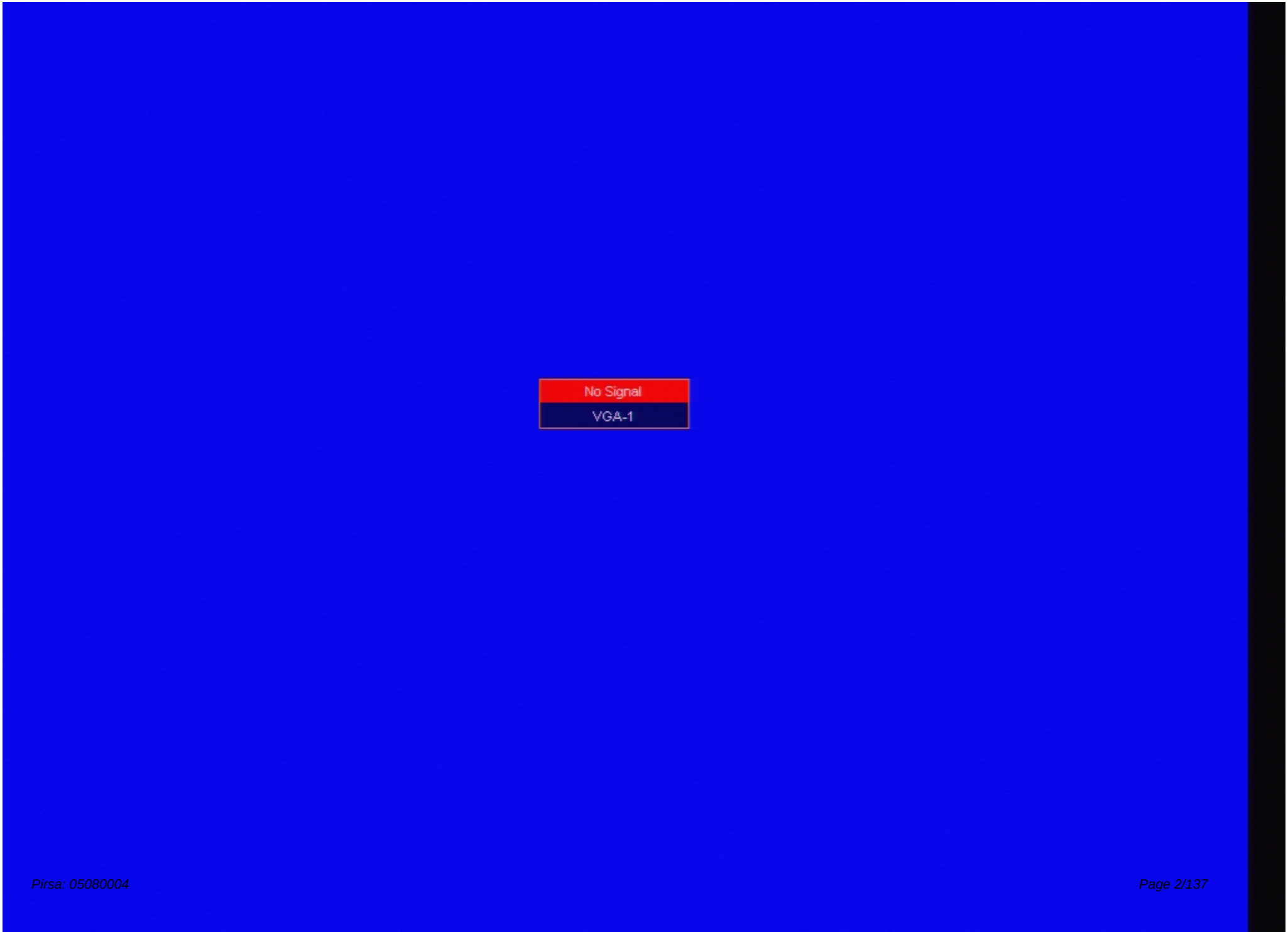
Title: ISSYP 2005 - Lecture B

Date: Aug 10, 2005 10:30 AM

URL: http://pirsa.org/05080004

Abstract:


No Signal
VGA-1

Space = L

math $M = F(q(t), p(t))$

$T_a : L \longrightarrow L$

$(T_a F)(t) := F(t+a) = F(t)$

↑ symmetry

"time translation symmetry"

$\Leftrightarrow \frac{\partial F}{\partial t} = 0 \quad \forall t$

Space = L

math $M = F(q(t), p(t))$

$T_a : L \longrightarrow L$

$(T_a F)(t) := F(t+a) = F(t)$

$\mathbb{R}$

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space = L

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$T_a : L \longrightarrow L$

$(T_a F)(t) := F(t+a) = F(t)$

$\mathbb{R}$; symmetry

$\Leftrightarrow$

"time translation symmetry"

$\Leftrightarrow \frac{dF}{dt} = 0 \quad \forall t$

$\{F, H\} = 0 \iff \frac{dF}{dt} = 0 \iff F$ is time translation invariant

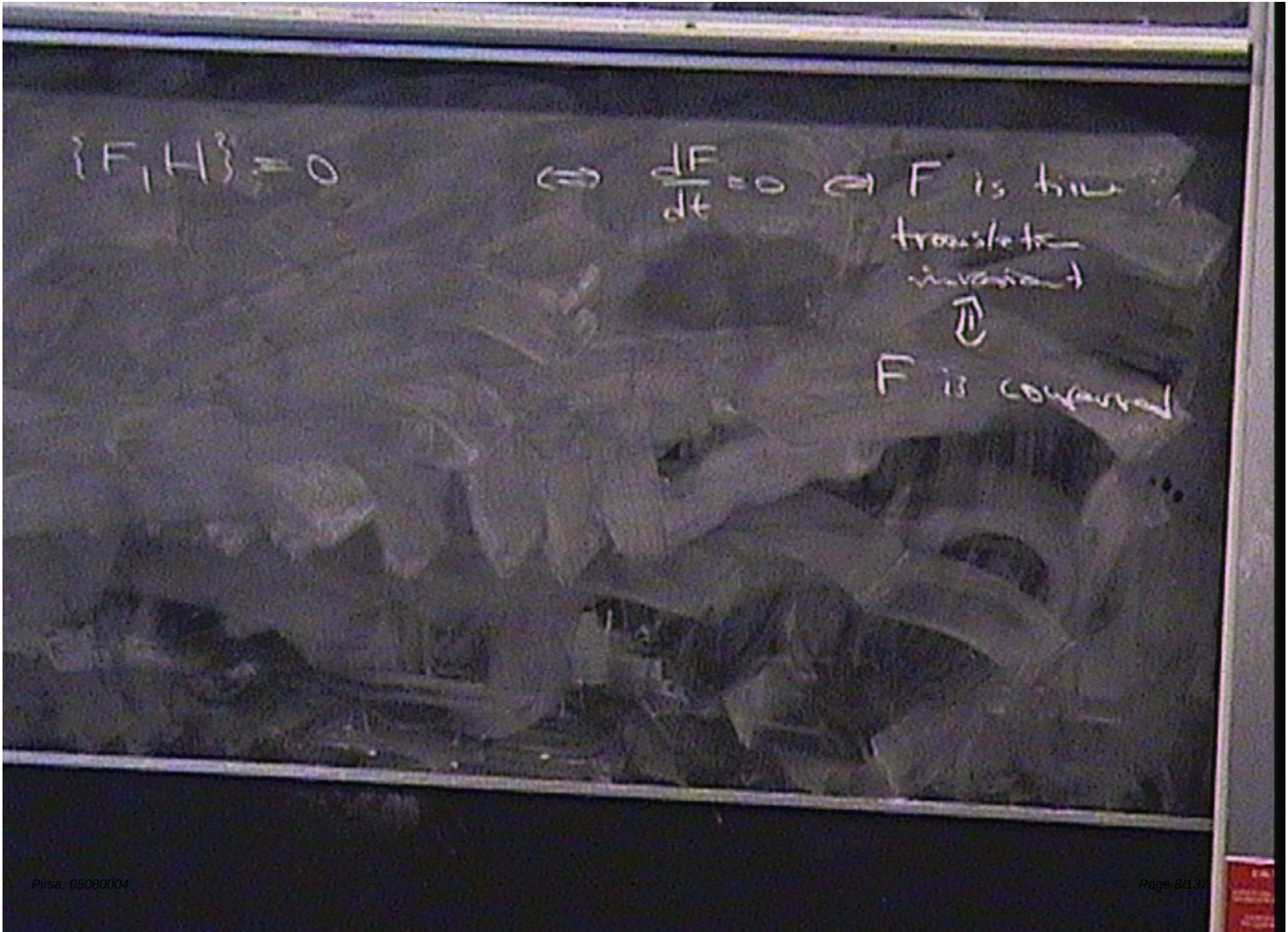
$\Downarrow$

F is conserved

$\{F, H\} = 0 \iff \frac{dF}{dt} = 0 \Rightarrow F$ is time translation invariant

