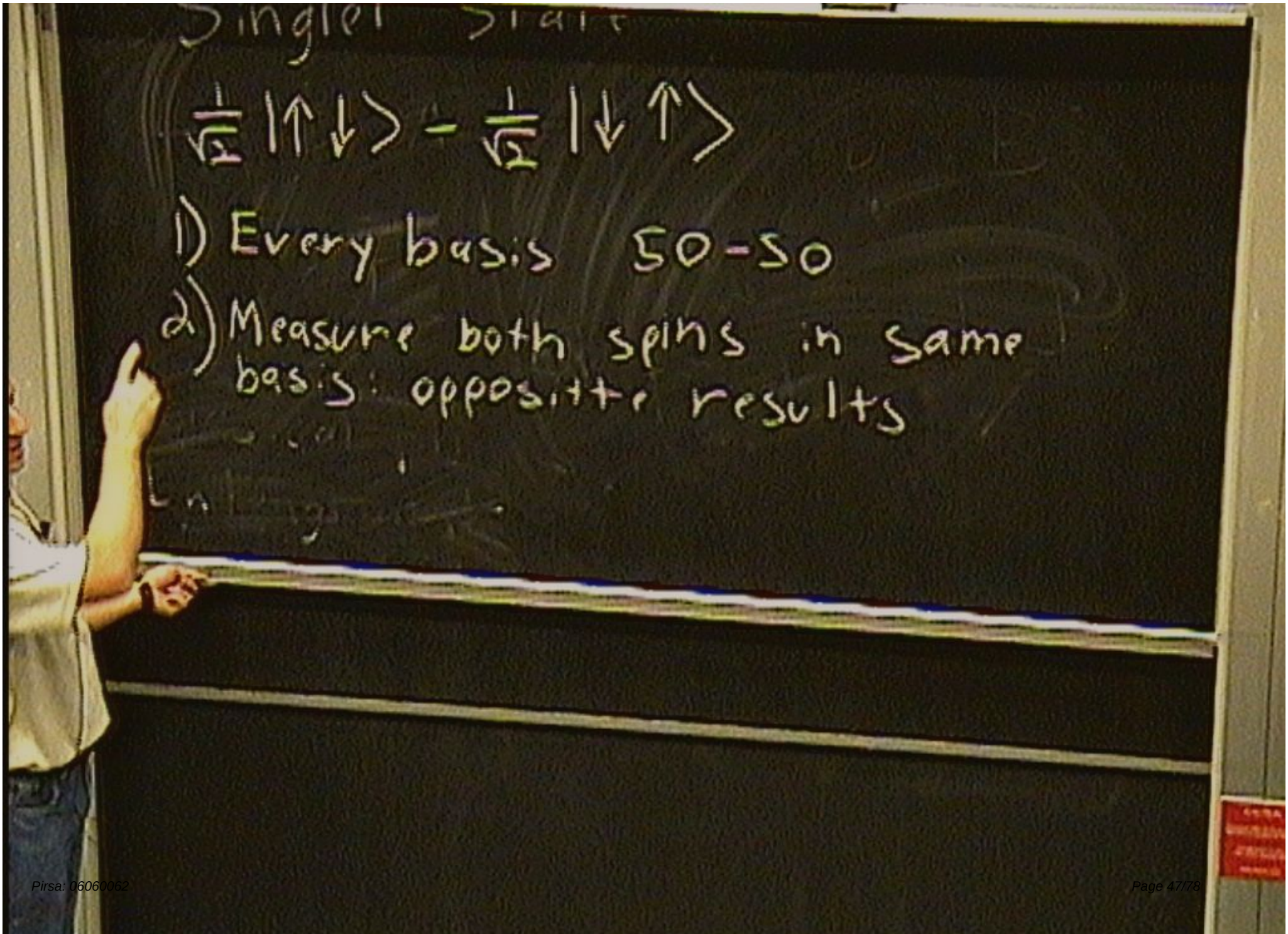
$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$

Singlet state

$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$

1) Every basis 50-50


Singlet state
$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$
1) Every basis 50-50
2) Measure both spins in same basis


Singlet State
$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$
1) Every basis 50-50
2) Measure both spins in same basis: opposite results

$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$

1) Every basis 50-50

2) Measure both spins in same basis: opposite results

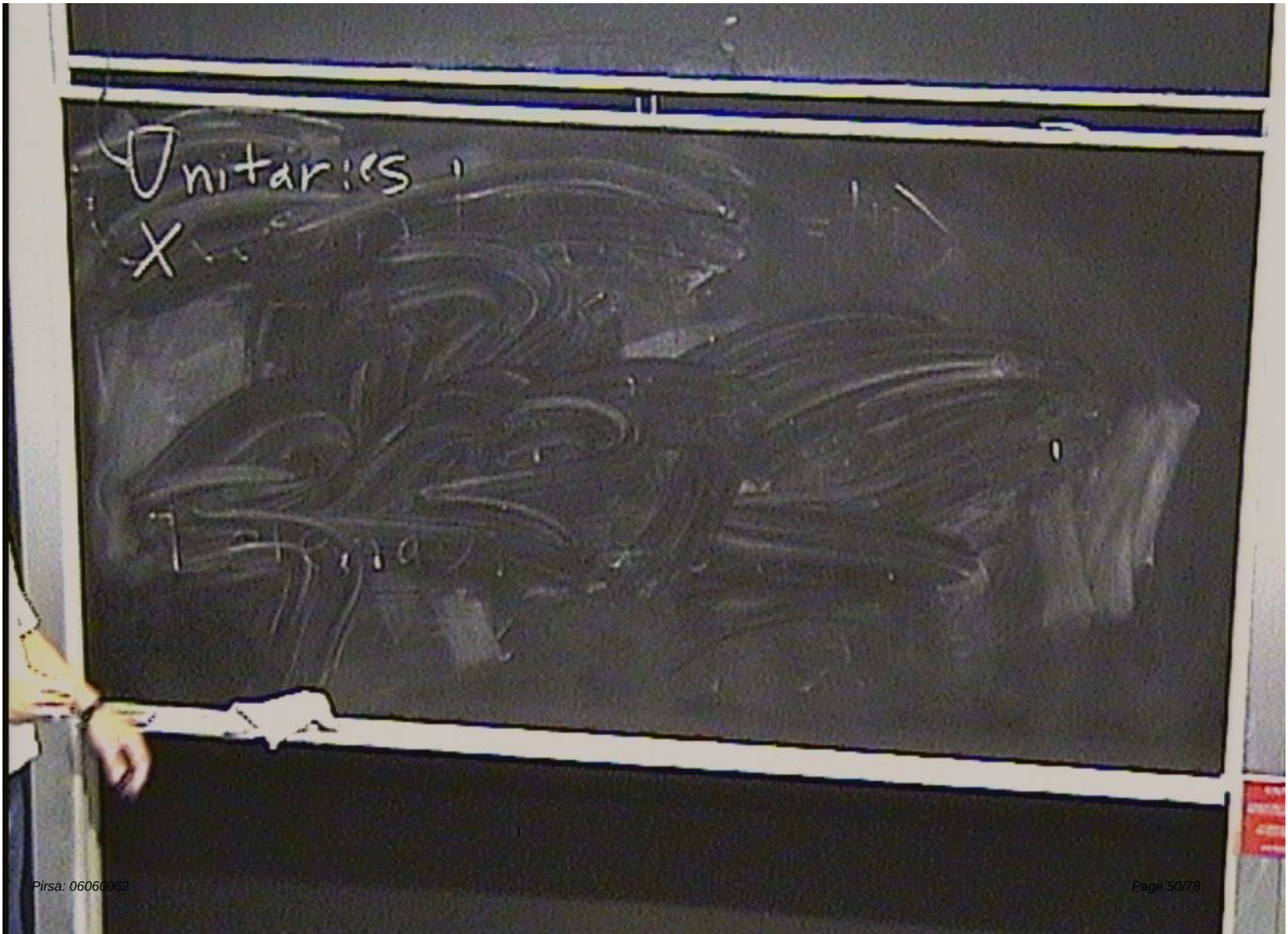
$= \frac{1}{\sqrt{2}}|\rightarrow\leftarrow| - \frac{1}{\sqrt{2}}|\leftarrow\rightarrow\rangle$

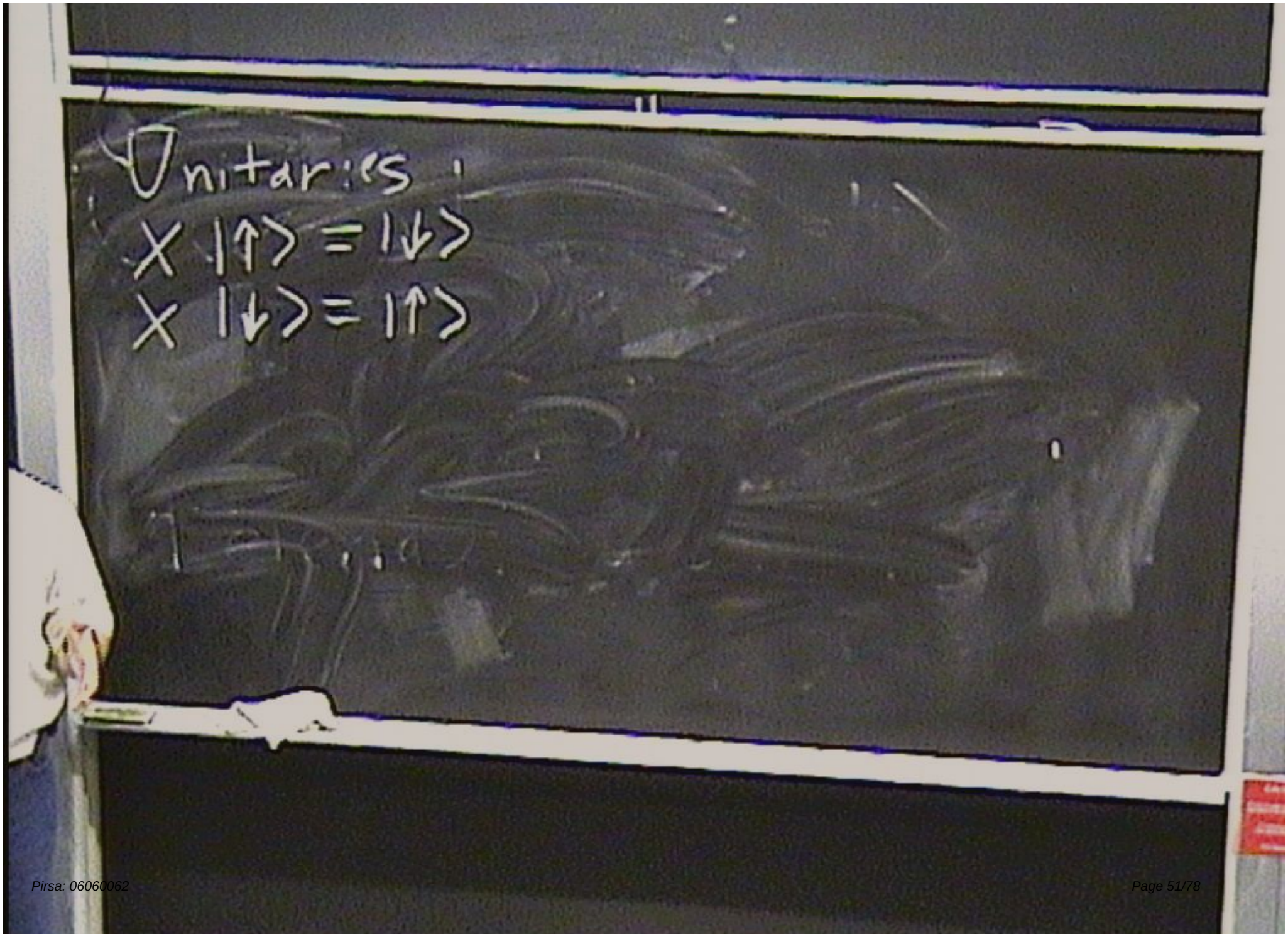
$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$

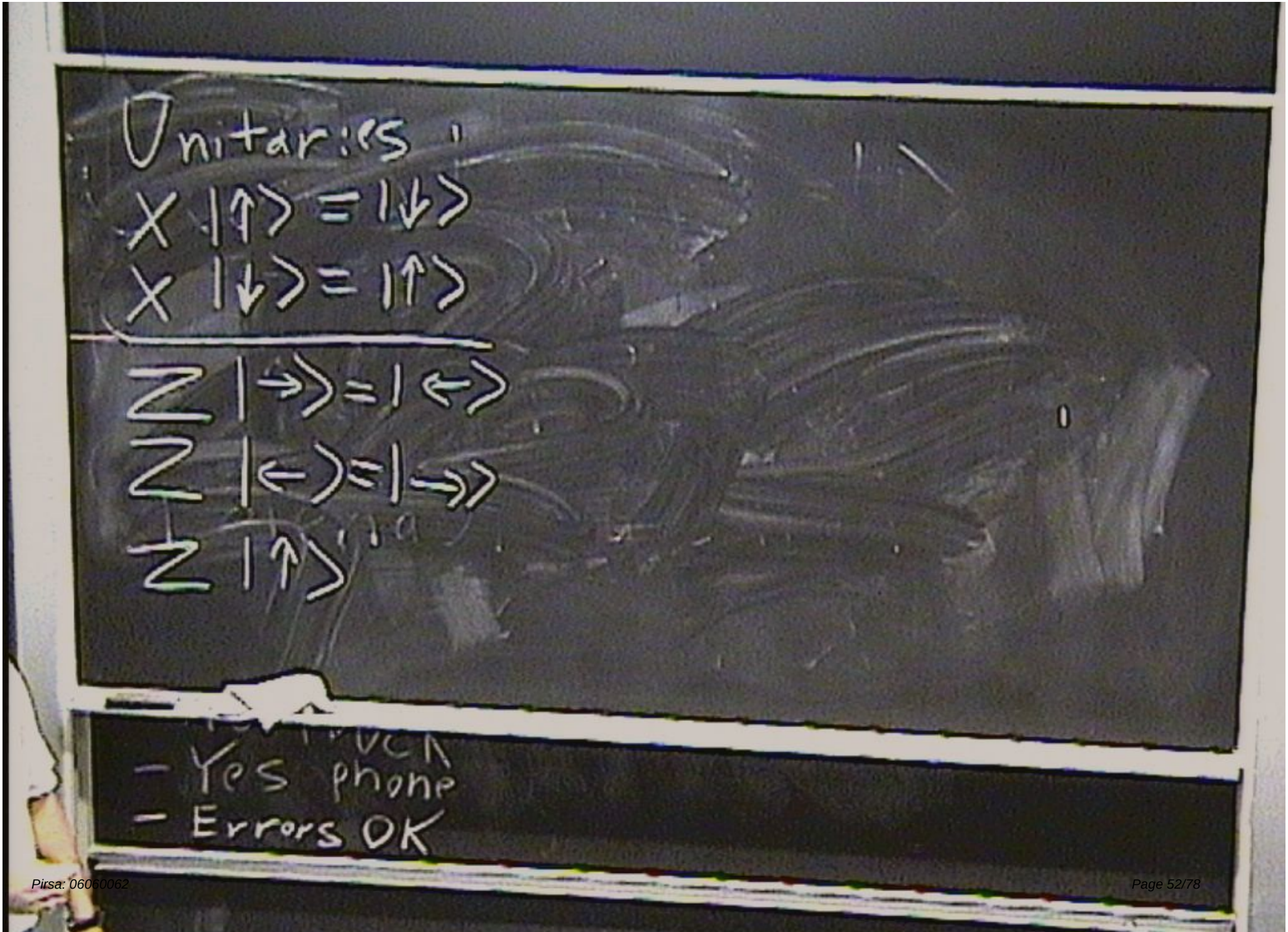
1) Every basis 50-50

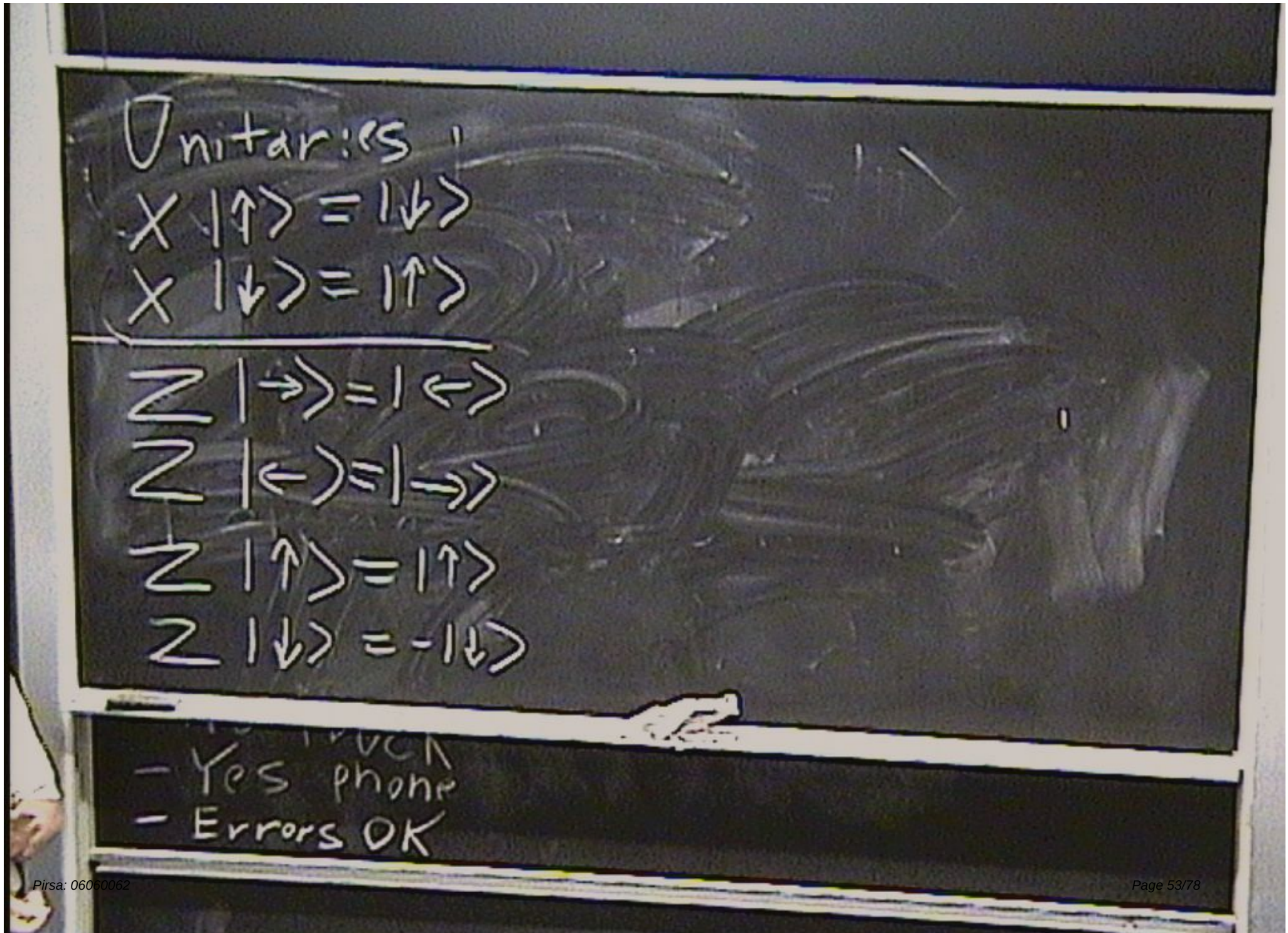
2) Measure both spins in same basis: opposite results

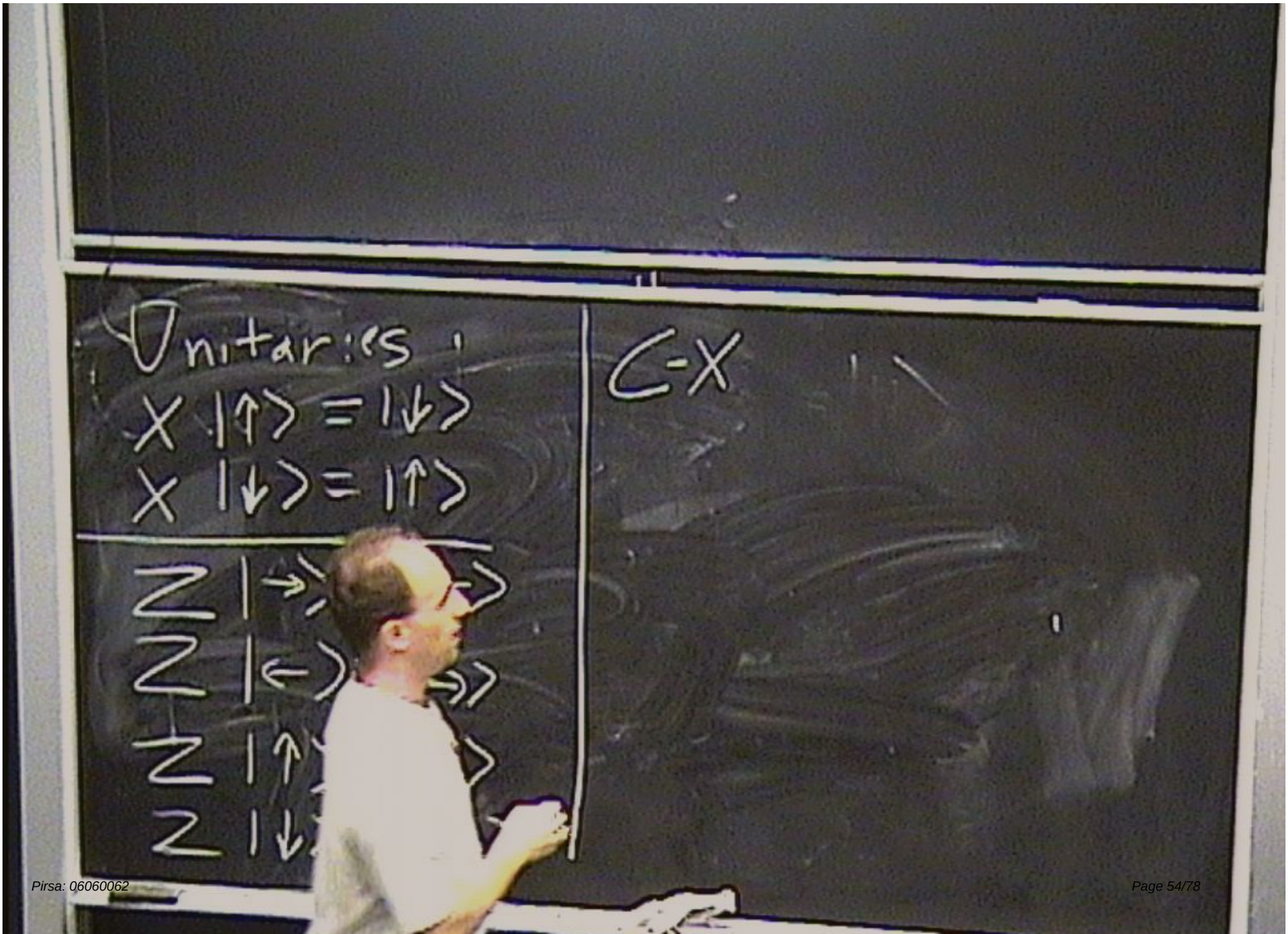
$= \frac{1}{\sqrt{2}}|\rightarrow\leftarrow\rangle - \frac{1}{\sqrt{2}}|\leftarrow\rightarrow\rangle$