$\Updownarrow$

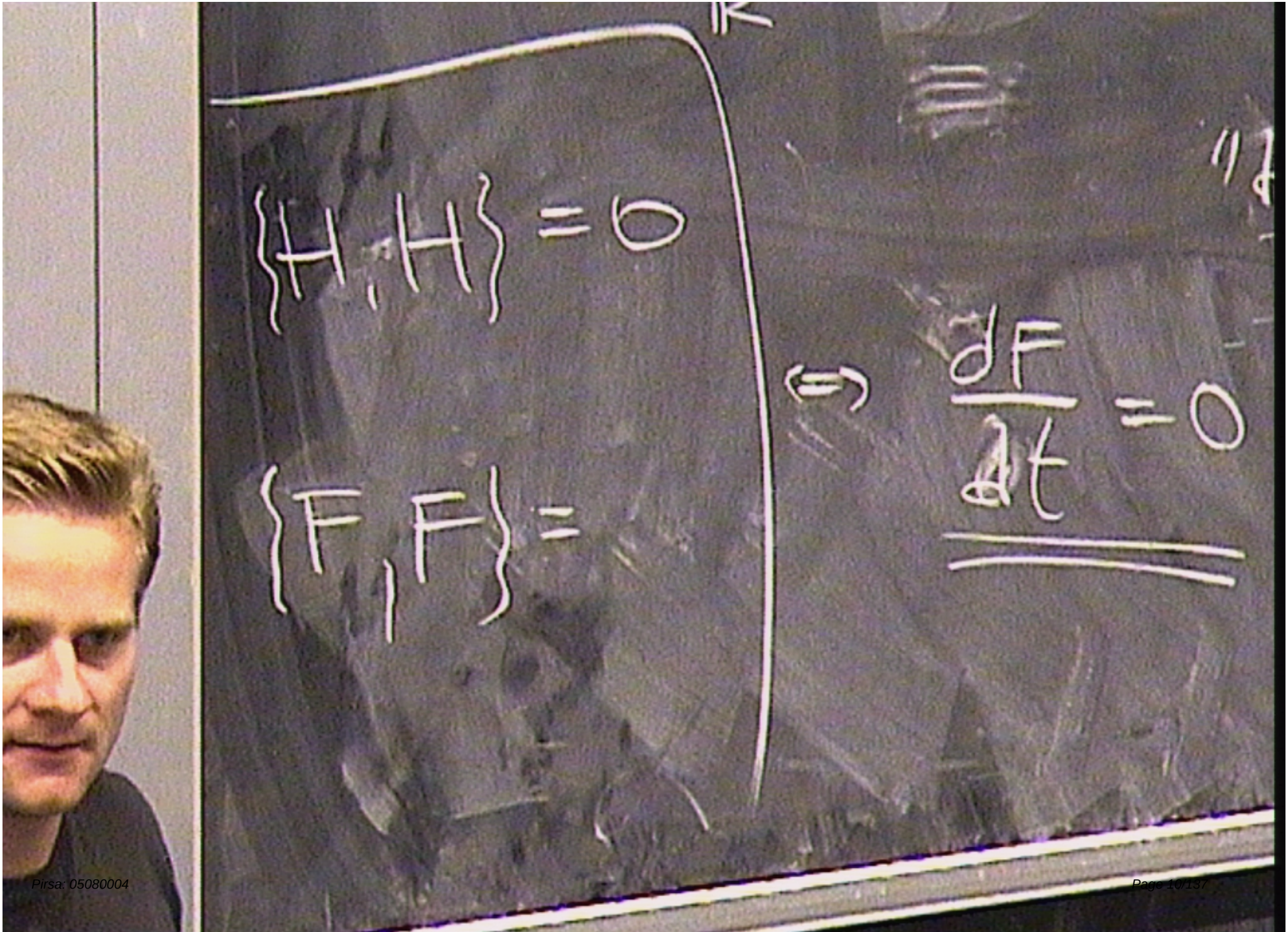
F is conserved

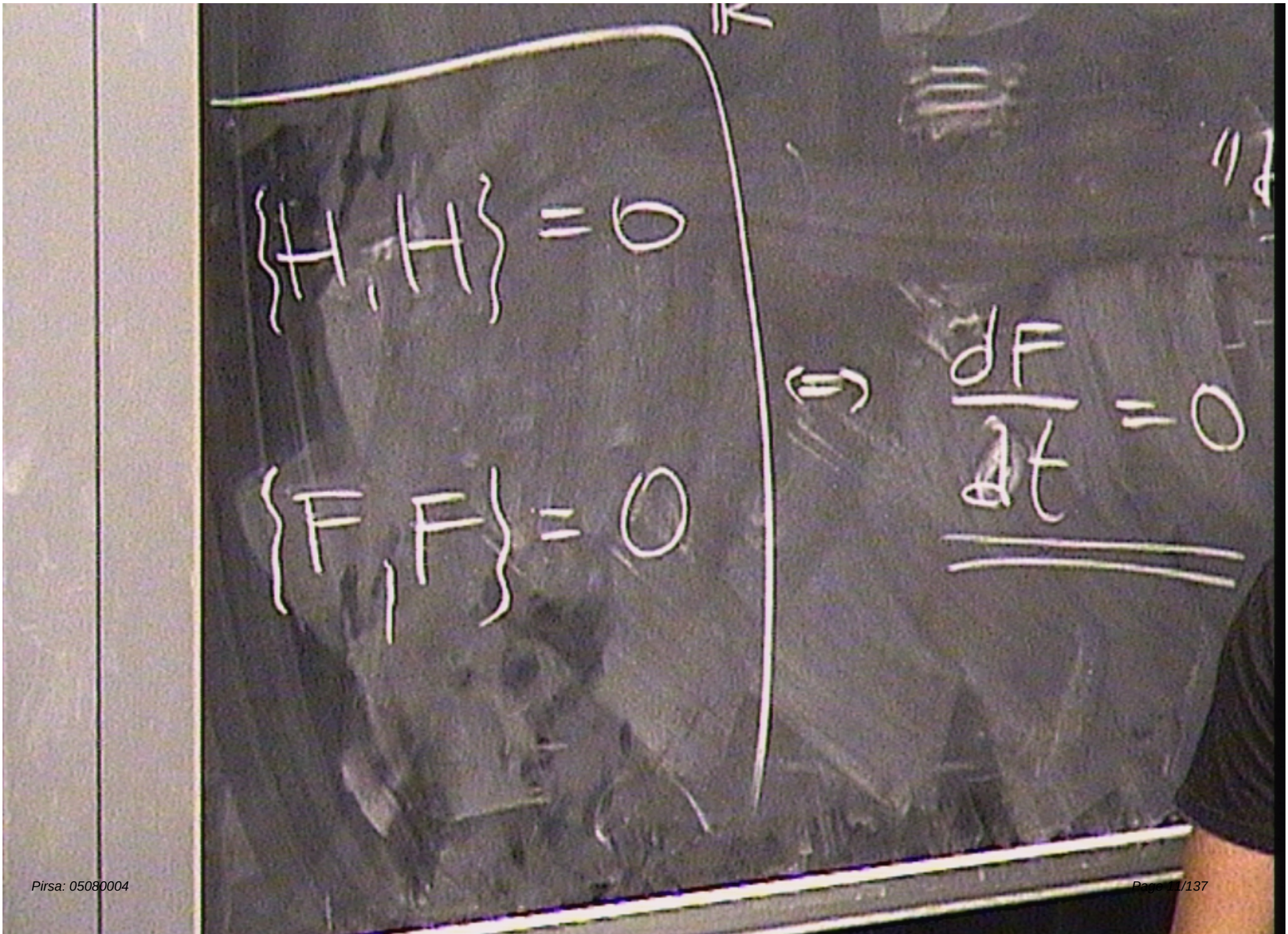

$\{F, H\} = 0 \iff \frac{dF}{dt} = 0$ ⇒ F is time
translation
invariant
⇕
F is conserved

$\{F, H\} = 0 \iff \frac{dF}{dt} = 0$ ⇒ F is time translation invariant

⇕

F is conserved


$\{H,H\} = 0$
$\{F,F\} =$
$\Leftrightarrow \frac{dF}{dt} = 0$


$\{H, H\} = 0$
$\{F, F\} = 0$
$\Leftrightarrow \frac{dF}{dt} = 0$

$L_3 = q_1 p_2 - q_2 p_1$

R ⟺ symmetry

"time translation symmetry"

$=0$

$=0$

$\Leftrightarrow \frac{dF}{dt} = 0 \quad \forall t$

$\{F, F\} = -\{H, F\}$

$\{H, F\} = 0$

$\frac{dF}{dt}$

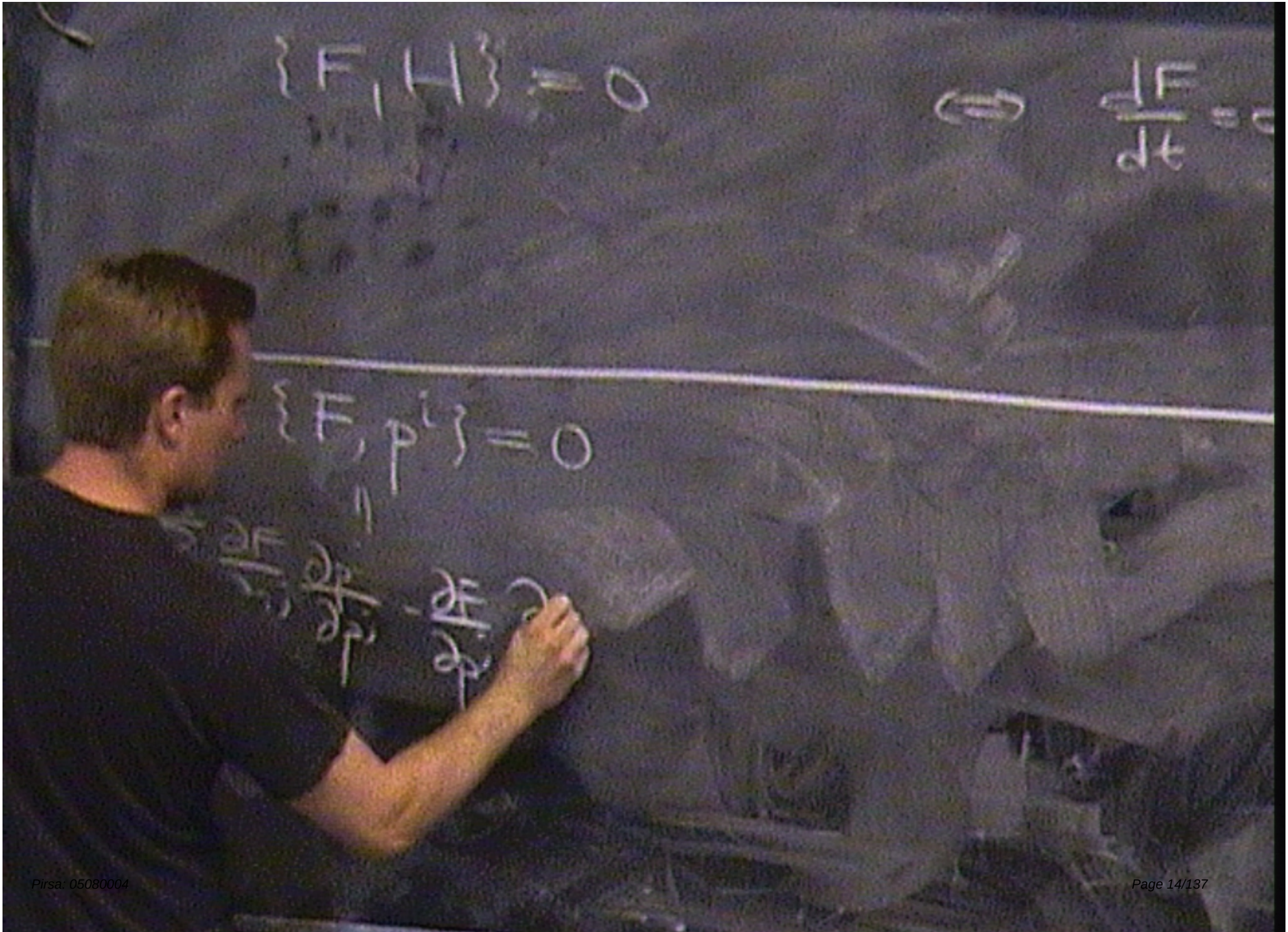
Poisson's eqn.

$\{F, H\} = 0 \iff \frac{dF}{dt} = 0 \iff F$ is time translate invariant

$\Updownarrow$

F is conserved

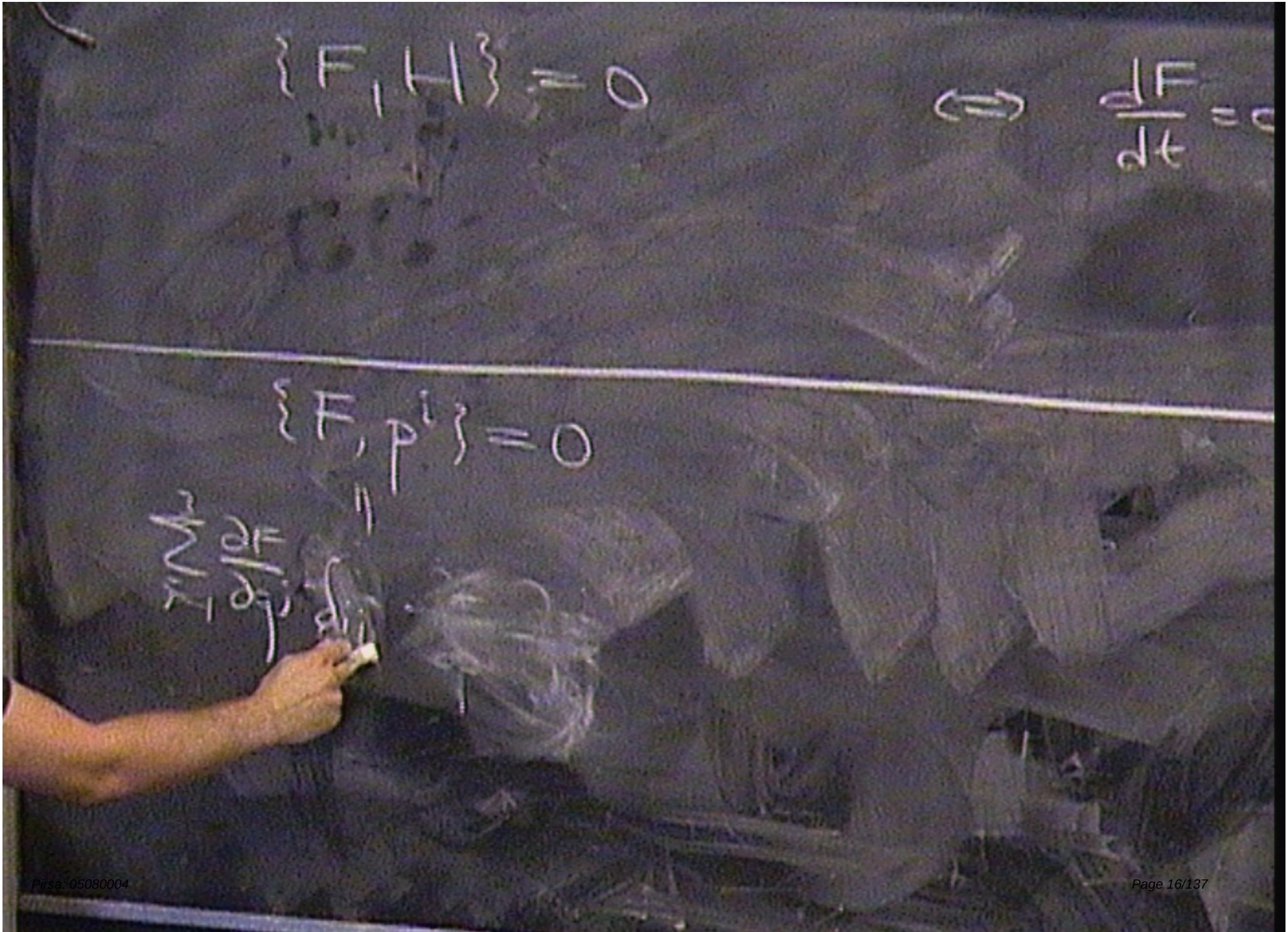
$\{F, p^i\} = 0$


{F, H} = 0
⟺
dF/dt
{F, p^i} = 0

$$\{F, H\} = 0 \iff \frac{dF}{dt} = 0$$

$$\{F, p^i\} = 0$$

$$= \sum_{j=1}^{M} \frac{\partial F}{\partial q^j} \frac{\partial q^j}{\partial x^i} - \frac{\partial F}{\partial p^j} \frac{\partial p^j}{\partial x^i}$$