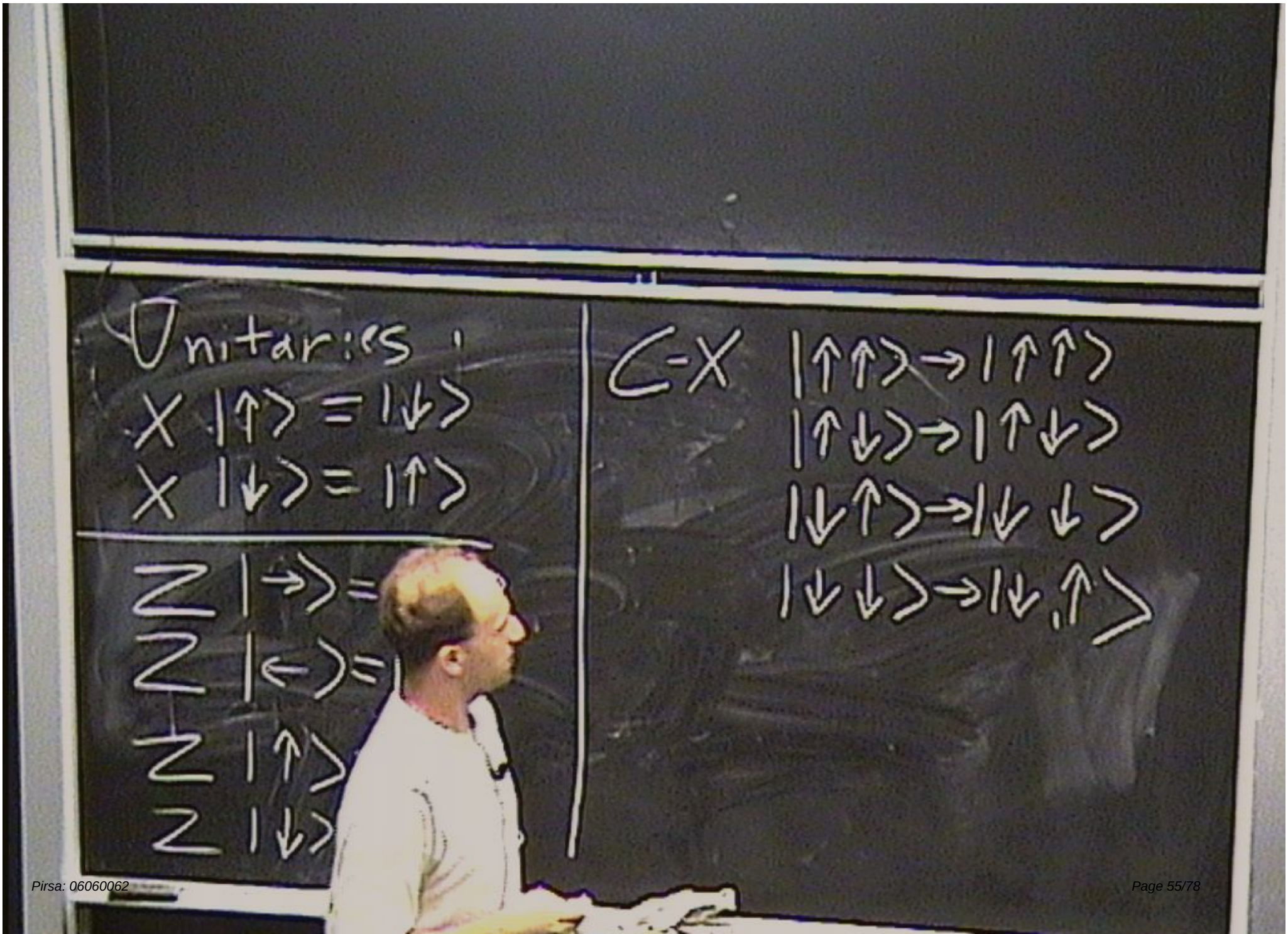

Unitarics

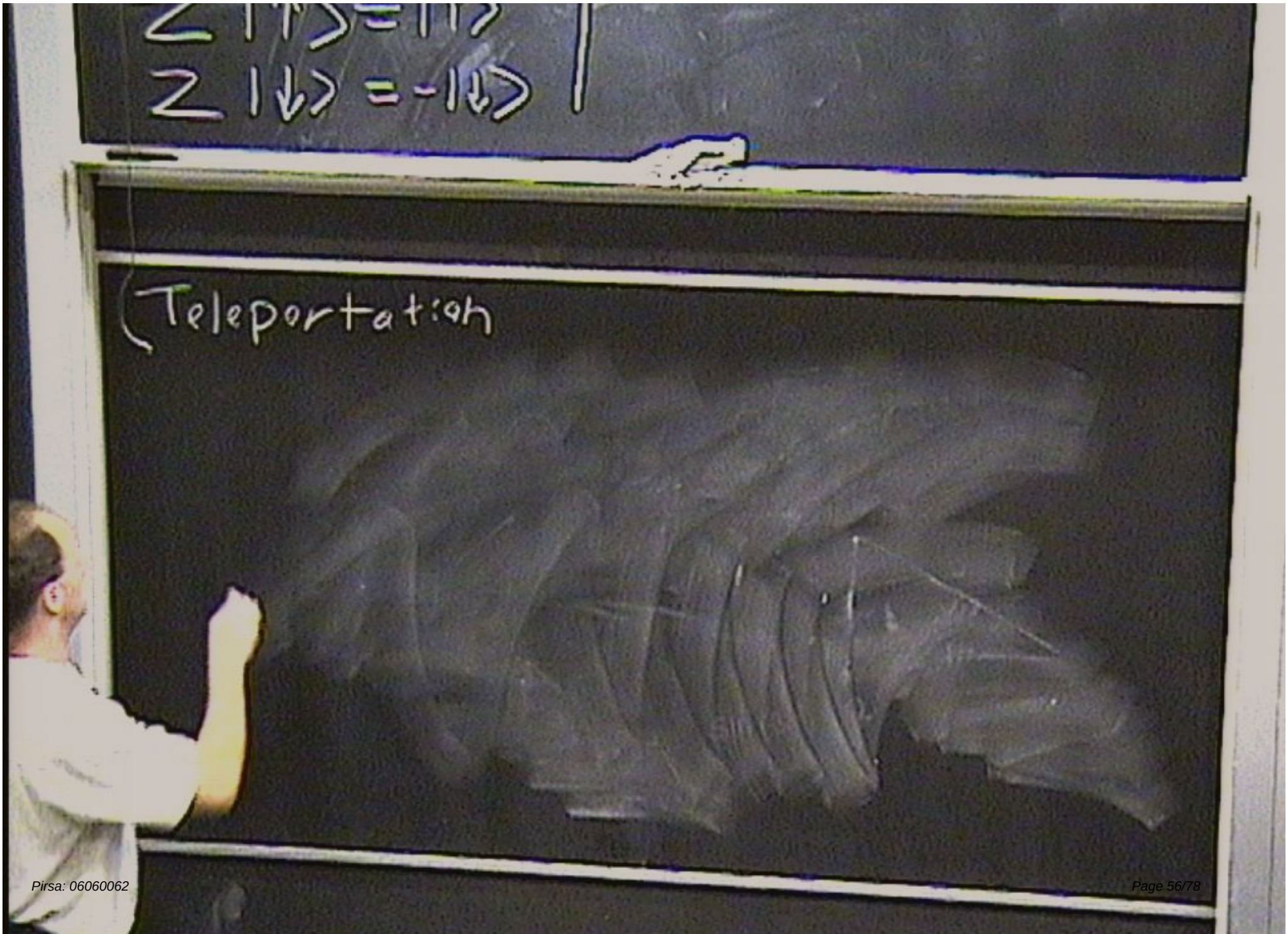

Unitaries:
X |↑⟩ = |↓⟩
X |↓⟩ = |↑⟩


Unitaries:
X |↑⟩ = |↓⟩
X |↓⟩ = |↑⟩
Z |→⟩ = |←⟩
Z |←⟩ = |→⟩
Z |↑⟩
- Yes phone
- Errors OK


Unitaries:
X |↑⟩ = |↓⟩
X |↓⟩ = |↑⟩
Z |→⟩ = |←⟩
Z |←⟩ = |→⟩
Z |↑⟩ = |↑⟩
Z |↓⟩ = -|↓⟩
- Yes phone
- Errors OK


Unitaries
X |↑⟩ = |↓⟩
X |↓⟩ = |↑⟩
Z |→⟩ =
Z |←⟩ =
Z |↑⟩ =
Z |↓⟩ =
C-X


Unitaries:
X |↑⟩ = |↓⟩
X |↓⟩ = |↑⟩
Z |→⟩ =
Z |←⟩ =
Z |↑⟩
Z |↓⟩
C-X |↑↑⟩ → |↑↑⟩
|↑↓⟩ → |↑↓⟩
|↓↑⟩ → |↓↓⟩
|↓↓⟩ → |↓↑⟩


Z|↑⟩=|↑⟩
Z|↓⟩=-|↓⟩
Teleportation

$\hat{Z}|\uparrow\rangle = |\uparrow\rangle$

$\hat{Z}|\downarrow\rangle = -|\downarrow\rangle$

Teleportation

Spin 1: "Unknown spin"

$Z|\psi\rangle = -|\psi\rangle$

$Z|\psi\rangle = -|\psi\rangle$

Teleportation

Spin 1: "Unknown Spin" in Lab A

Spin 2&3:

$Z|\downarrow\rangle = -|\downarrow\rangle$

Teleportation

Spin 1: "Unknown spin" in Lab A

Spin 2 & 3:

$Z|\uparrow\rangle = |\uparrow\rangle$

$Z|\downarrow\rangle = -|\downarrow\rangle$

Teleportation

Spin 1 : "Unknown Spin" in Lab A

Spin 2 & 3 : $\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$

Spin 2 Lab A

Spin 3 Lab B

$Z|\downarrow\rangle = -|\downarrow\rangle$

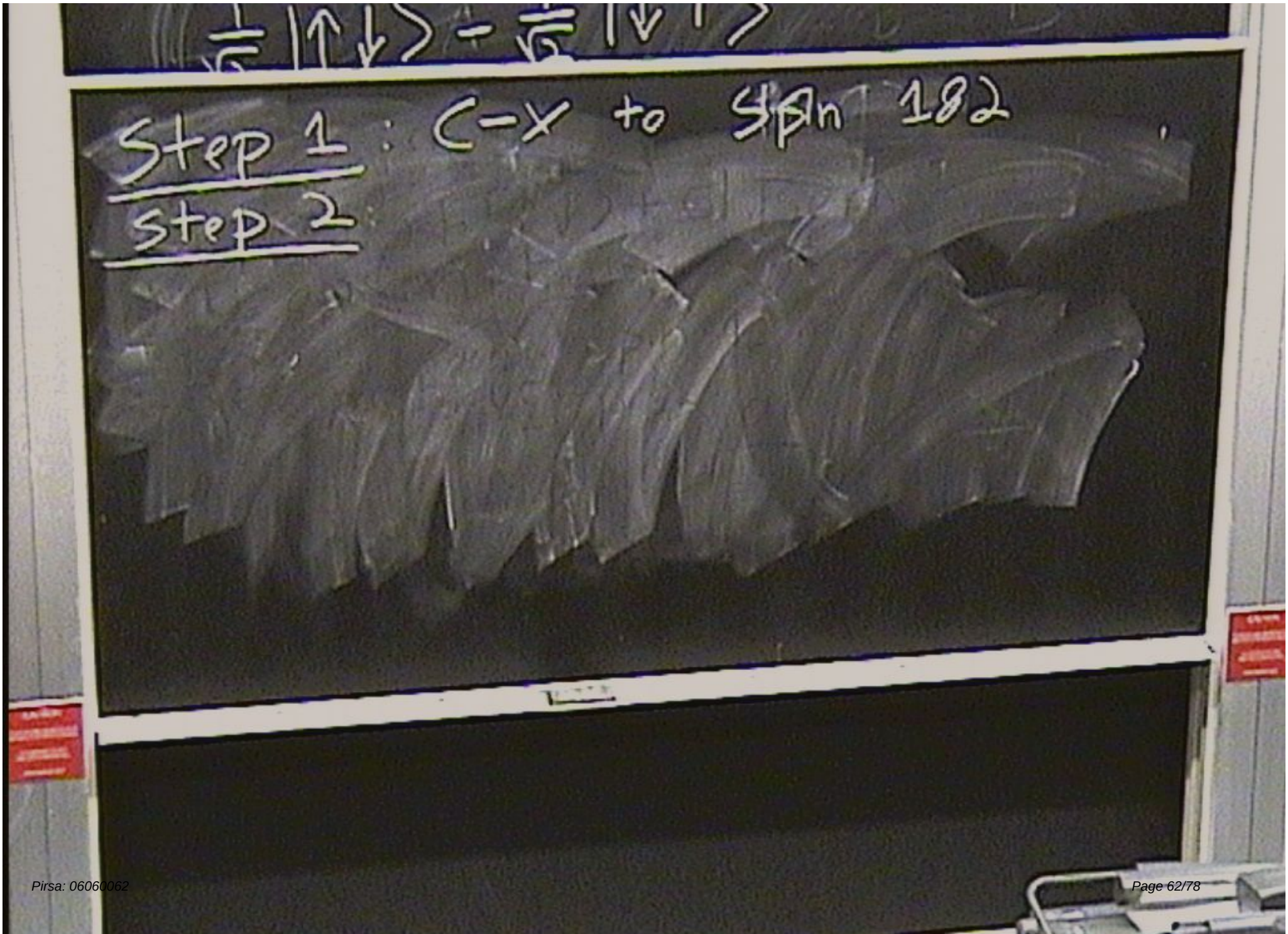
Teleportation

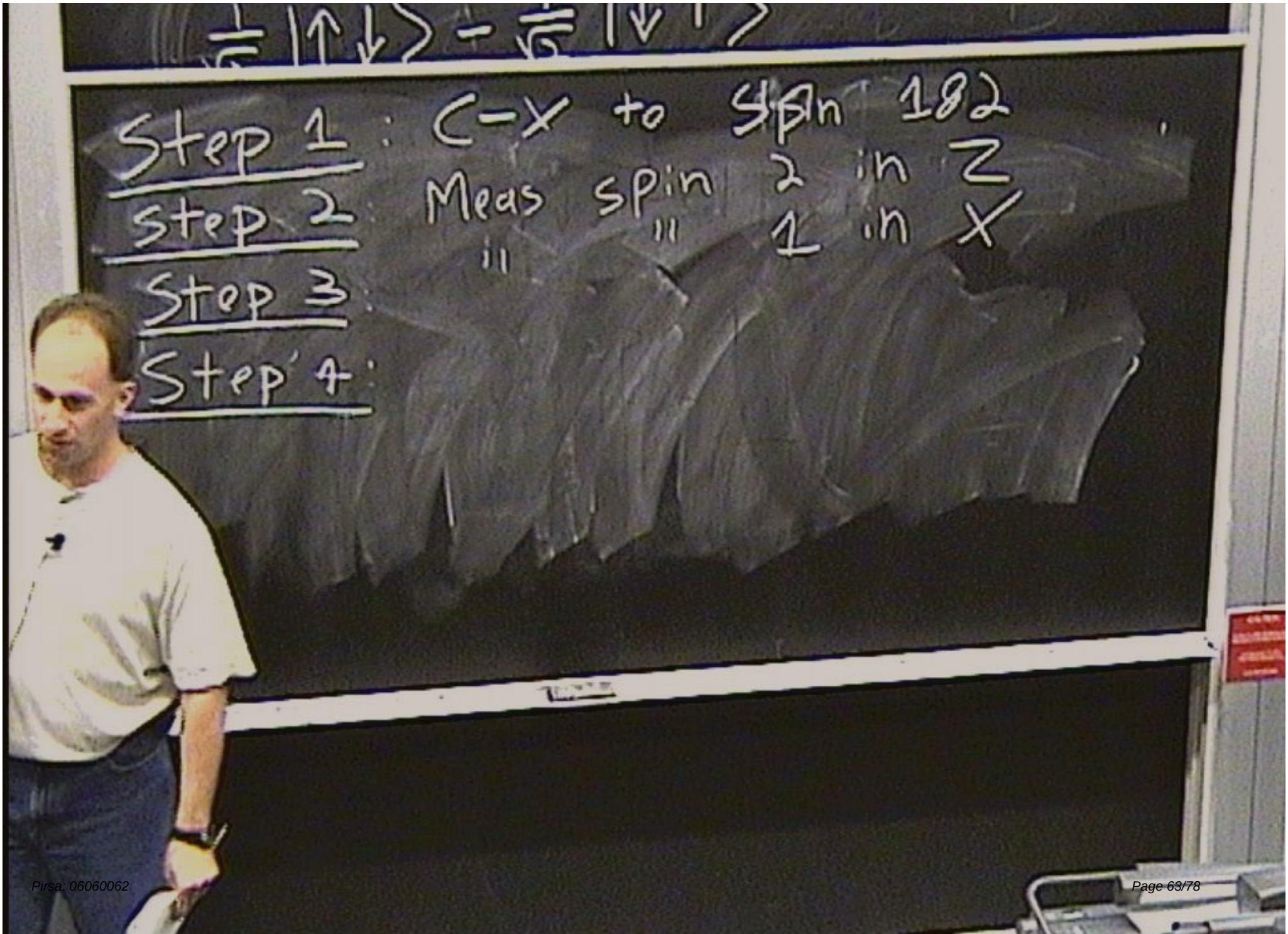
Spin 1 : "Unknown Spin" in Lab A

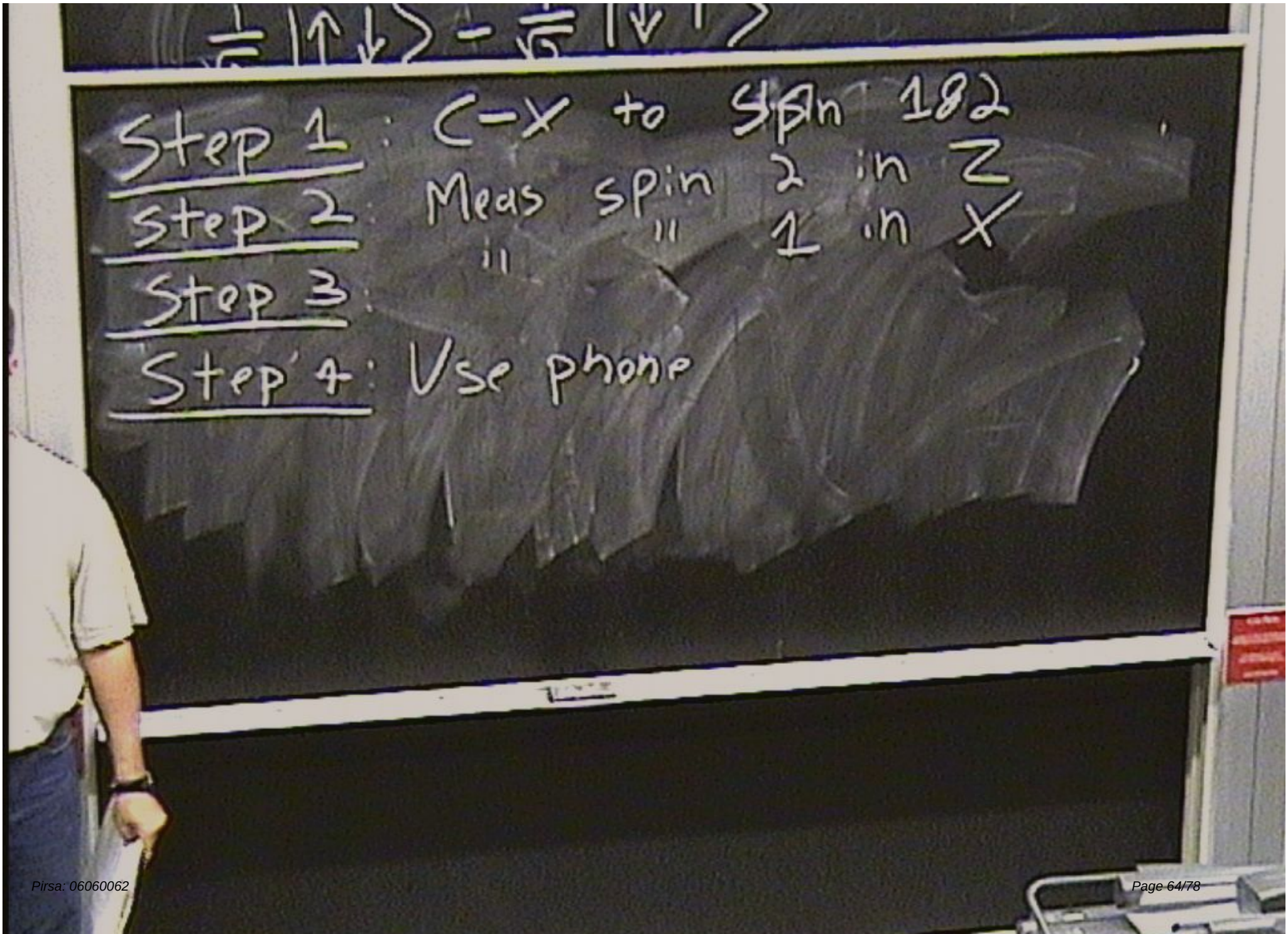
Spin 2&3 : $\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$