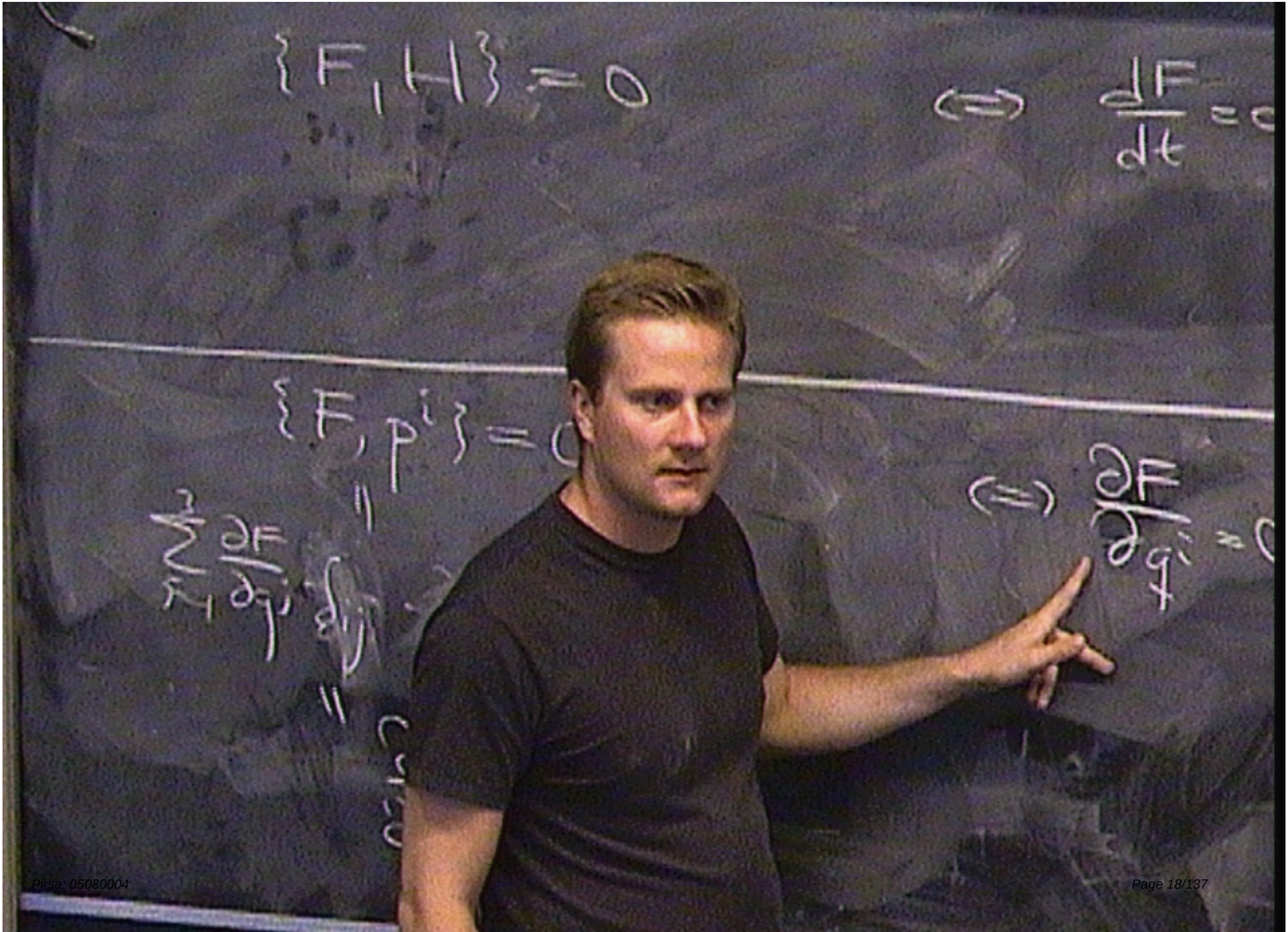

$\{F, H\} = 0 \iff \frac{dF}{dt} =$
$\{F, p^i\} = 0$
$\sum_{i=1}^{n} \frac{\partial F}{\partial q^i}$

$\{F, H\} = 0 \iff \frac{dF}{dt} = 0$

$\{F, p^i\} = 0$

$= \sum_j \frac{\partial F}{\partial q^j} \{q^j, p^i\}$

$= \frac{\partial F}{\partial q^i}$

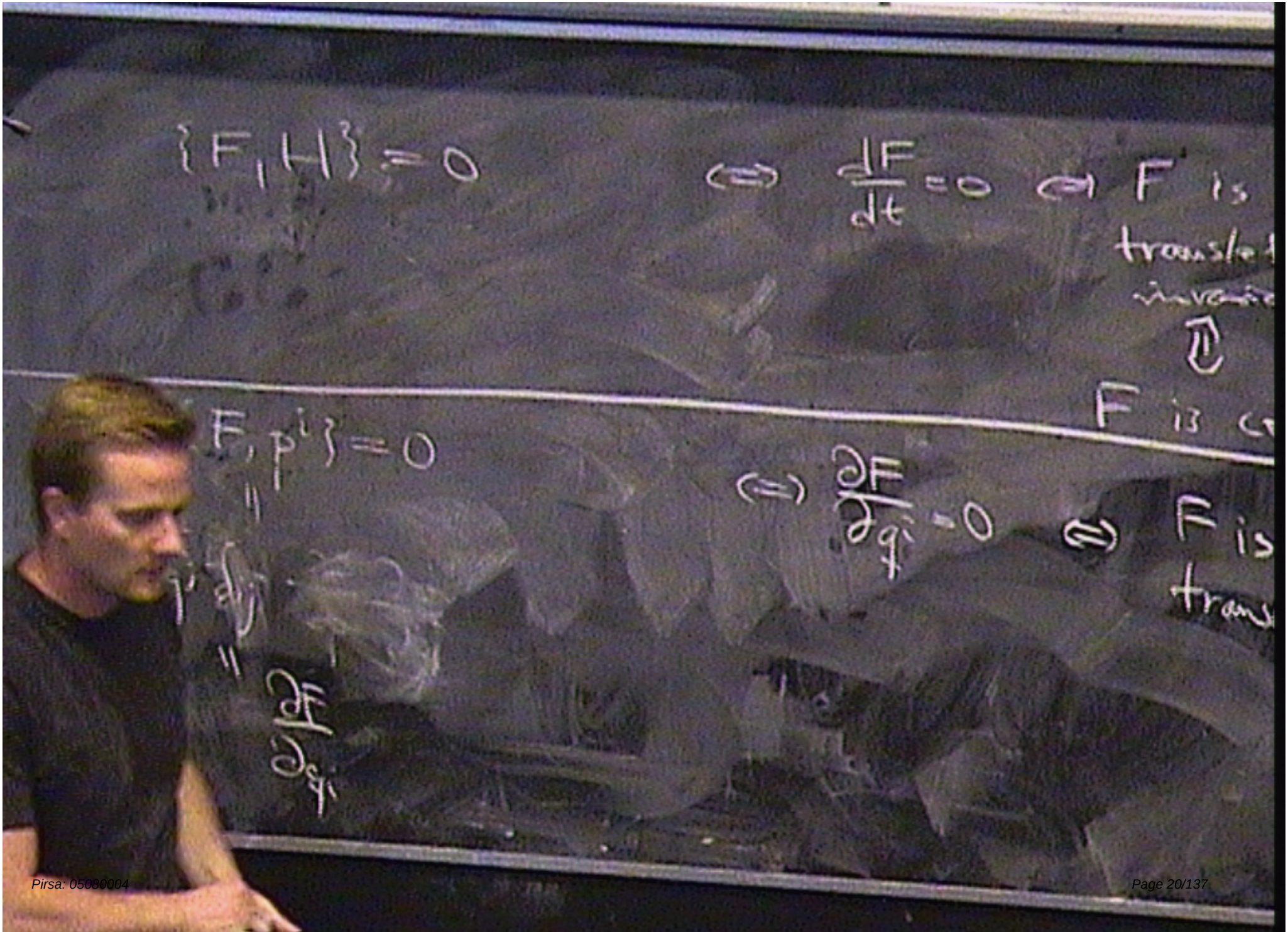

{F, H} = 0
⟺ dF/dt = 0
{F, p^i} = 0
⟺ ∂F/∂q^i = 0

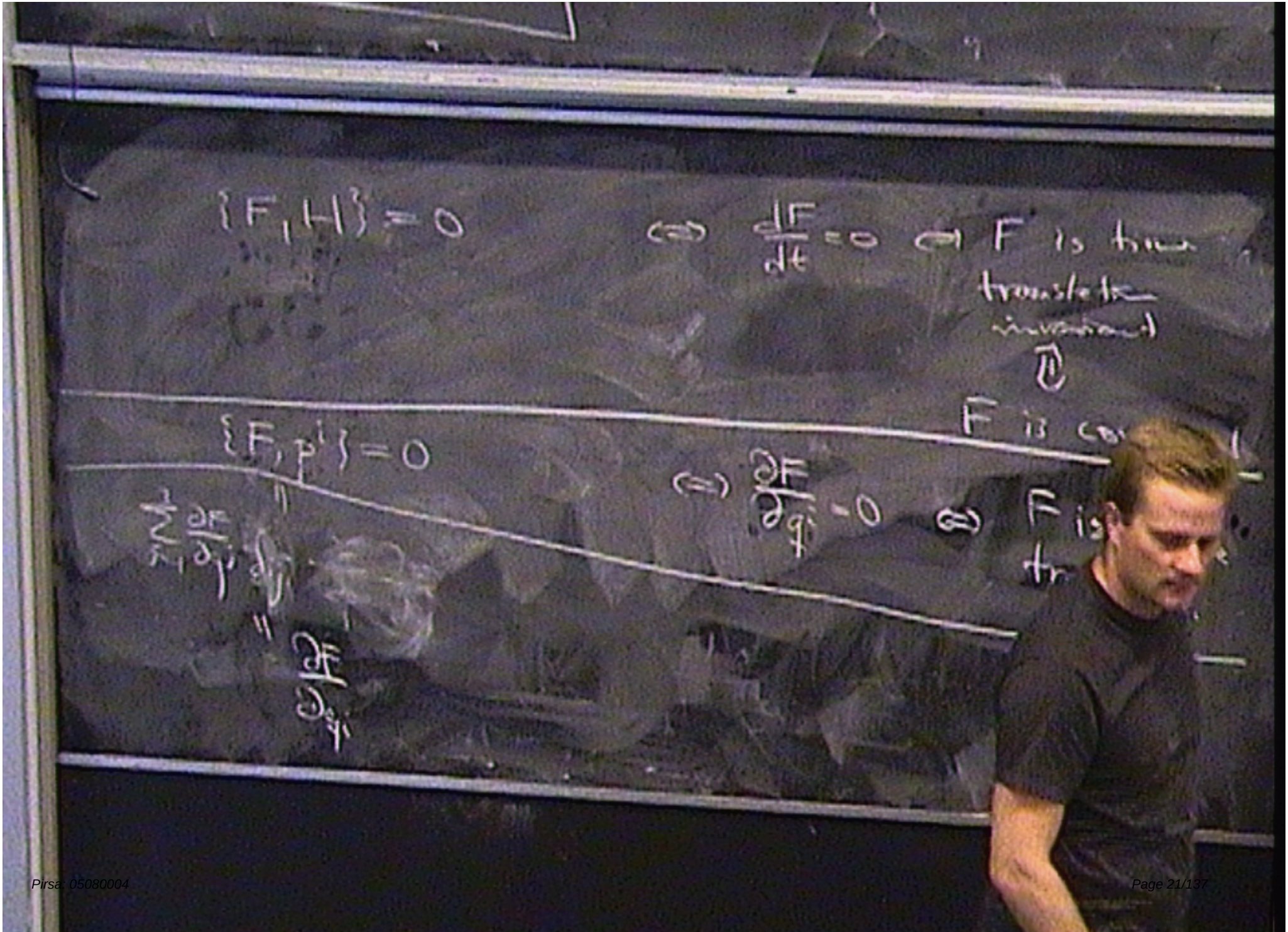
$\{F, H\} = 0 \iff \frac{dF}{dt} = 0$

$\{F, p^i\} = 0 \iff \frac{\partial F}{\partial q^i} = 0$

$= \sum_i \frac{\partial F}{\partial q^i} \frac{\partial q^i}{\partial x^i}$

$= \frac{\partial F}{\partial x^i}$


$\{F, H\} = 0 \iff \frac{dF}{dt} = 0 \iff F$ is
translate
invariant
$\Updownarrow$
F is
$\{F, p^i\} = 0$
$\iff \frac{\partial F}{\partial q^i} = 0 \iff F$ is
trans
$\frac{\partial F}{\partial q^i}$


$\{F, H\} = 0$
$\Leftrightarrow \frac{dF}{dt} = 0$
F is
translate
invariant
$\vec{n}$
F is
$\{F, p^i\} = 0$
$\Leftrightarrow \frac{\partial F}{\partial q^i} = 0$
F is
tr
$\sum_i \frac{\partial F}{\partial p^i} \delta p^i$
$= \frac{\partial F}{\partial q^i}$

$\{F, H\} = 0 \iff \frac{dF}{dt} = 0 \iff F$ is time translate-invariant

$\Updownarrow$

F is conserved

$\{F, p^i\} = 0 \iff \frac{\partial F}{\partial q^i} = 0 \iff F$ is space transl. inv.

$\sum_i \frac{\partial F}{\partial p^i} \frac{\partial}{\partial q^i} = \frac{\partial F}{\partial q^i}$

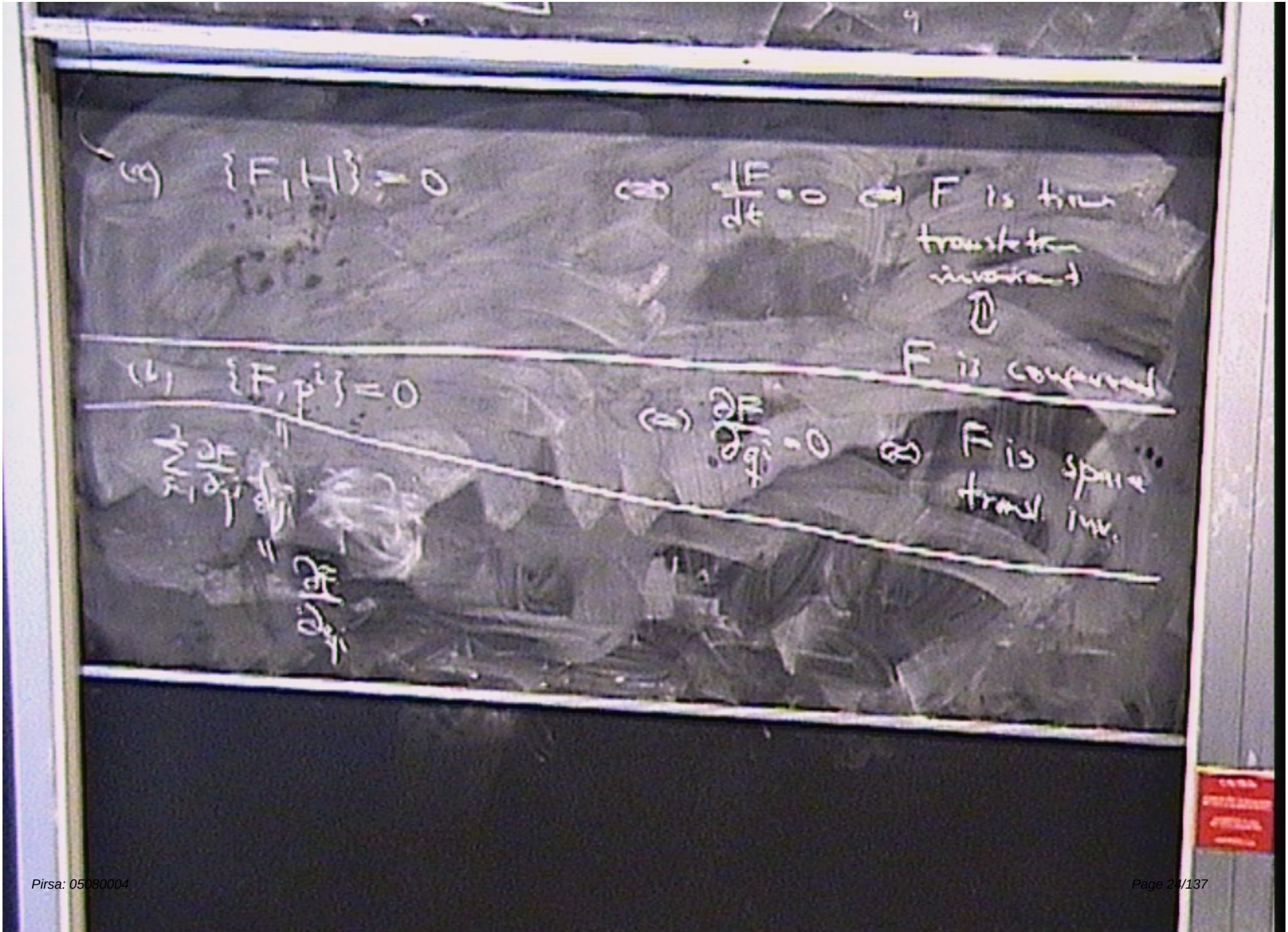
$\{p^i, H\} = 0$

$\Rightarrow$ for any conservative system energy is conserved in time

Hamiltonian formulation of CM

$\dot{q}_i = \left(\frac{p_i}{m}\right)$ "momentum" (1)