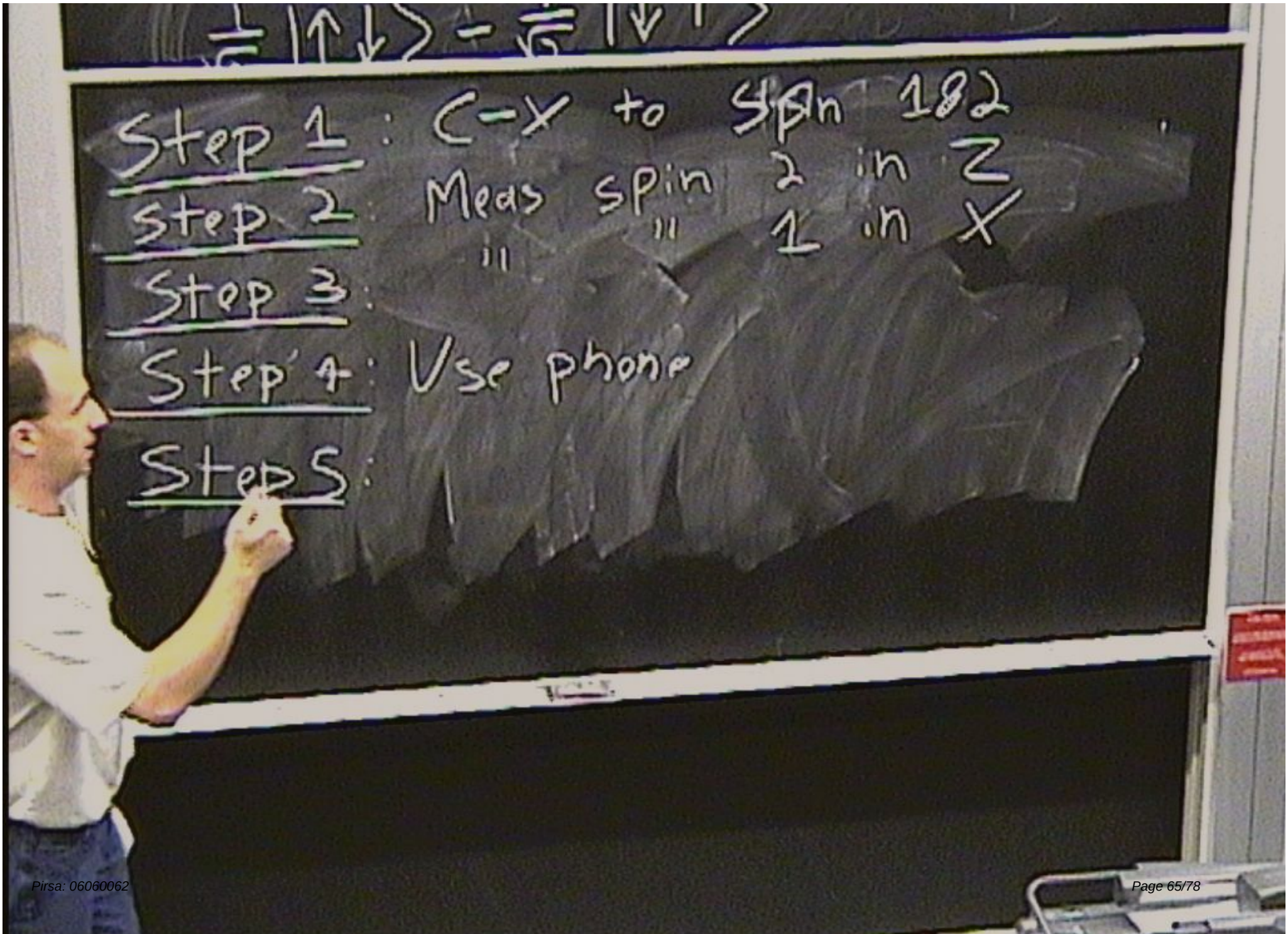
Spin 2 Lab A

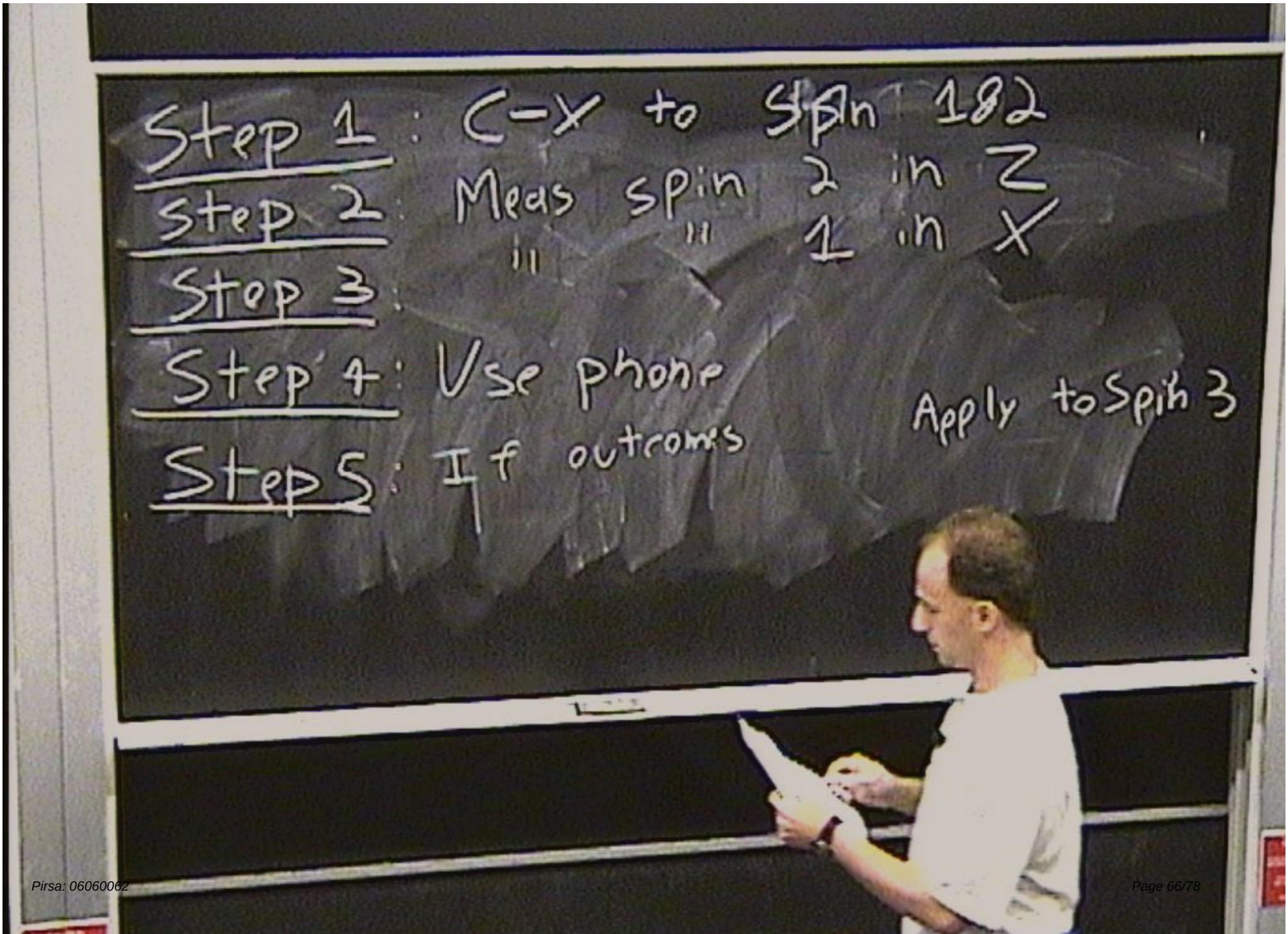
Spin 3 Lab B

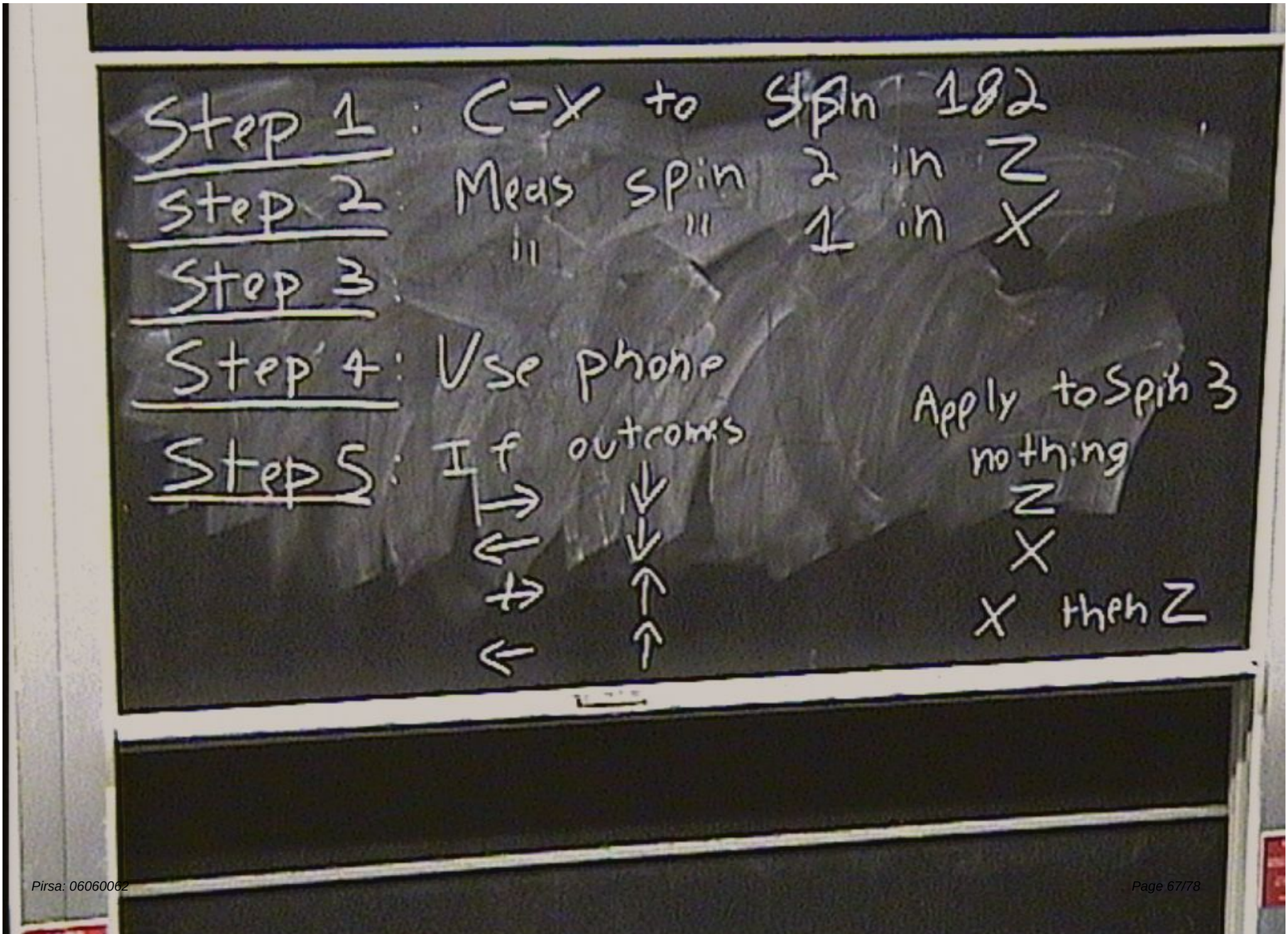

Step 1 : C-X to Span 182
Step 2

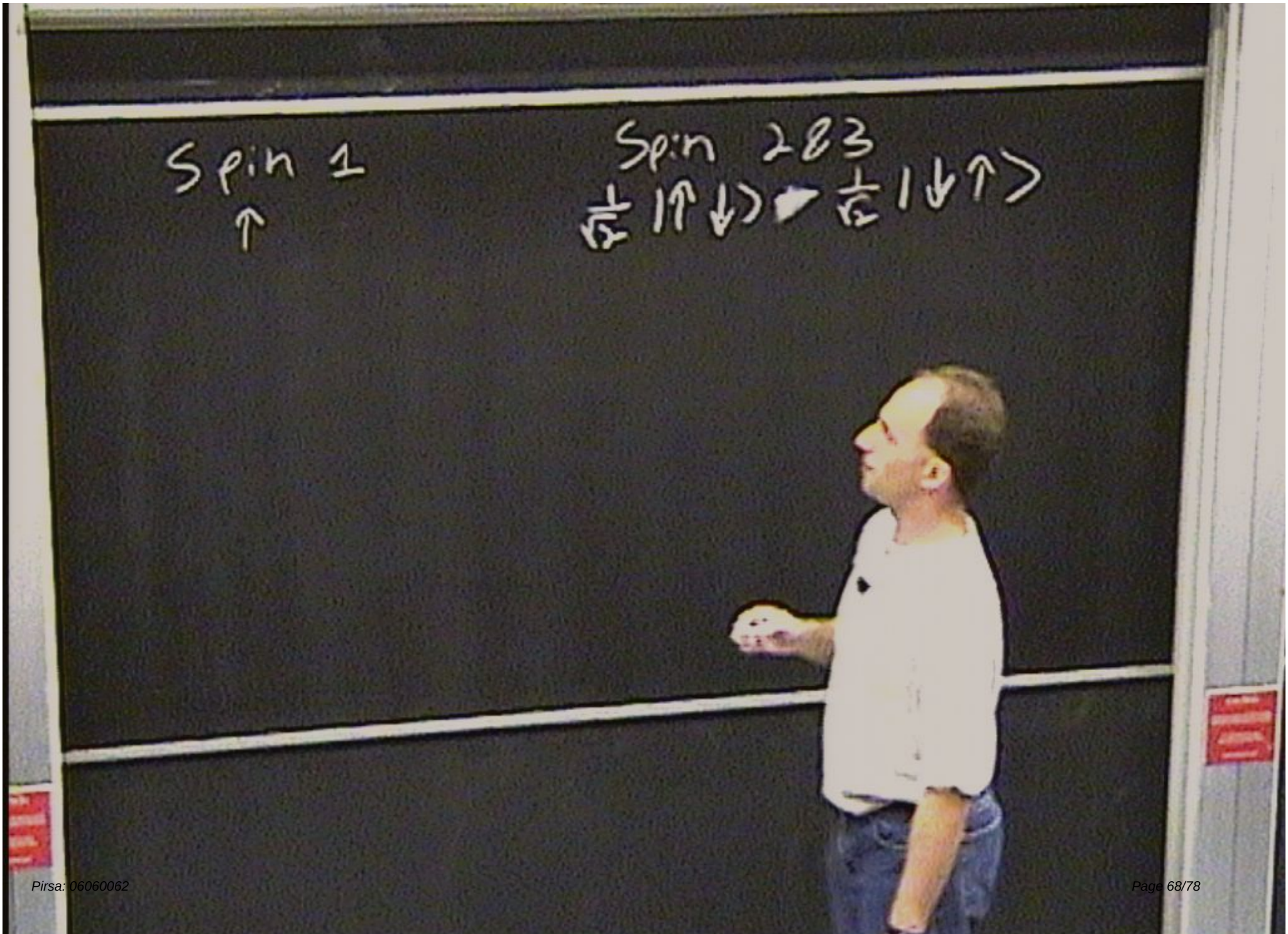

$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$
Step 1 : C-X to Spin 1&2
Step 2 : Meas spin 2 in Z
=> 1 in X
Step 3 :
Step 4 :

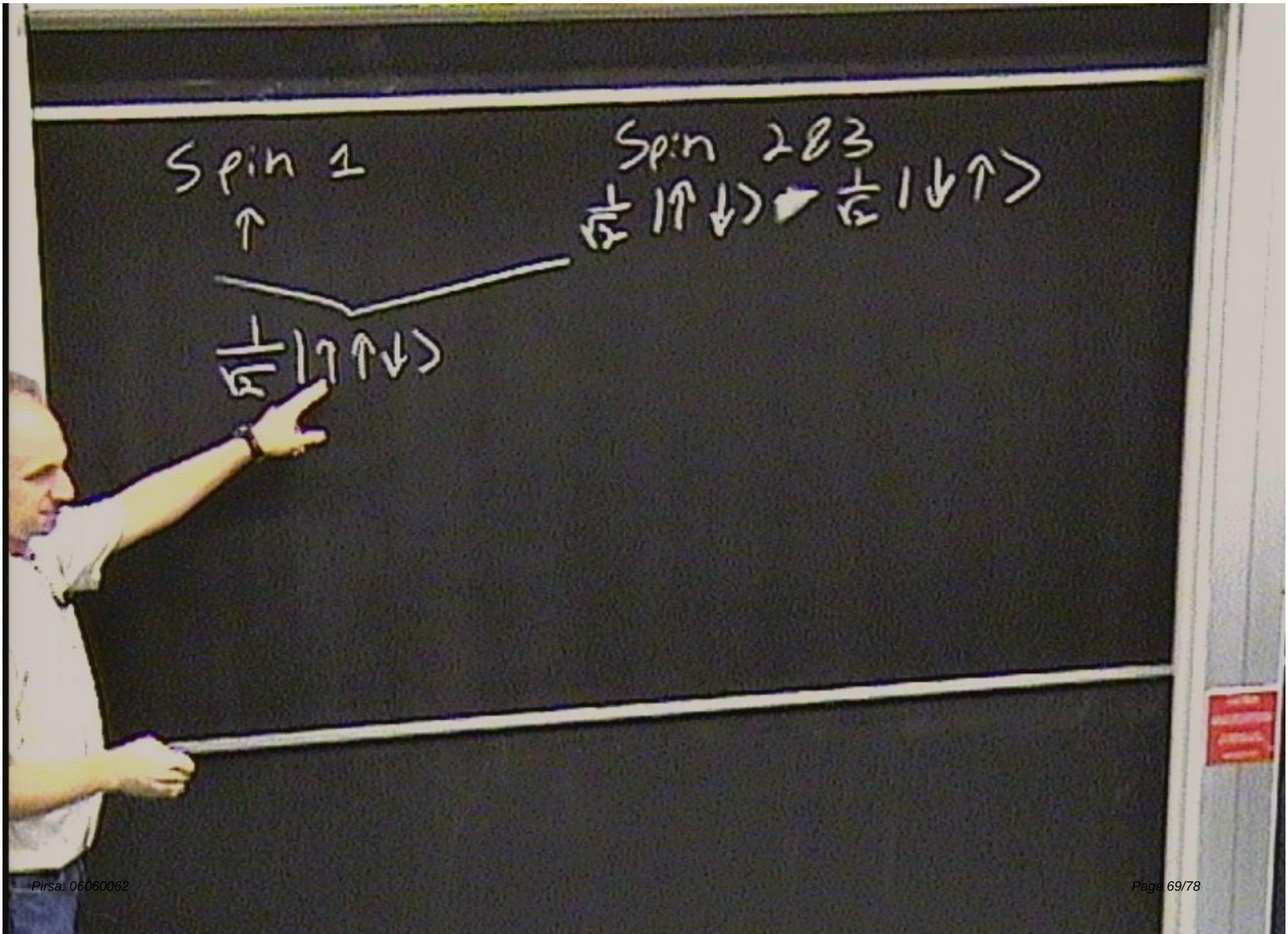

$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$
Step 1 : C-X to Spin 182
Step 2 : Meas spin 2 in Z
= = 1 in X
Step 3 :
Step 4 : Use phone

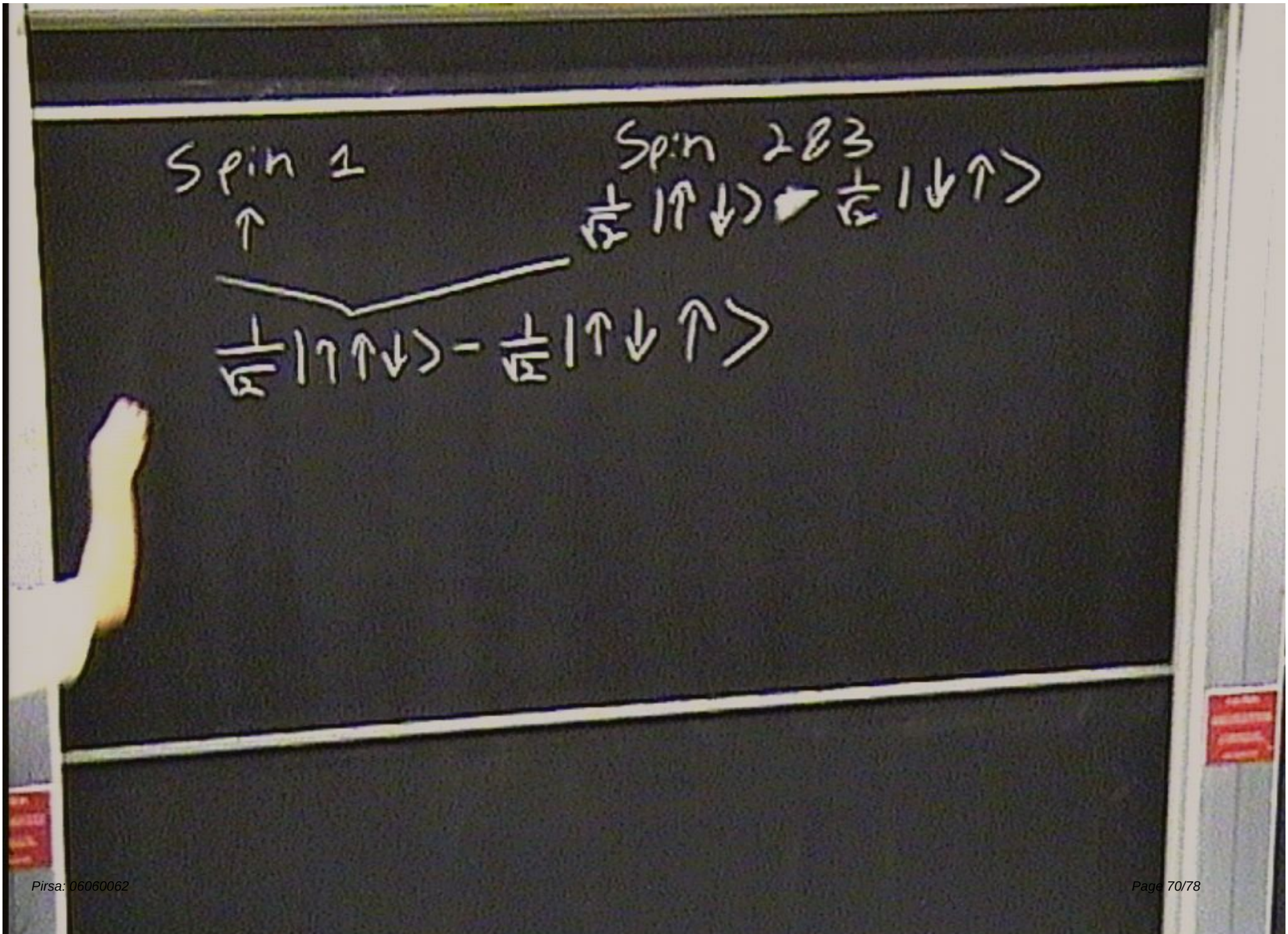

Step 1 : C-X to Spin 1&2
Step 2 : Meas spin 2 in Z
" " 1 in X
Step 3 :
Step 4 : Use phone
Step 5 :