$H = \frac{p^2}{2m} + V(q)$


(a) $\{F, H\} = 0$ $\Leftrightarrow$ $\frac{dF}{dt} = 0$ $\Leftrightarrow$ F is time translation invariant
$\Updownarrow$
F is conserved
(b) $\{F, p^i\} = 0$
$\sum_i \frac{\partial F}{\partial q^i}$
$\frac{\partial F}{\partial q^i}$
(c) $\frac{\partial F}{\partial q^i} = 0$ $\Leftrightarrow$ F is space translation inv.

(a) $\{F, H\} = 0 \iff \frac{dF}{dt} = 0 \iff F$ is time translation invariant

(b) $\{F, p^i\} = 0$

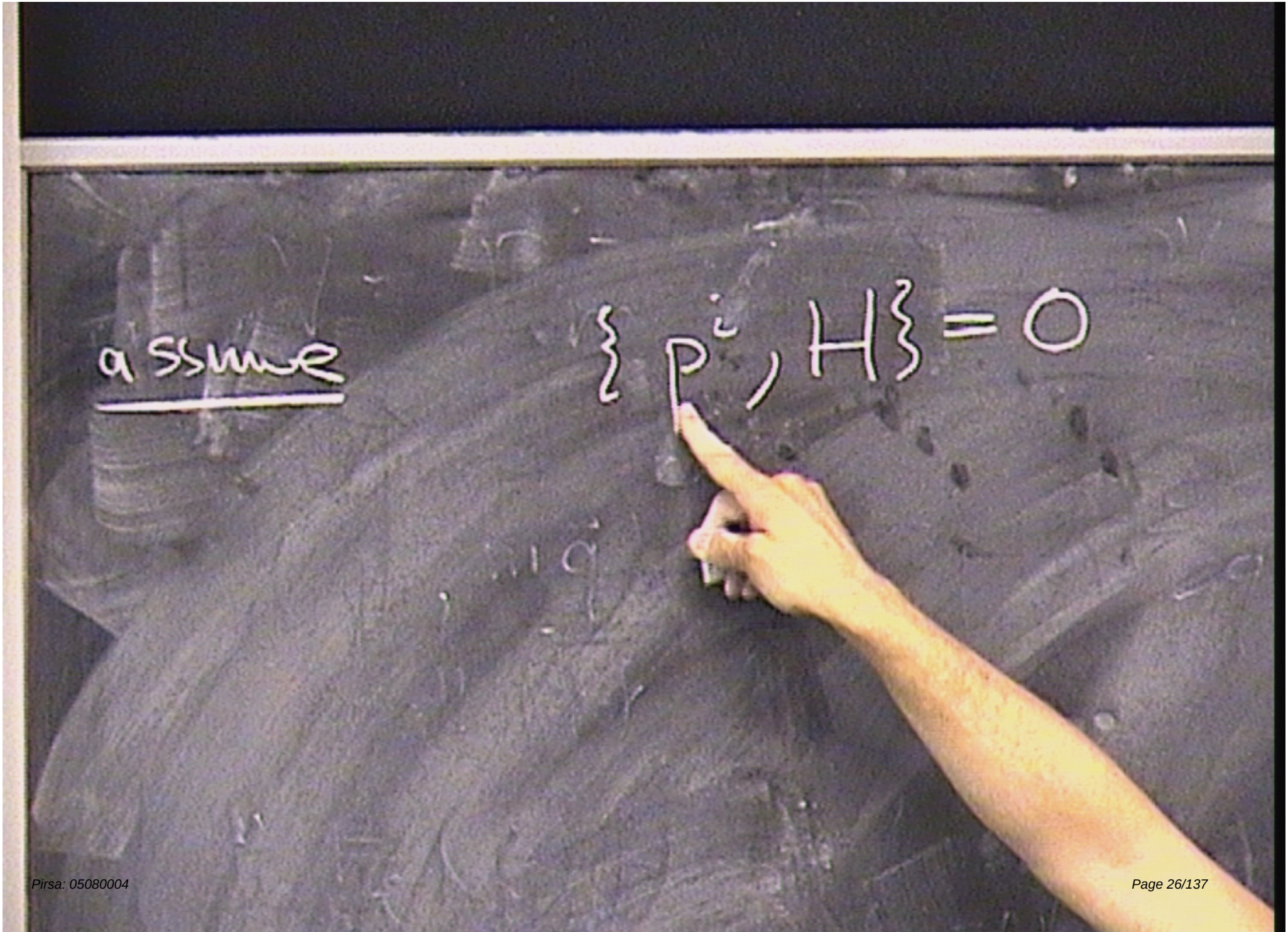
$\sum_i \frac{\partial F}{\partial p^i} \frac{\partial}{\partial q^i}$

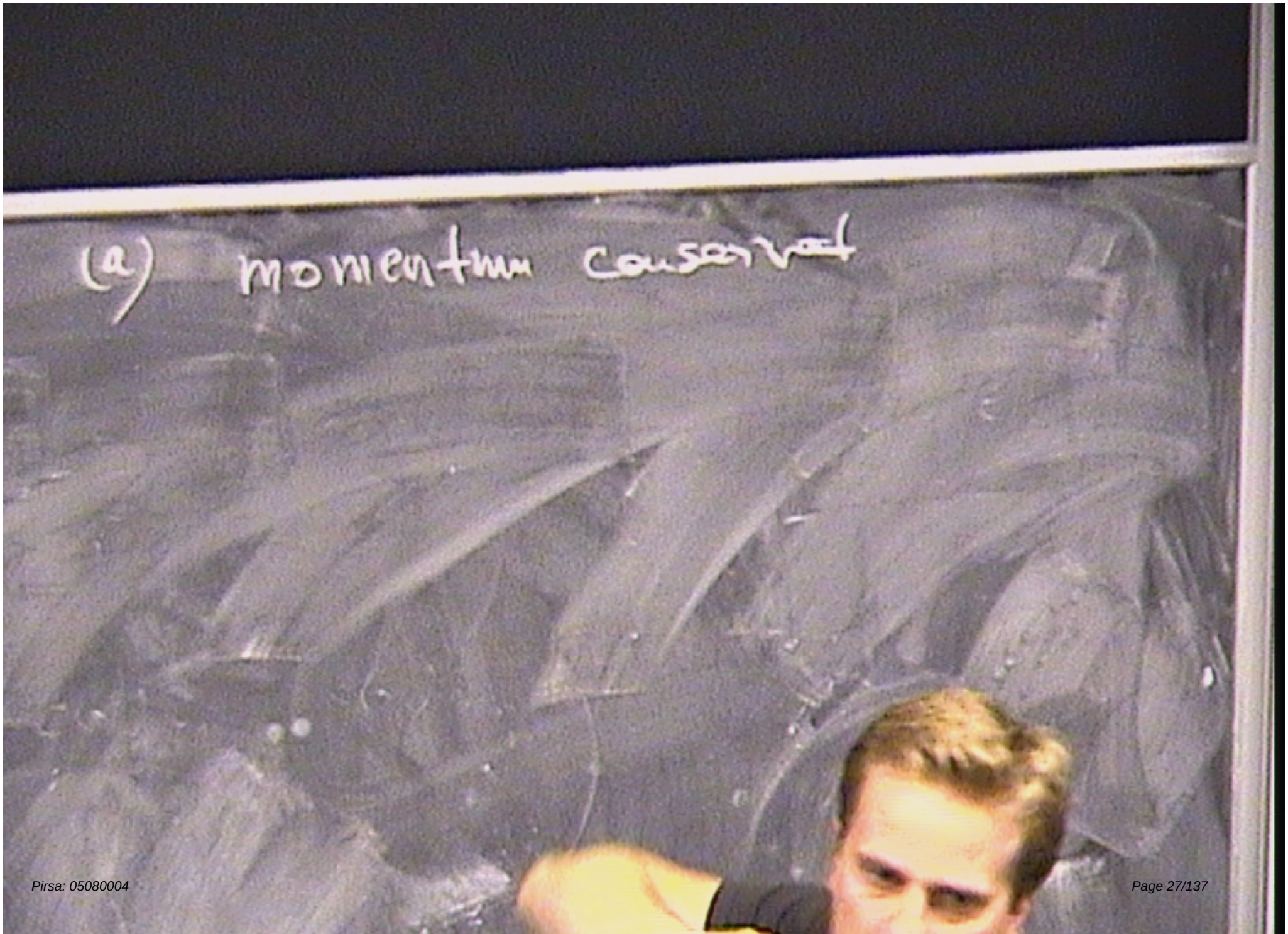
$\frac{\partial F}{\partial q^i}$

$\iff \frac{\partial F}{\partial q^i} = 0 \iff F$ is space translation inv.