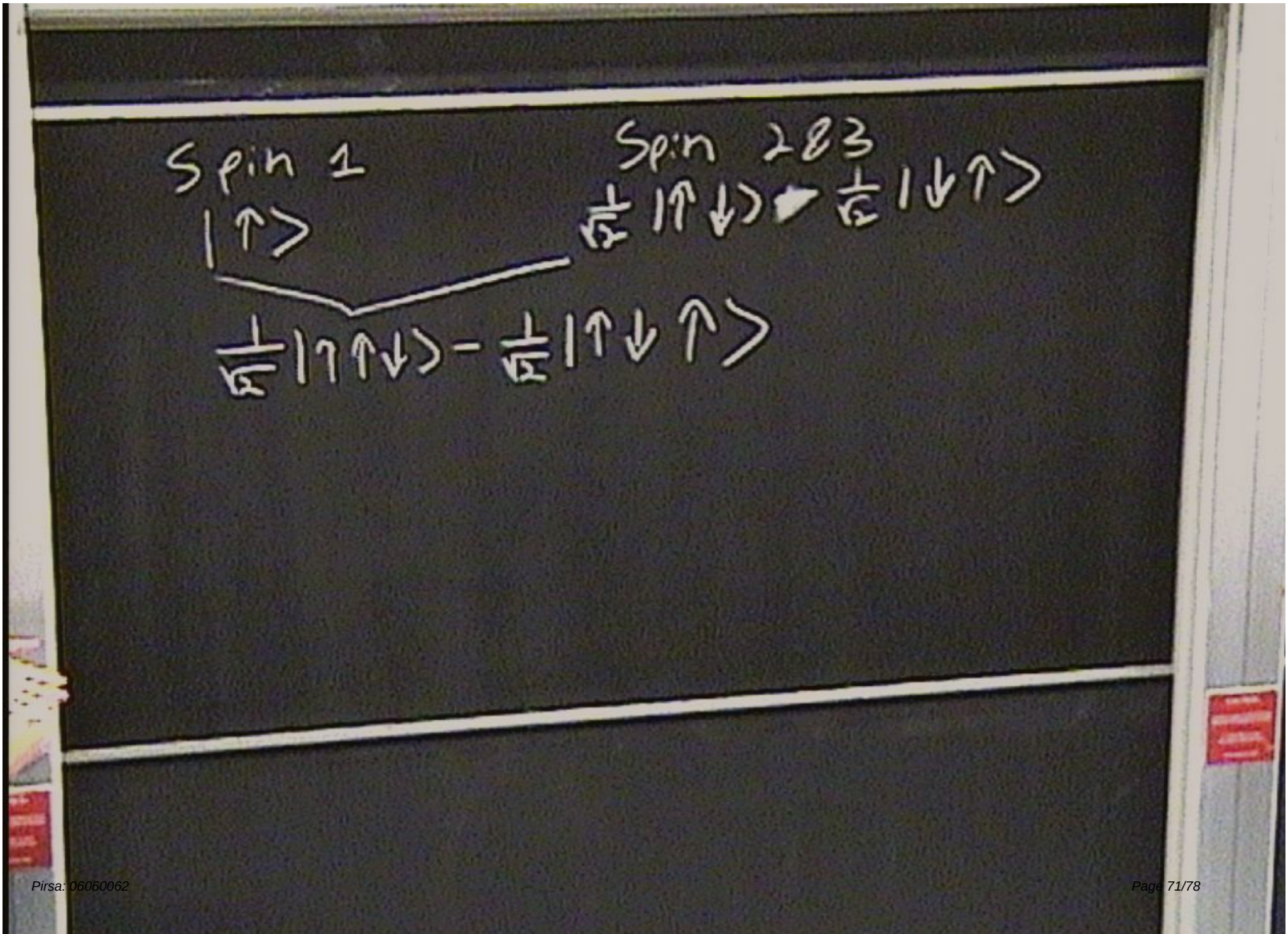

Step 1 : C-X to Spin 182
Step 2 : Meas spin 2 in Z
" " 1 in X
Step 3 :
Step 4 : Use phone
Step 5 : If outcomes
Apply to Spin 3

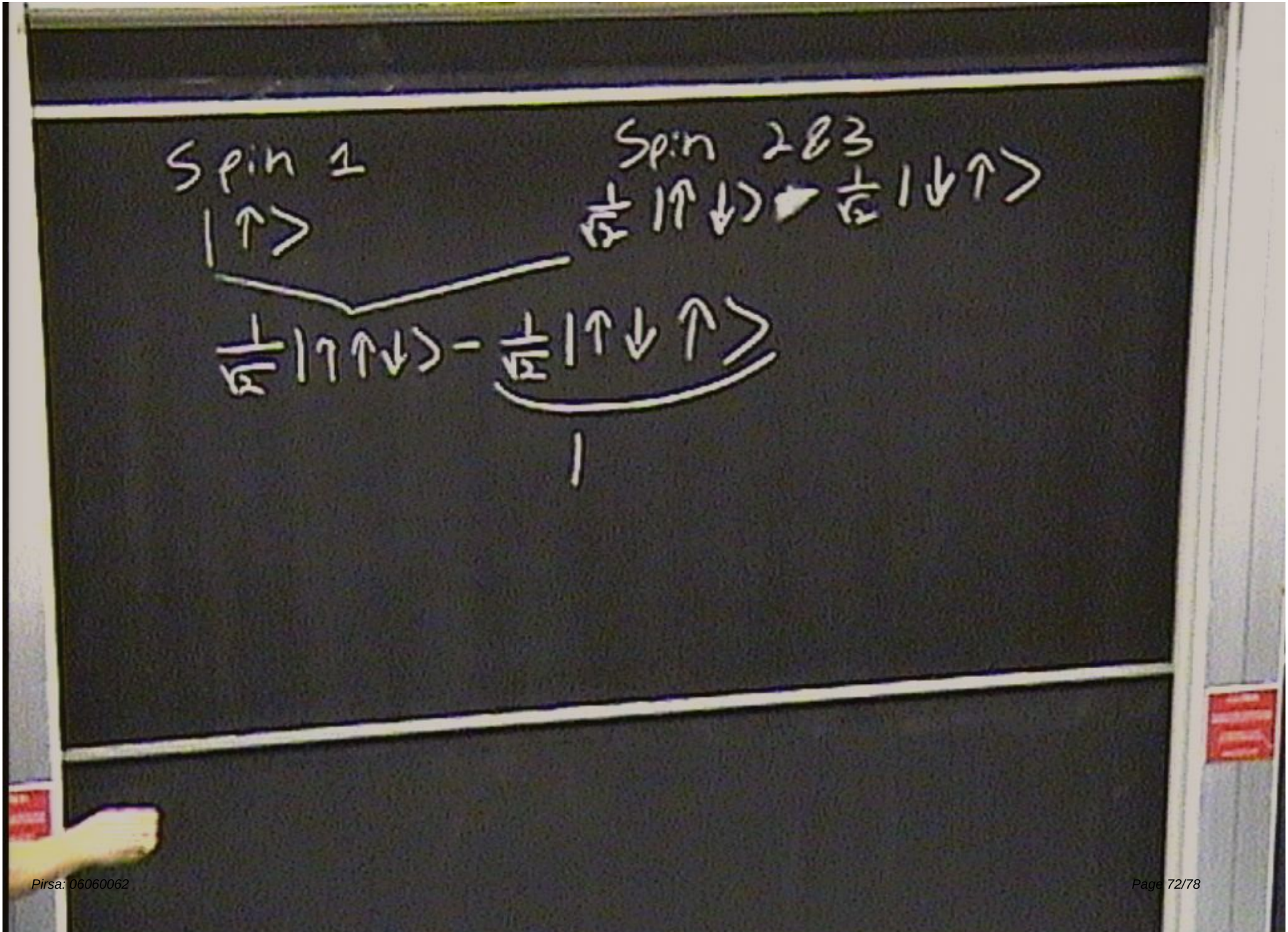

Step 1: C-X to Spin 1&2
Step 2: Meas spin 2 in Z
1 in X
Step 3:
Step 4: Use phone
Step 5: If outcomes
Apply to Spin 3
nothing
Z
X
X then Z

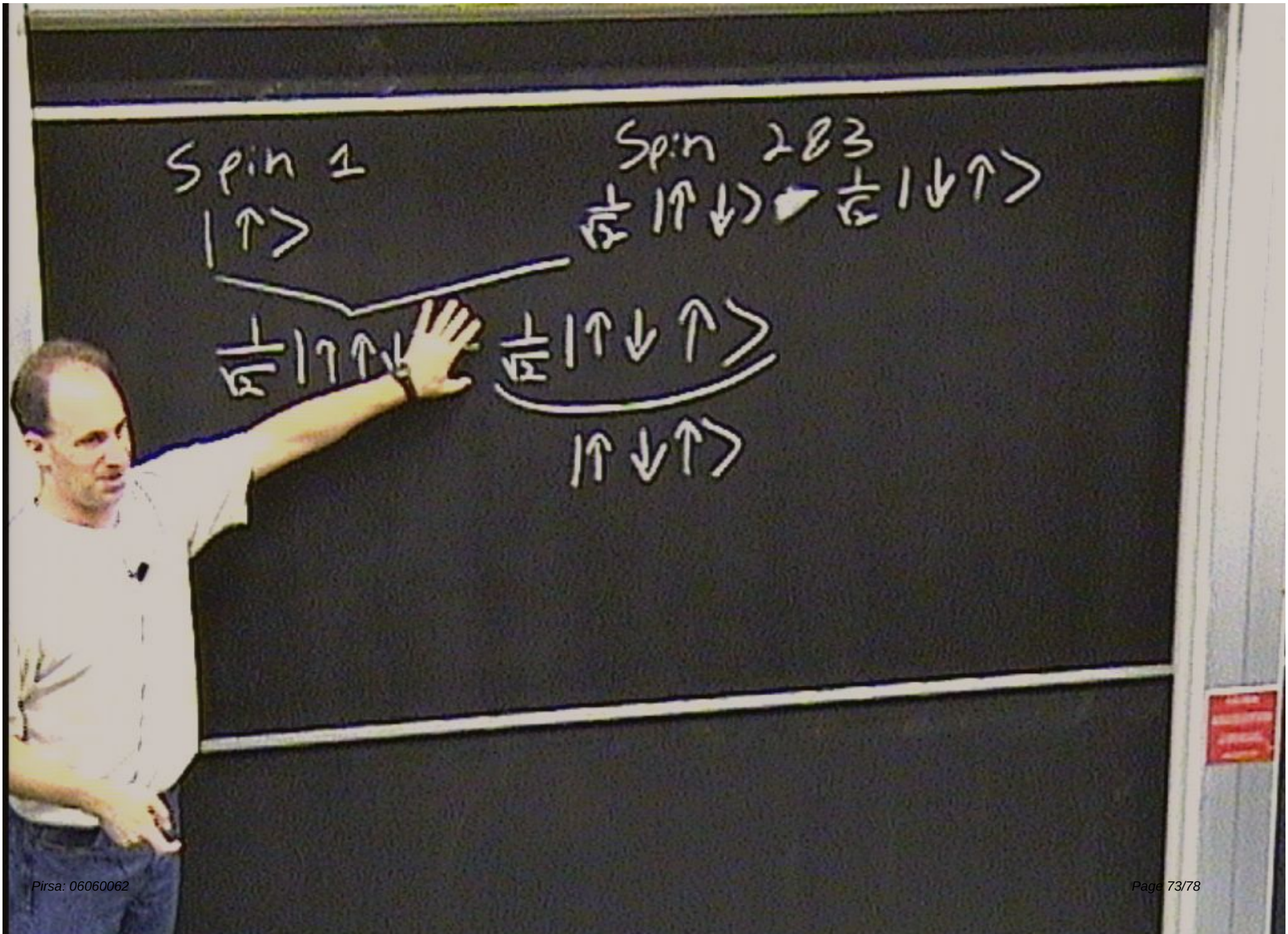

Spin 1
↑
Spin 2&3
1/√2 (↑↓) → 1/√2 (↓↑)