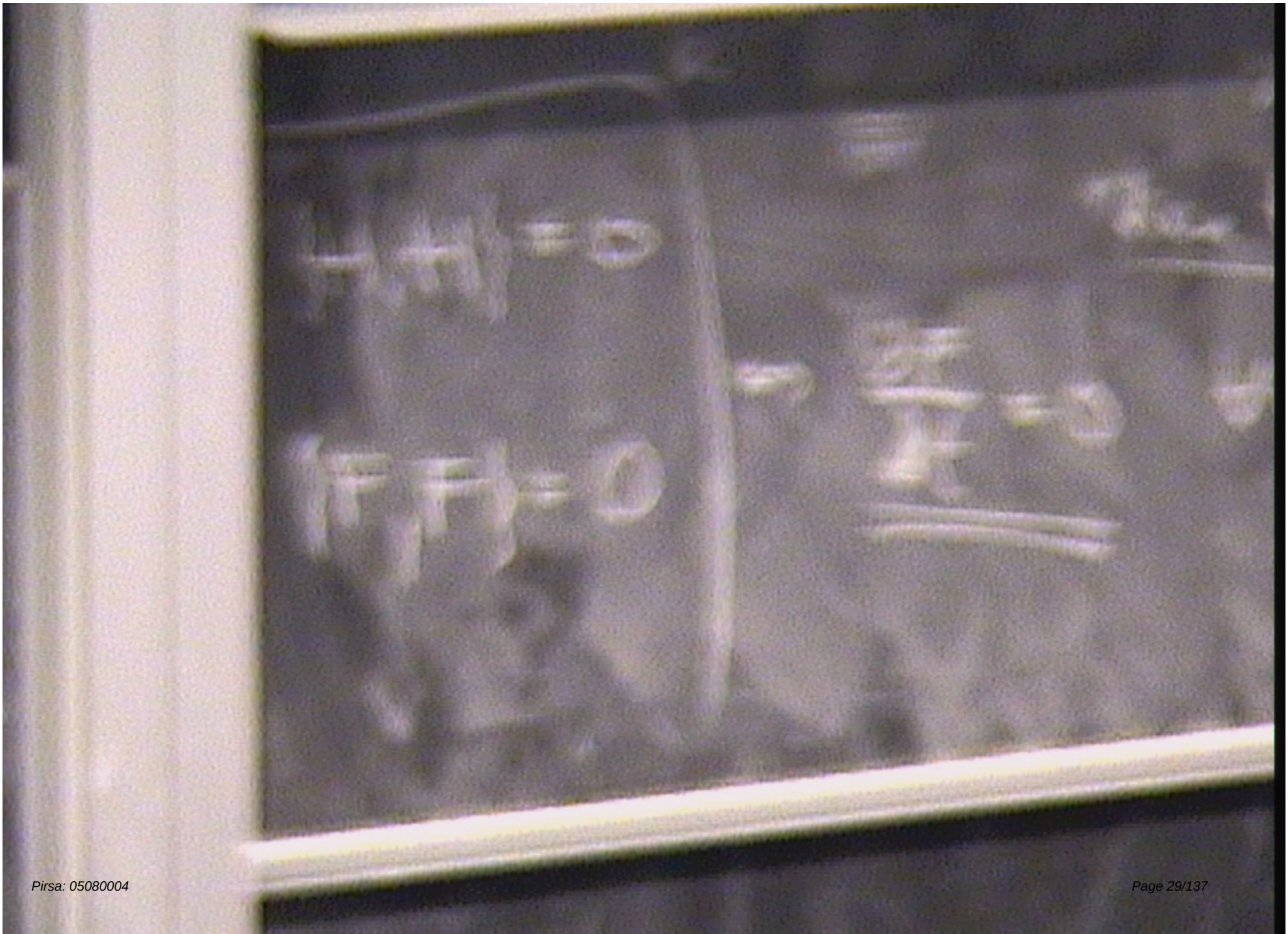
$\Downarrow$

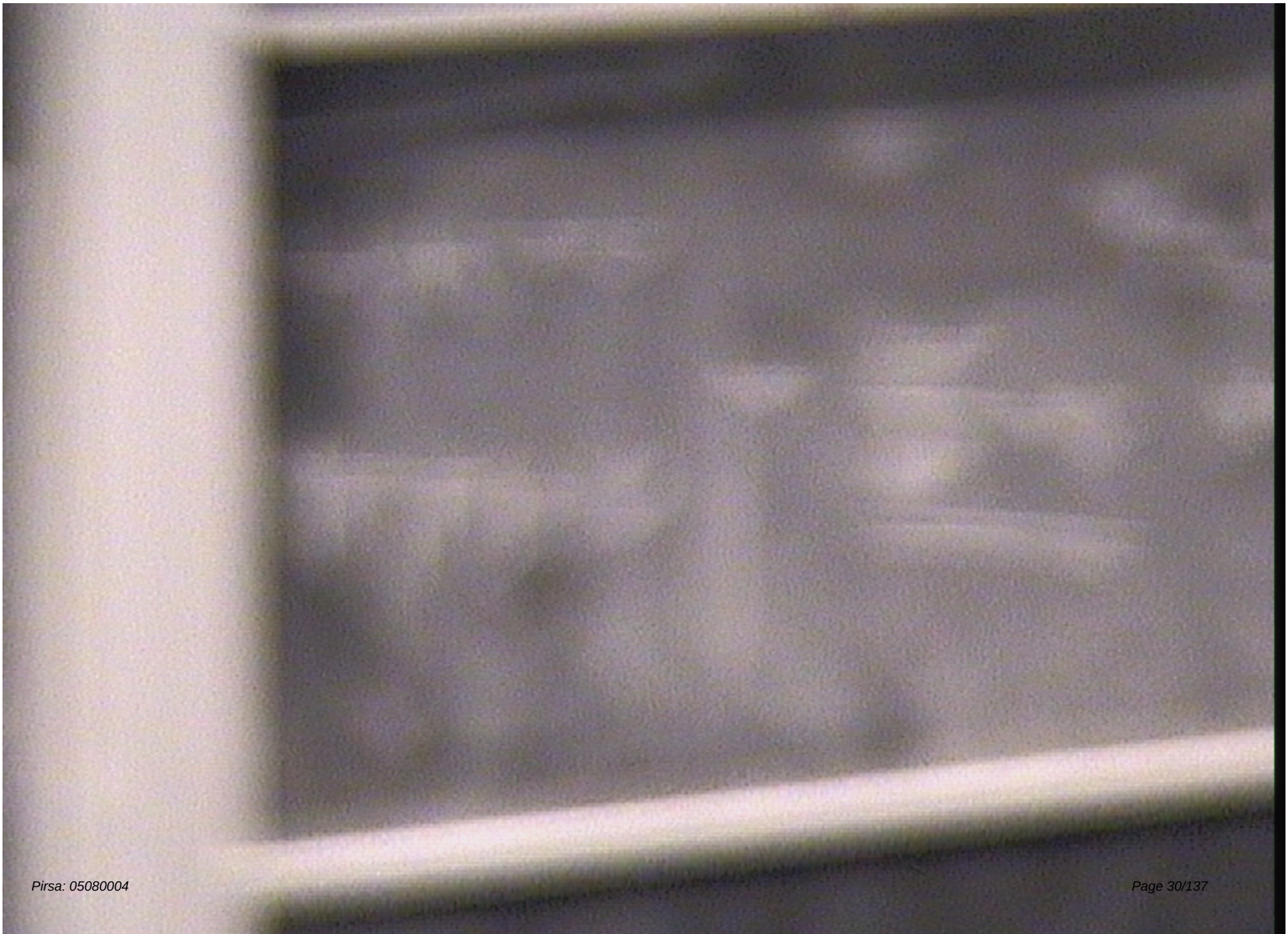
F is conserved

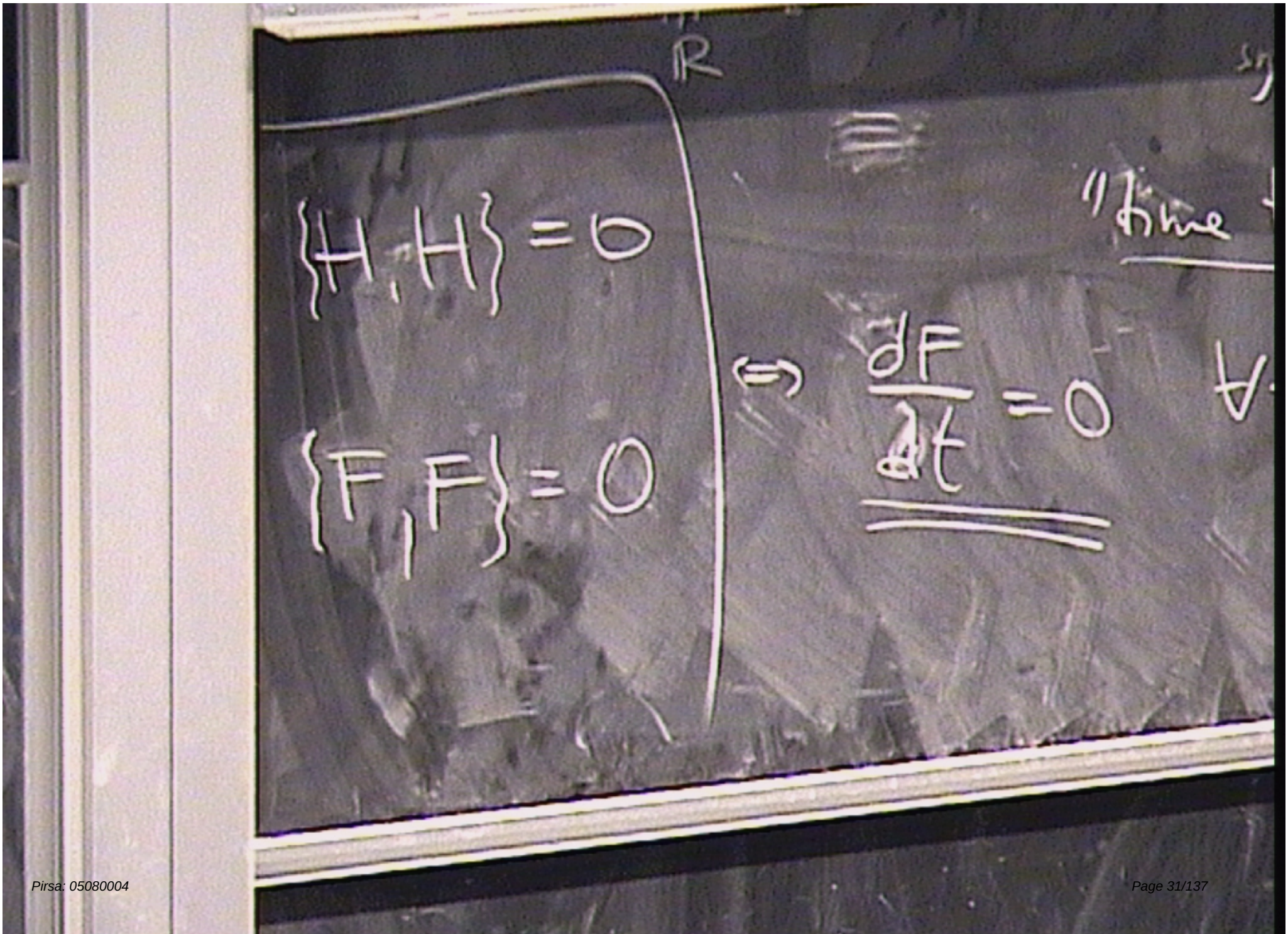

assume
$\{p^i, H\} = 0$

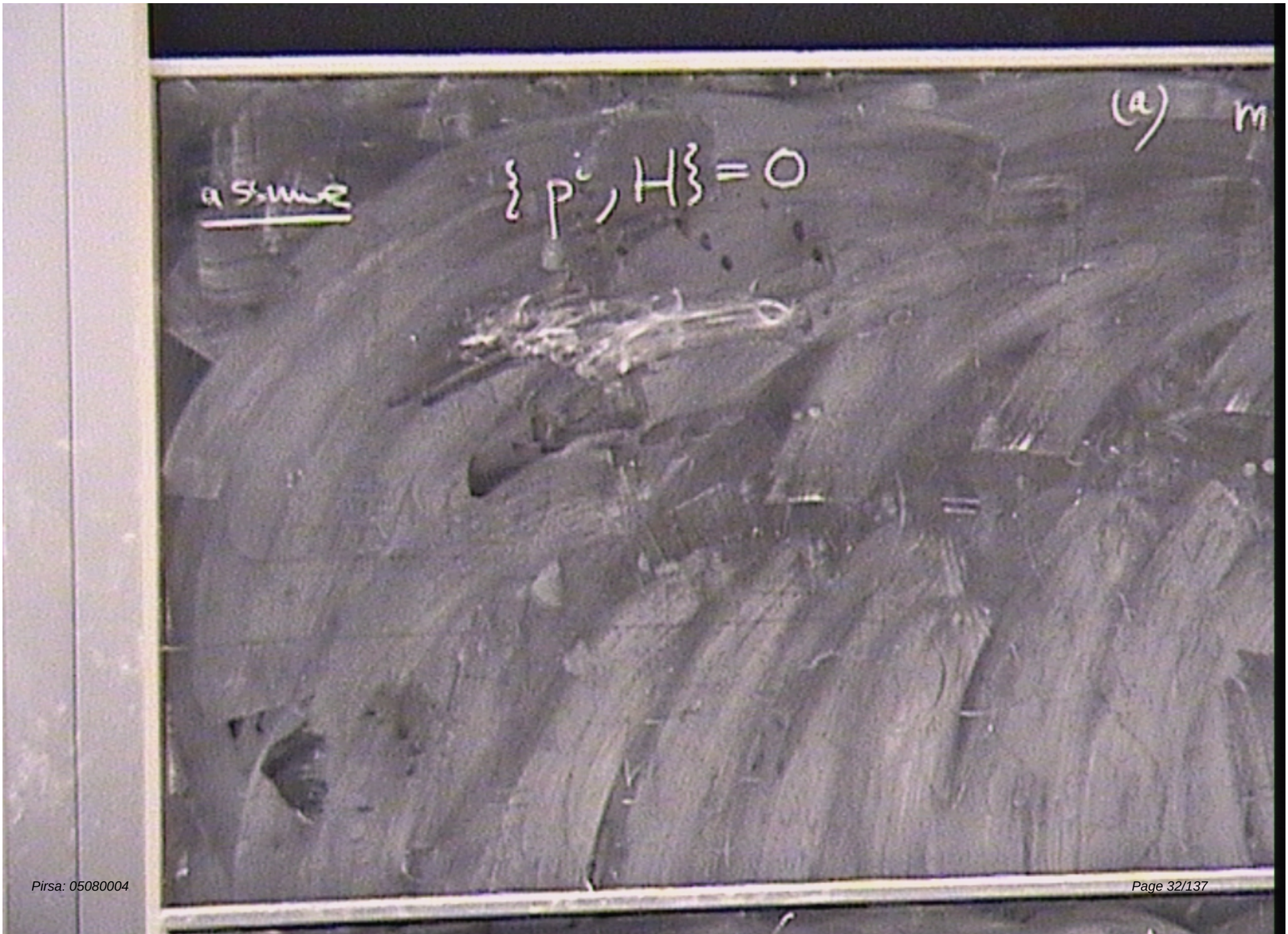

(a) momentum conservat

(a) momentum conservat

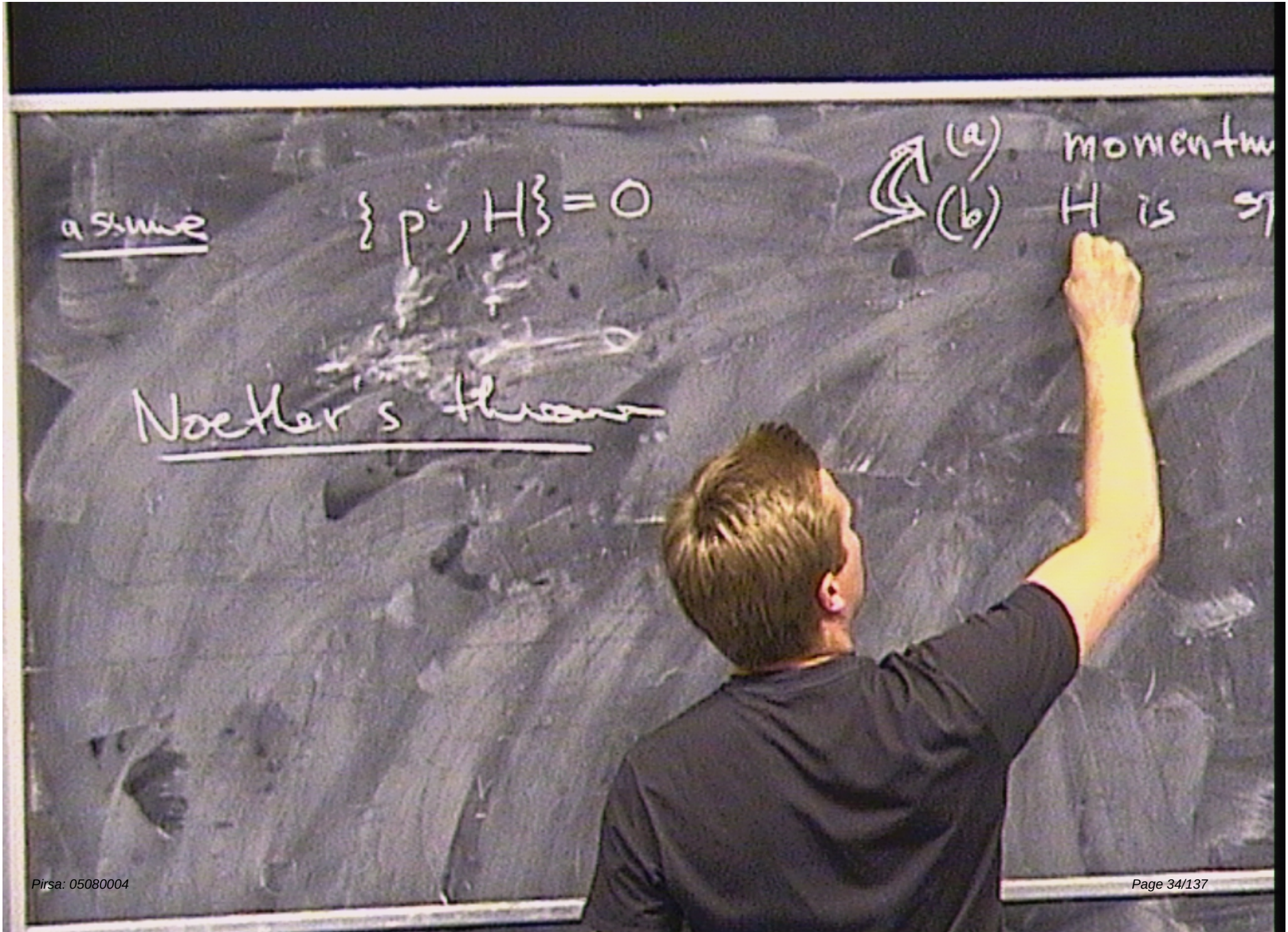


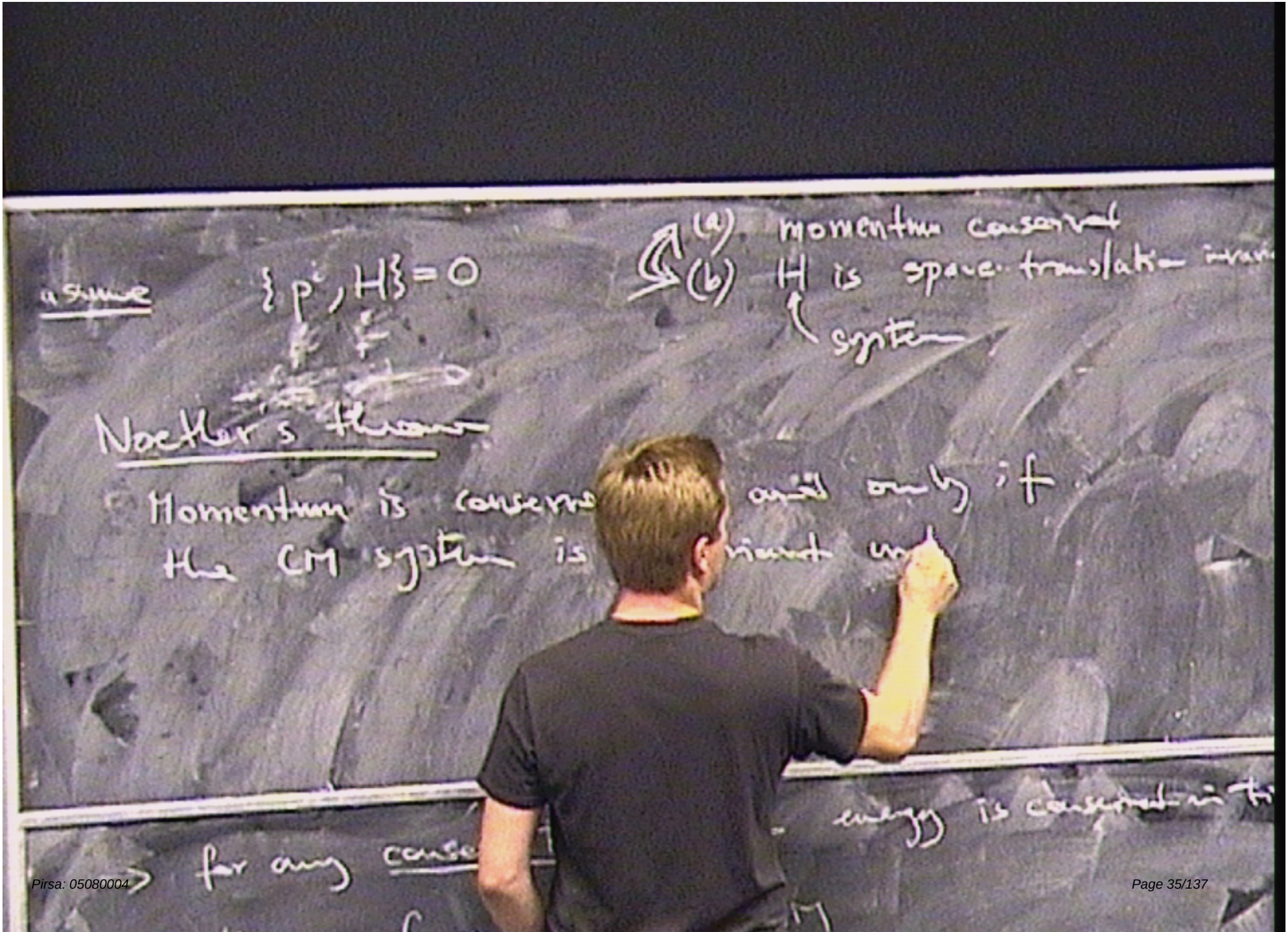



R
$\{H, H\} = 0$
$\{F, F\} = 0$
$\Leftrightarrow \frac{dF}{dt} = 0$


(a) m
a Simuz
$\{p^i, H\} = 0$

(a) momentum conserved
(b) H is space-translation invariant.


assume
$\{p^i, H\} = 0$
(a)
(b)
momentu
H is
Noether's


assume
$\{p^i, H\} = 0$
(a) momentum conserved
(b) H is space translation invariant
system
Noether's theorem
Momentum is conserved if and only if
the CM system is
energy is conserved in
for any

sume $\{p^i, H\} = 0$

(a) momentum conserved
(b) H is space translation in system

Emmy

Noether's theorem

Momentum is conserved if and only if the CM system is invariant under translations

$\Rightarrow$ for any conservative system energy is conserved

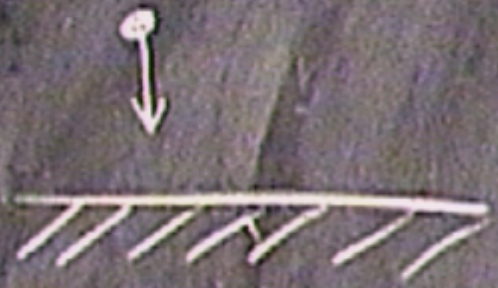
same $\{p^i, H\} = 0$

(b) H is ∃
↑ syste

Emmy
Noether's theorem

Momentum is conserved if and on
the CM syste is invariant un

ex



for any conservative syste

assume $\{p^i, H\} = 0$

(b) H is

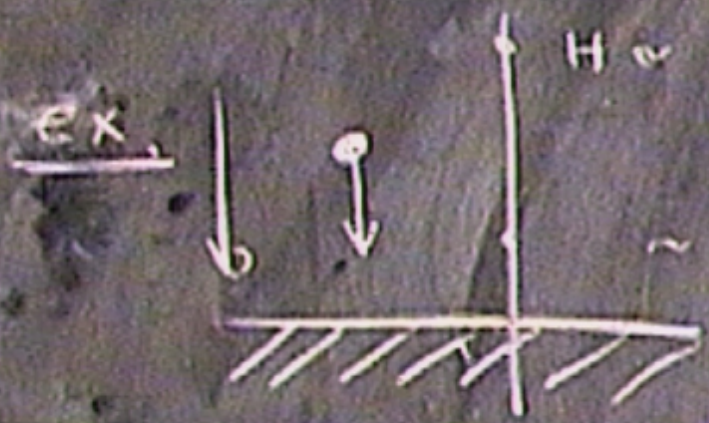
syste

Emmy

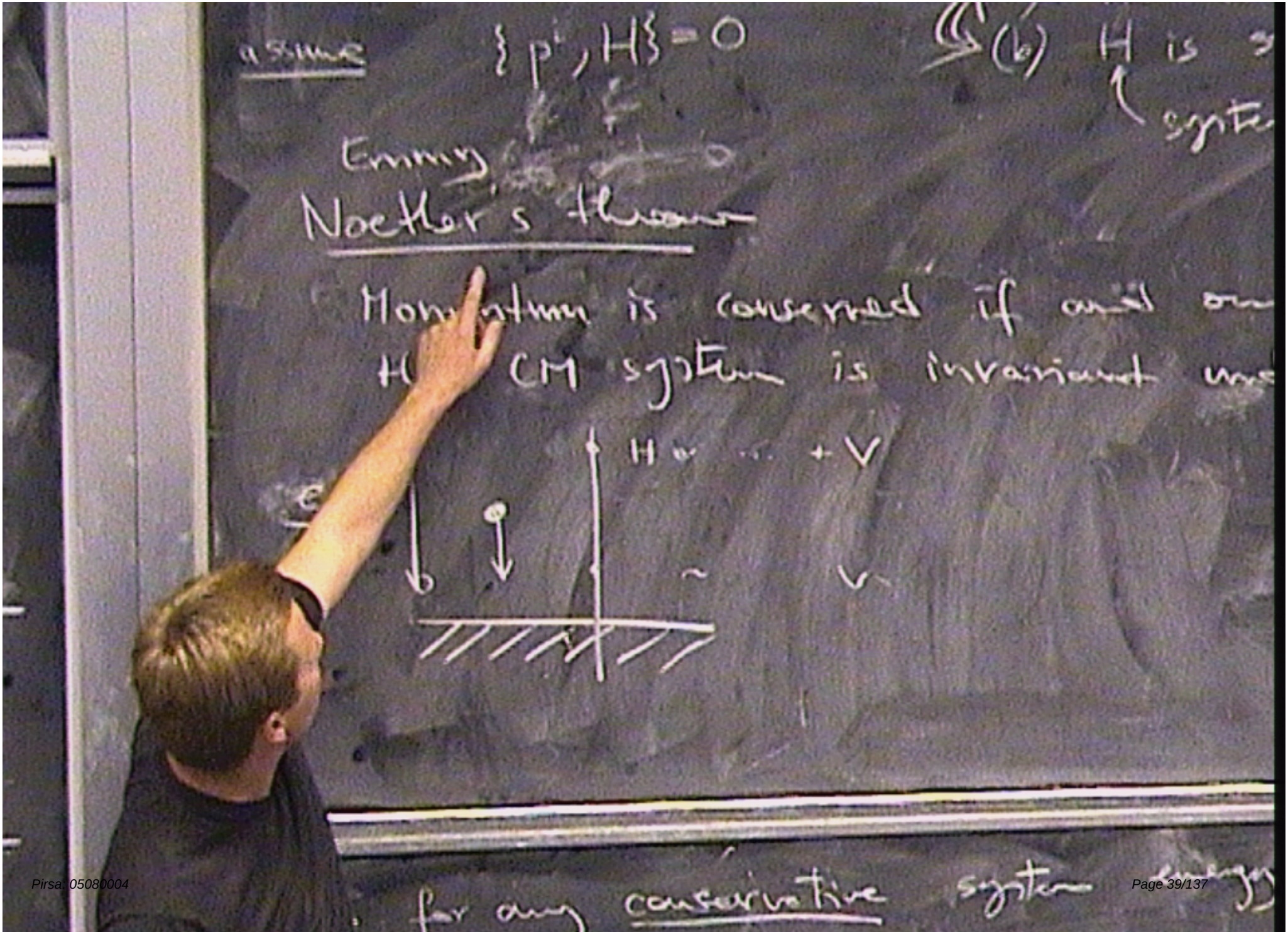
Noether's theorem

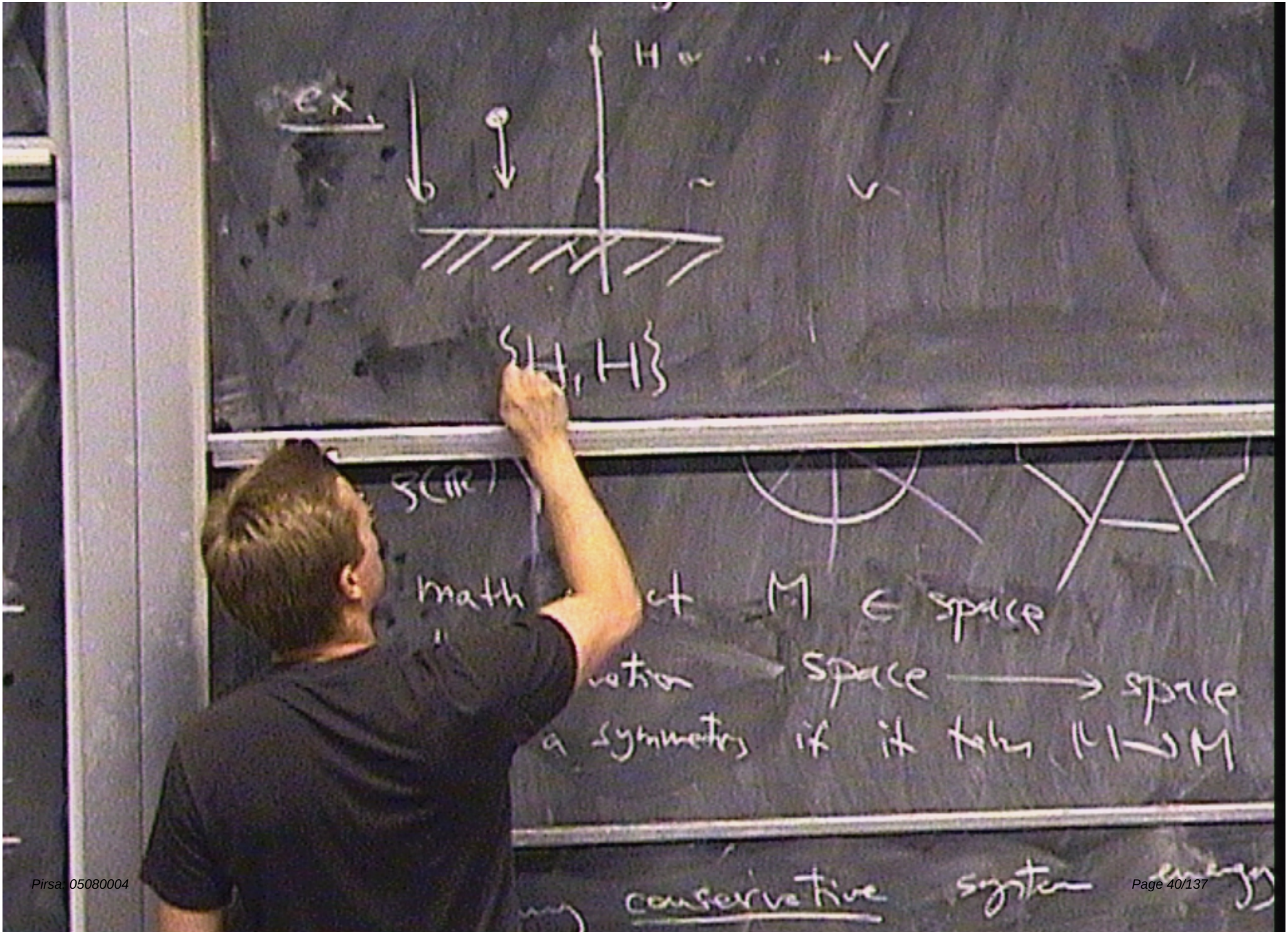
Momentum is conserved if and o

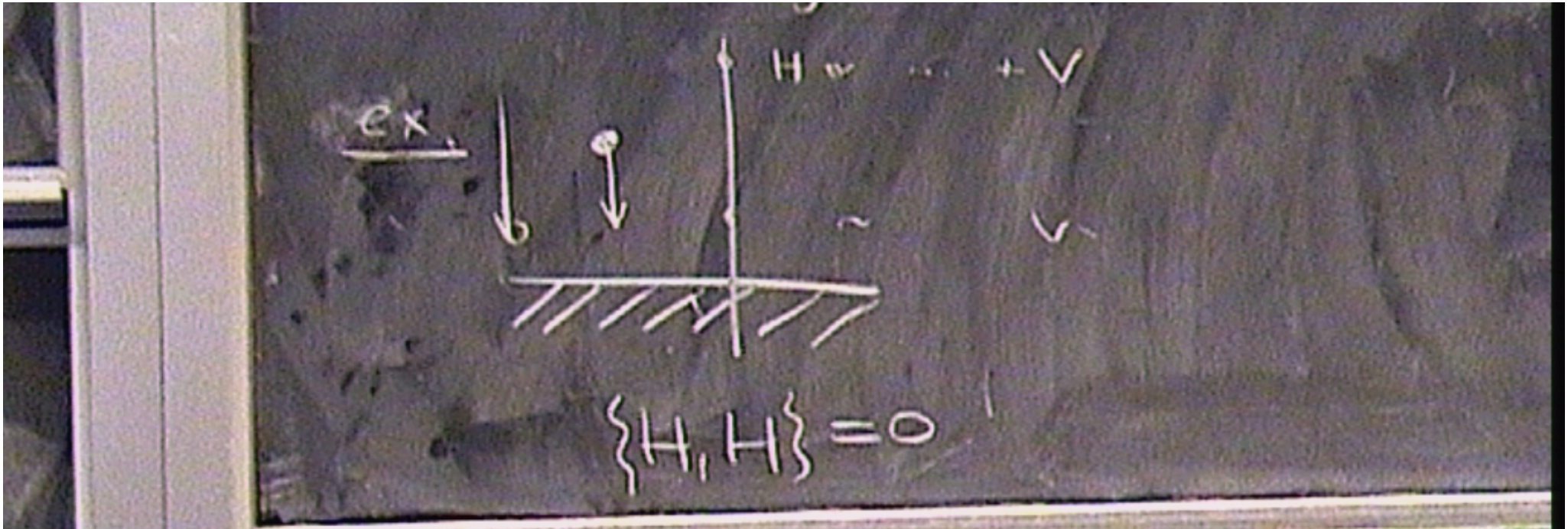
the CM syste is invariant u

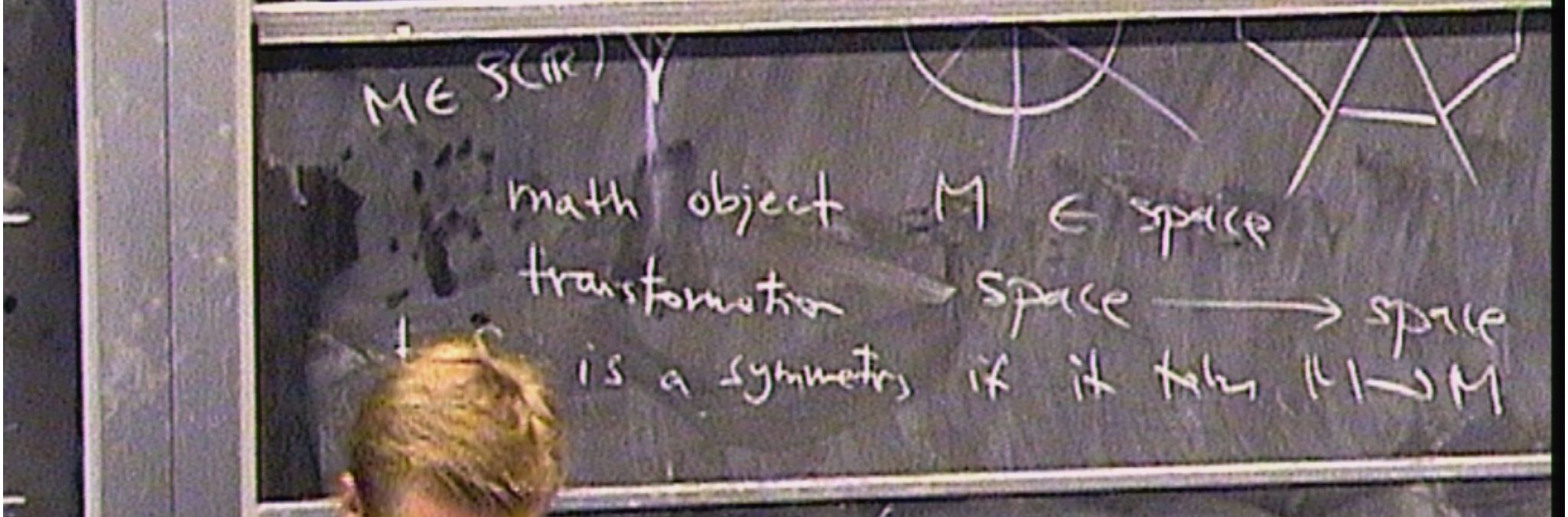


conservative syste


assume
$\{p^i, H\} = 0$
(b) H is
Emmy
Noether's theorem
Momentum is conserved if and
H CM system is invariant
H = ... + V
for any conservative system


ex.
H
+V
V
{H, H}
5(IR)
math
ct M ∈ space
space → space
a symmetry if it takes M → M
conservative system





conservative system

momentum conserv

(b) H is space-translation invariant.

system

conserved if and only if

gation is invariant under translations.

(a) F time cons

$\{F, H\}$ (b) H is F-cons

momentum conserved

(b) H is space translation invariant.

system

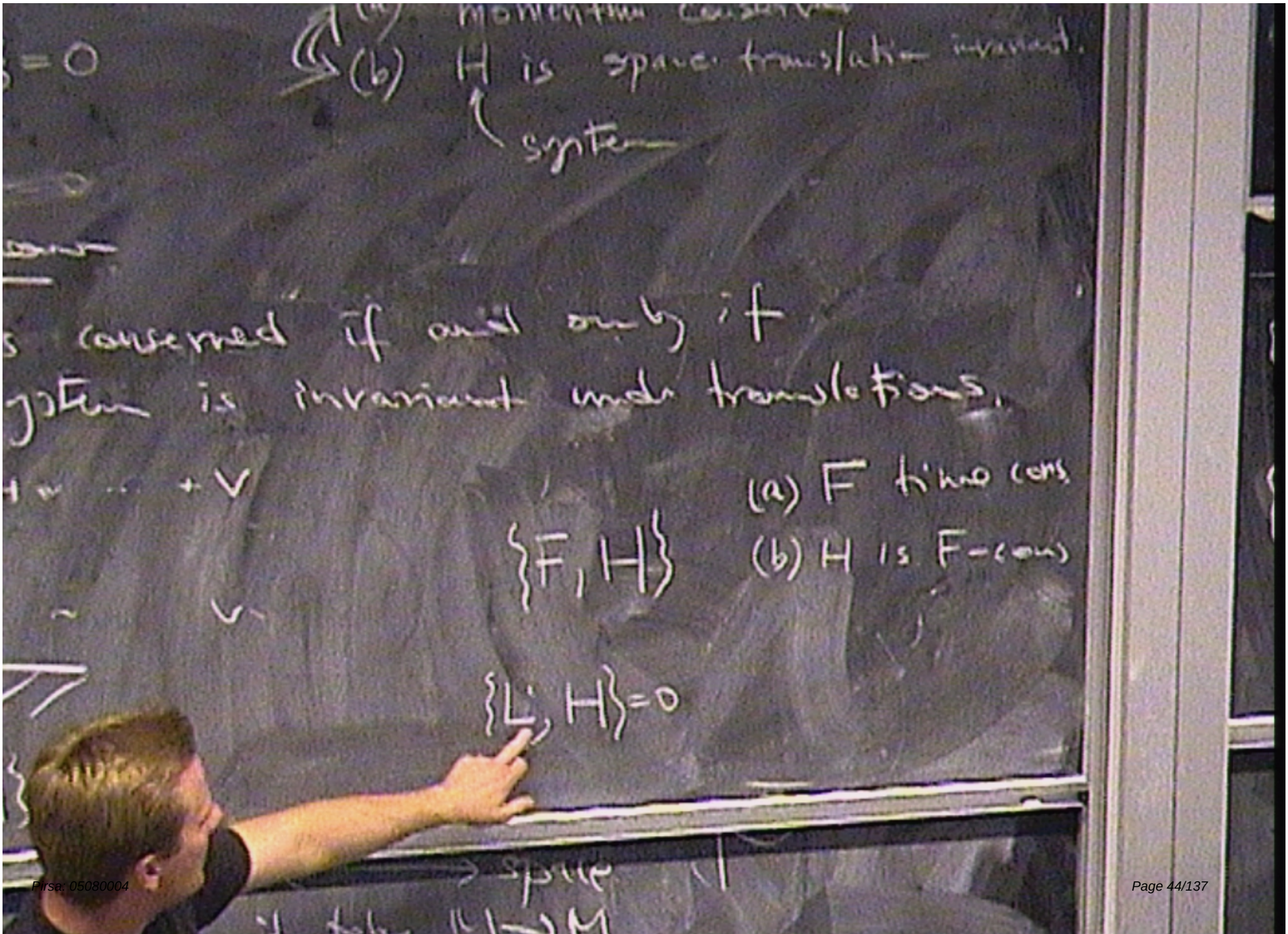
s conserved if and only if

gstem is invariant under translations.