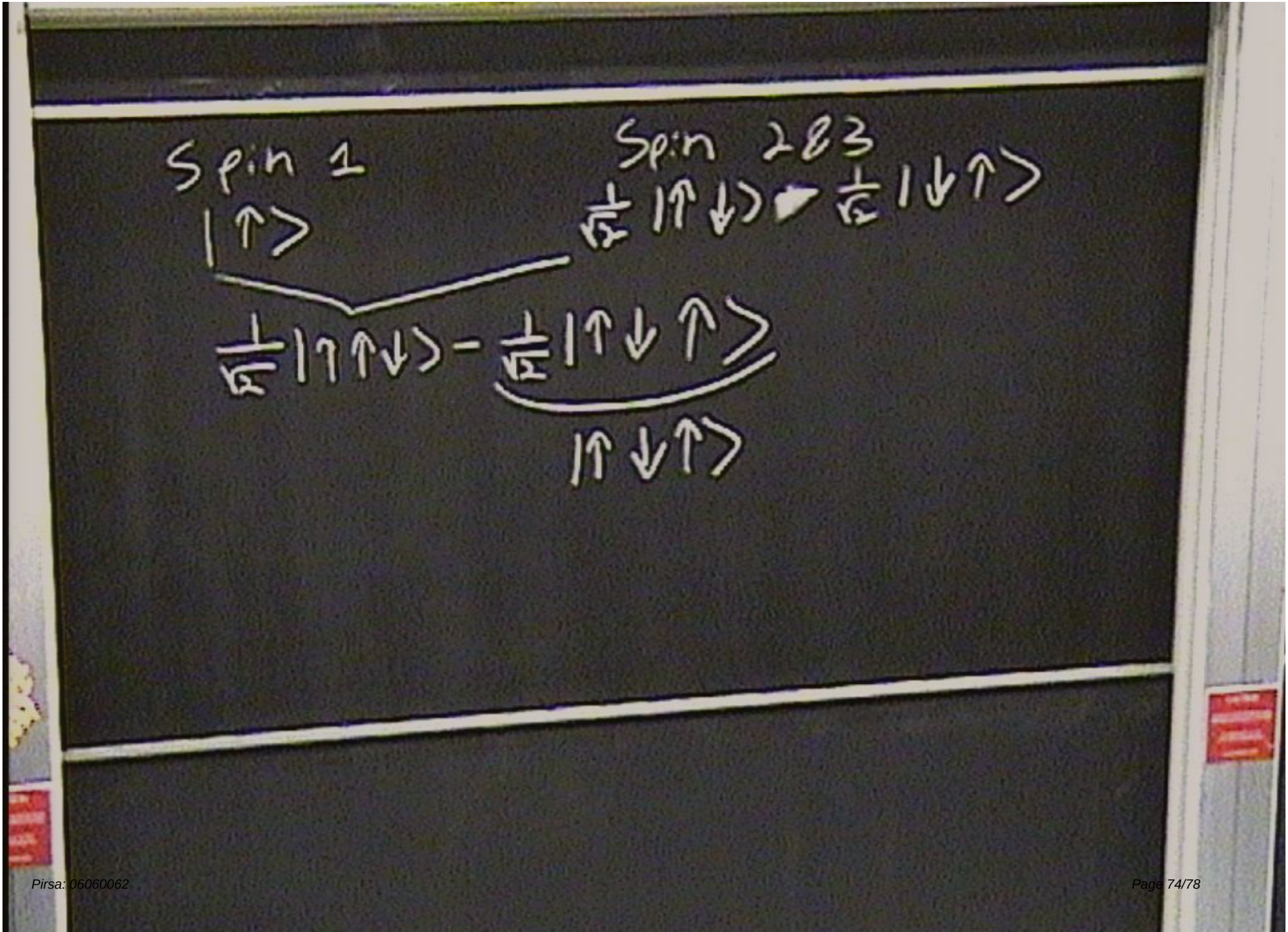

Spin 1
↑
$\frac{1}{\sqrt{2}}|\uparrow\downarrow\uparrow\rangle$
Spin 2&3
$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle$ $\frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$

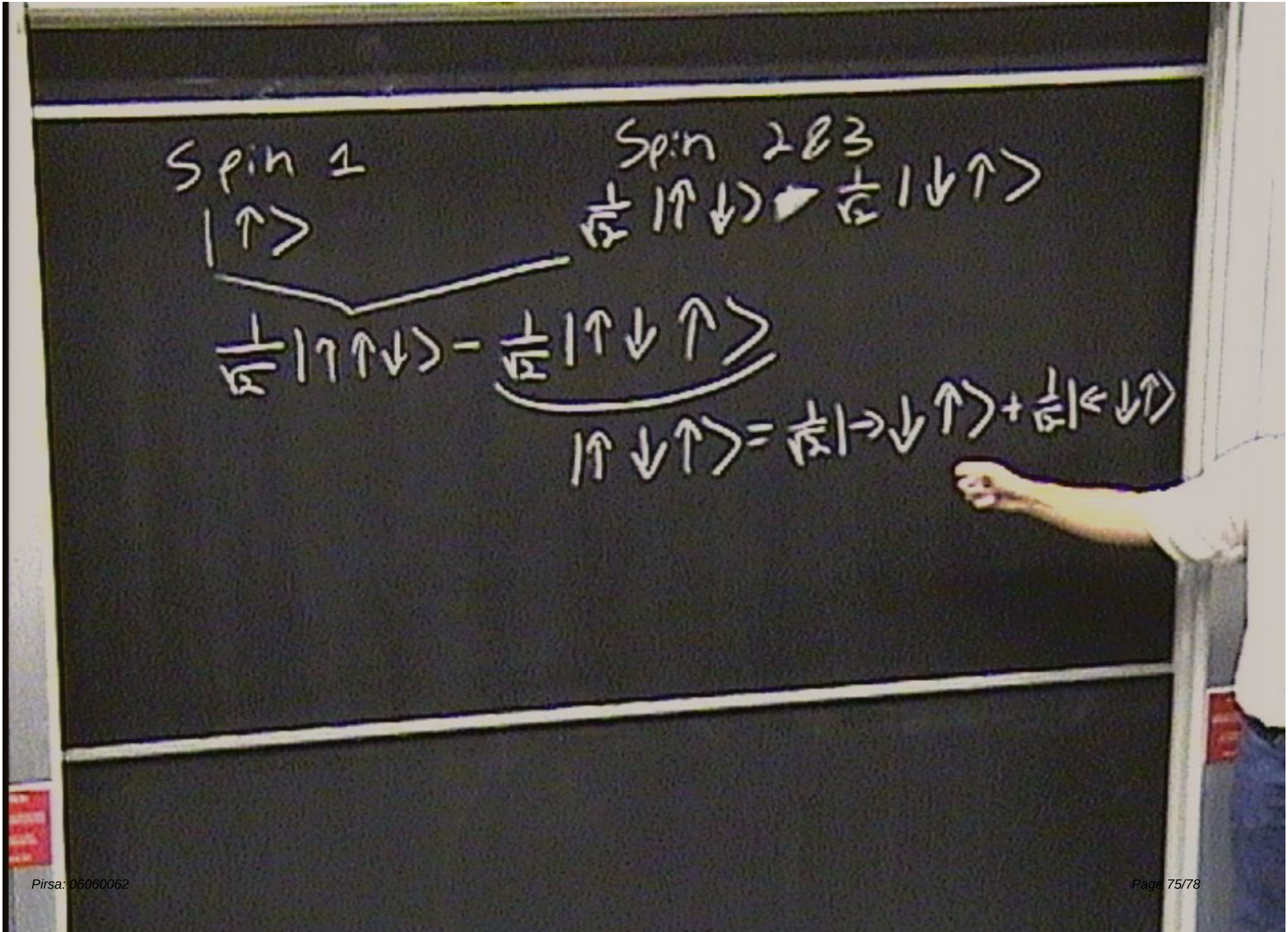

Spin 1
↑
Spin 2&3
$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle$ $\frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$
$\frac{1}{\sqrt{2}}|\uparrow\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\uparrow\downarrow\uparrow\rangle$


Spin 1
|↑>
Spin 283
1/√2 |↑↓> → 1/√2 |↓↑>
1/√2 |↑↑↓> - 1/√2 |↑↓↑>
Pirsa: 06060062
Page 71/78


Spin 1
|↑>
Spin 2⊗3
1/√2 |↑↓> → 1/√2 |↓↑>
1/√2 |↑↑↓> - 1/√2 |↑↓↑>
1


Spin 1
|↑>
Spin 2&3
1/√2 |↑↓> → 1/√2 |↓↑>
1/√2 |↑↑↓> 1/√2 |↑↓↑>
|↑↓↑>


Spin 1
|↑>
Spin 2⊗3
1/√2 |↑↓> → 1/√2 |↓↑>
1/√2 |↑↑↓> - 1/√2 |↑↓↑>
|↑↓↑>


Spin 1
|↑>
Spin 2⊗3
1/√2 |↑↓> 1/√2 |↓↑>
1/√2 |↑↑↓> - 1/√2 |↑↓↑>
|↑↓↑> = 1/√2 |→↓↑> + 1/√2 |←↓↑>

Spin 1

$|\uparrow\rangle$

Spin 2 ⊗ 3

$\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle \leftarrow \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle$

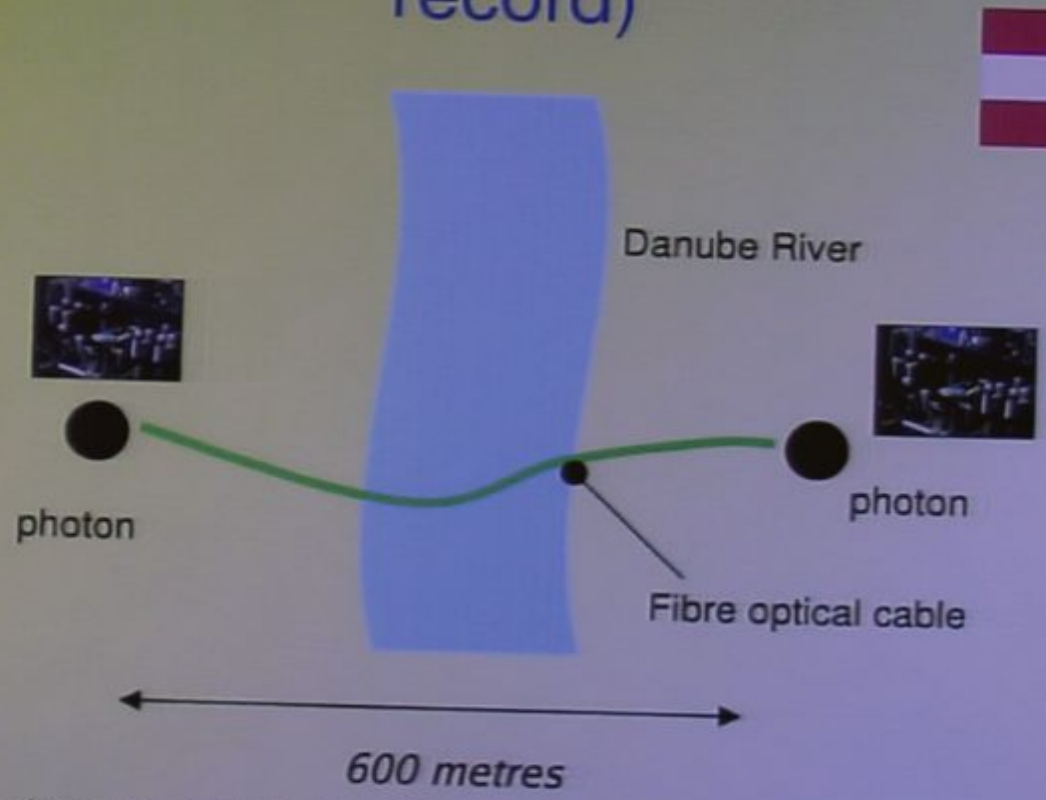
$\frac{1}{\sqrt{2}}|\uparrow\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\uparrow\downarrow\uparrow\rangle$

$|\uparrow\downarrow\uparrow\rangle = \frac{1}{\sqrt{2}}|\rightarrow\downarrow\uparrow\rangle + \frac{1}{\sqrt{2}}|\leftarrow\downarrow\uparrow\rangle$

1997: Vienna, Austria
a single photon (About 50 cms)

Picture of equipment used to perform an early teleportation experiment with individual particles of light (photons). (University of Vienna, Austria.)

2004: Vienna, Austria
a single photon: 600 metres (world record)



For more information visit http://news.bbc.co.uk/2/hi/science/nature/3576594.stm