(a) F time com

$\{F, H\}$ (b) H is F-com

$\{L, H\} = 0$


(b) H is space translation invariant.
system
is conserved if and only if
system is invariant under translations.
(a) F this cons
(b) H is F-cons
$\{F, H\}$
$\{L, H\} = 0$

(b) H is space translation invariant.

system

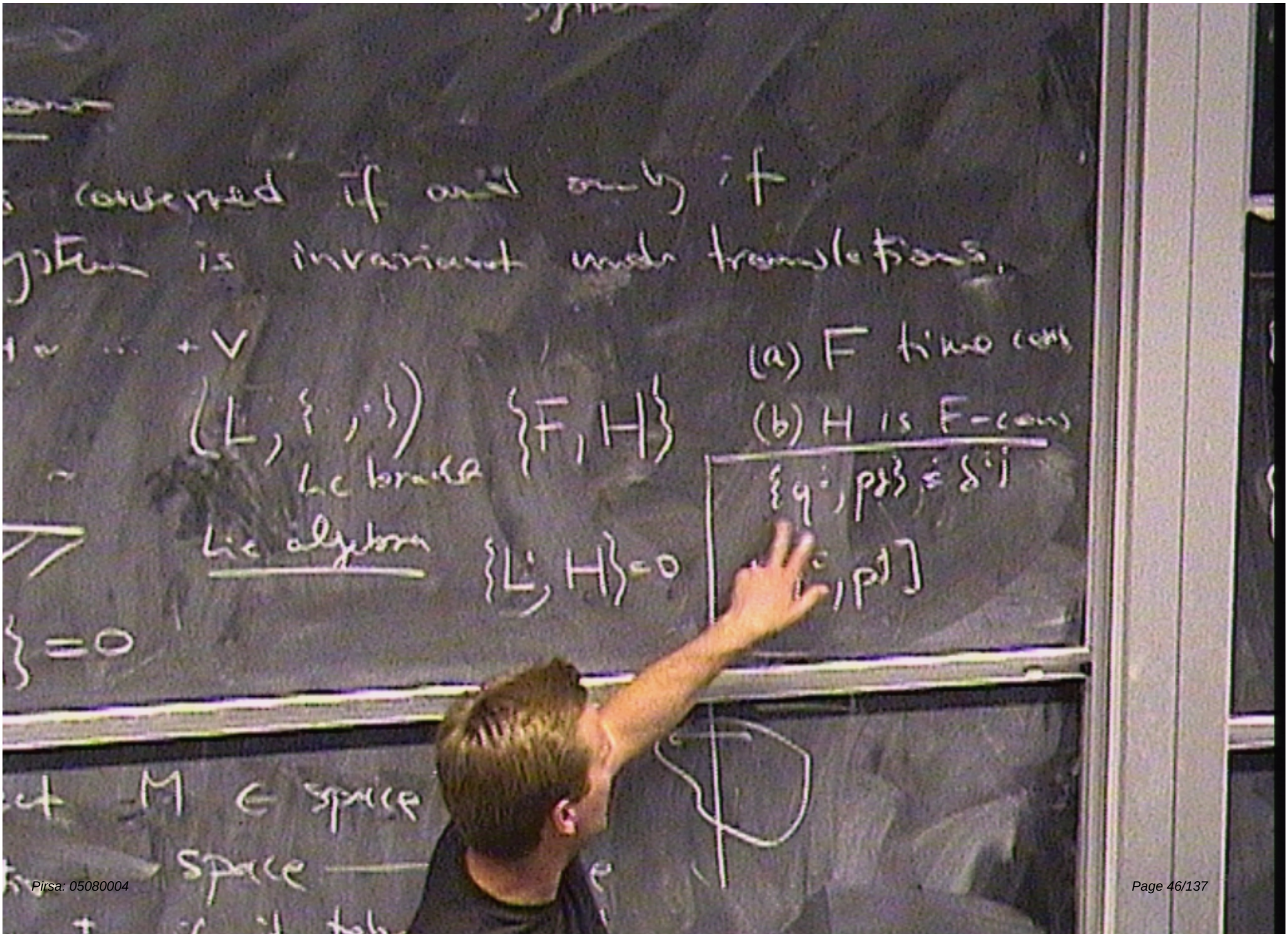
conserved if and only if

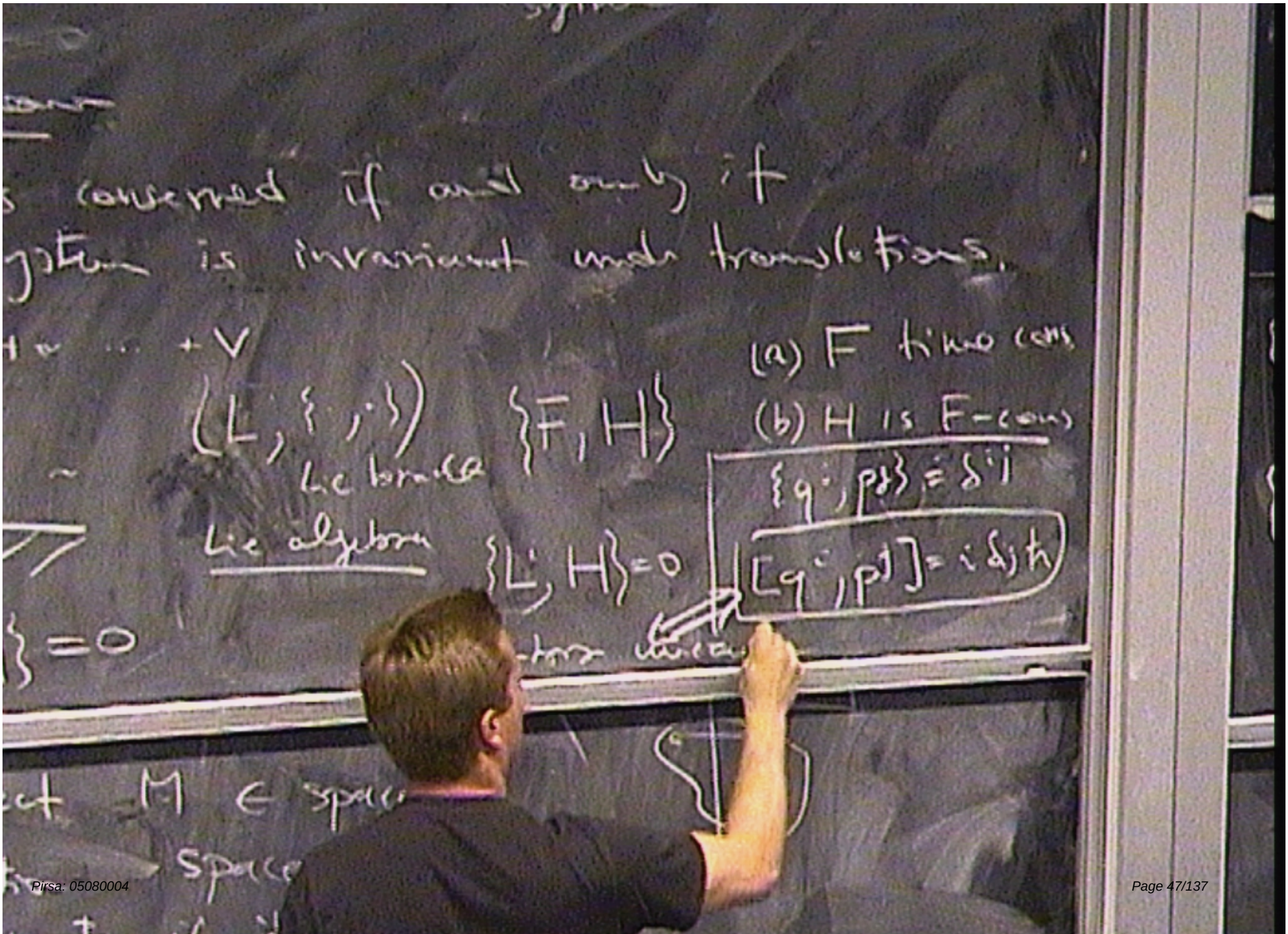
system is invariant under translations.

(a) F time

$\{F, H\}$ (b) H is F-

$\{L, H\} = 0$


conserved if (and only) if
is invariant under translations.
+V
$(L, \{\cdot,\cdot\})$
Lie bracket
Lie algebra
$\{F, H\}$
$\{L_i, H\} = 0$
(a) F time con
(b) H is F-con
$\{q^i, p_j\} = \delta^i_j$
$=0$
M ∈ space
space


(a) F time cons
(b) H is F-cons
$\{q^i, p^j\} = \delta^{ij}$
$[q^i, p^j] = i\delta^{ij}$
$\{L, H\} = 0$
Lie algebra
Lie bracket
$\{F, H\}$

conserved if and only if

is invariant under translations.

$+V$

$(L, \{\cdot,\cdot\})$ Lie bracket

Lie algebra

$\{L_i, H\} = 0$

(a) F time (con)

(b) H is F-(con)

$\{q^i, p^j\} = \delta^{ij}$

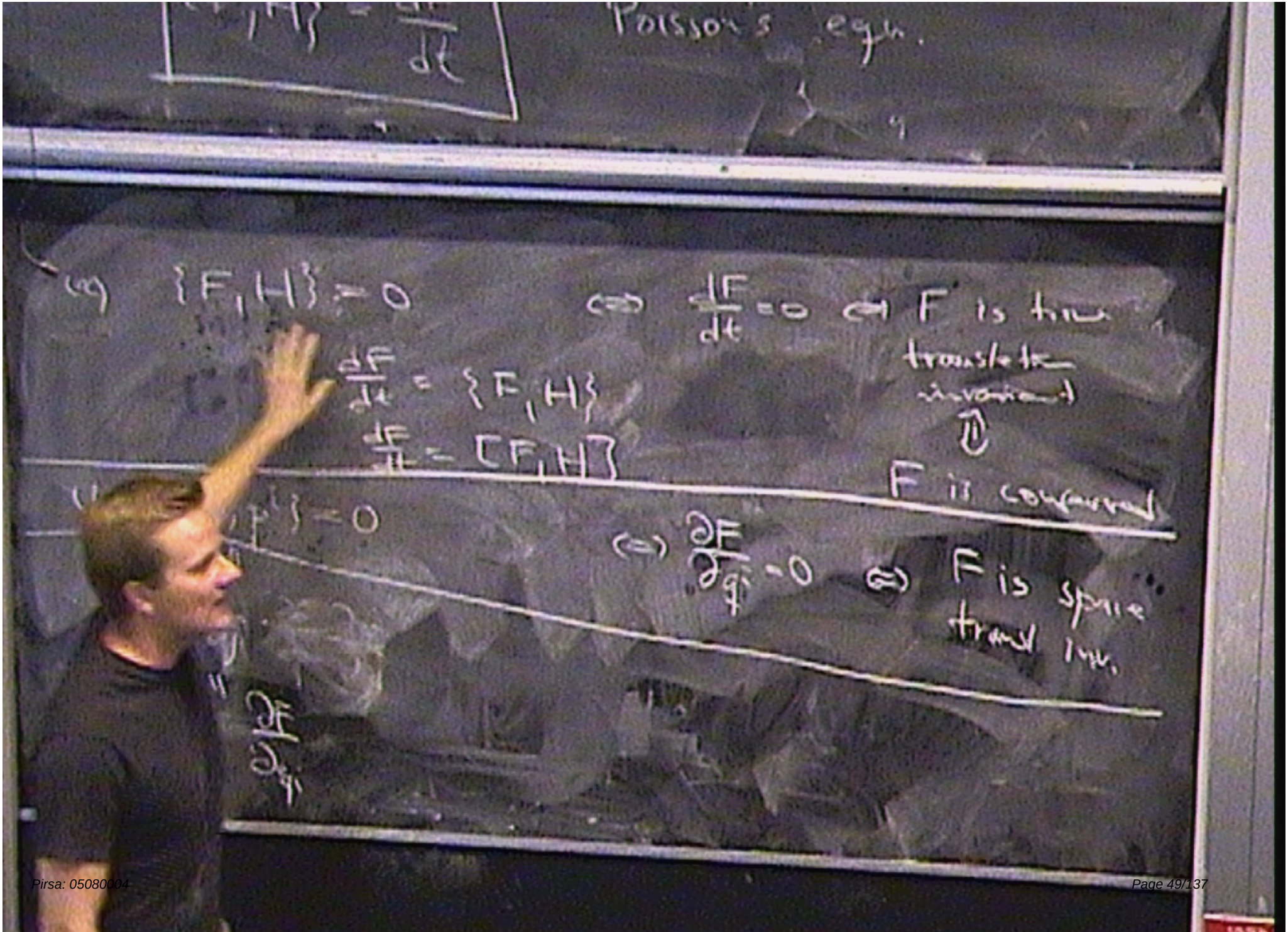
$[q^i, p^j] = i\delta^{ij}\hbar$

Heisenberg uncertainty

$\{\ \} = 0$

$M \in$ space

space $\longrightarrow$ space


Poisson's eqn.
$\{F,H\}=0 \iff \frac{dF}{dt}=0$ F is time translate invariant
$\frac{dF}{dt}=\{F,H\}$
$\frac{dF}{dt}=[F,H]$
F is conserved
$\{F,H\}=0 \iff \frac{\partial F}{\partial q_i}=0$ F is spatial transl inv.
$\frac{\partial F}{\partial q_i}$

$\frac{dF}{dt} = \{F, H\}$ Poisson's eqn.

(a) $\{F, H\} = 0 \iff \frac{dF}{dt} = 0 \iff F$ is time translation invariant

$\frac{dF}{dt} = \{F, H\}$

$\frac{dF}{dt} = [F, H]$

$\Updownarrow$

F is conserved

(b) $\{F, p^i\} = 0 \iff \frac{\partial F}{\partial q^i} = 0 \iff F$ is space transl. inv.

$\sum_i \frac{\partial F}{\partial q^i} \frac{\partial p^i}{\partial q^j} = \frac{\partial F}{\partial q^j}$

$\frac{dF}{dt} = \{F, H\}$

Poisson's eqn.

(a) $\{F, H\} = 0 \iff \frac{dF}{dt} = 0 \iff F$ is time translation invariant

$\frac{dF}{dt} = \{F, H\}$

$\frac{dF}{dt} = [F, H]$

$\Updownarrow$

F is conserved

(b) $\{F, p^i\} = 0$

$\sum_i \frac{\partial F}{\partial p^i} \frac{\partial p^i}{\partial q^i} = \frac{\partial F}{\partial q^i}$

$\iff \frac{\partial F}{\partial q^i} = 0 \iff F$ is space transl. inv.

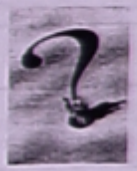
Today's summary

- What actually is quantum mechanics?
- The double-slit experiment
- De Broglie wavelength
- Heisenberg's uncertainty principle
- Superposition & bound states
- How classical physics fails to explain the stability of a single atom

PI

What actually is quantum mechanics?





PI

Prsa: 05080004

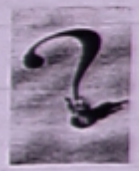
Today's summary

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PI

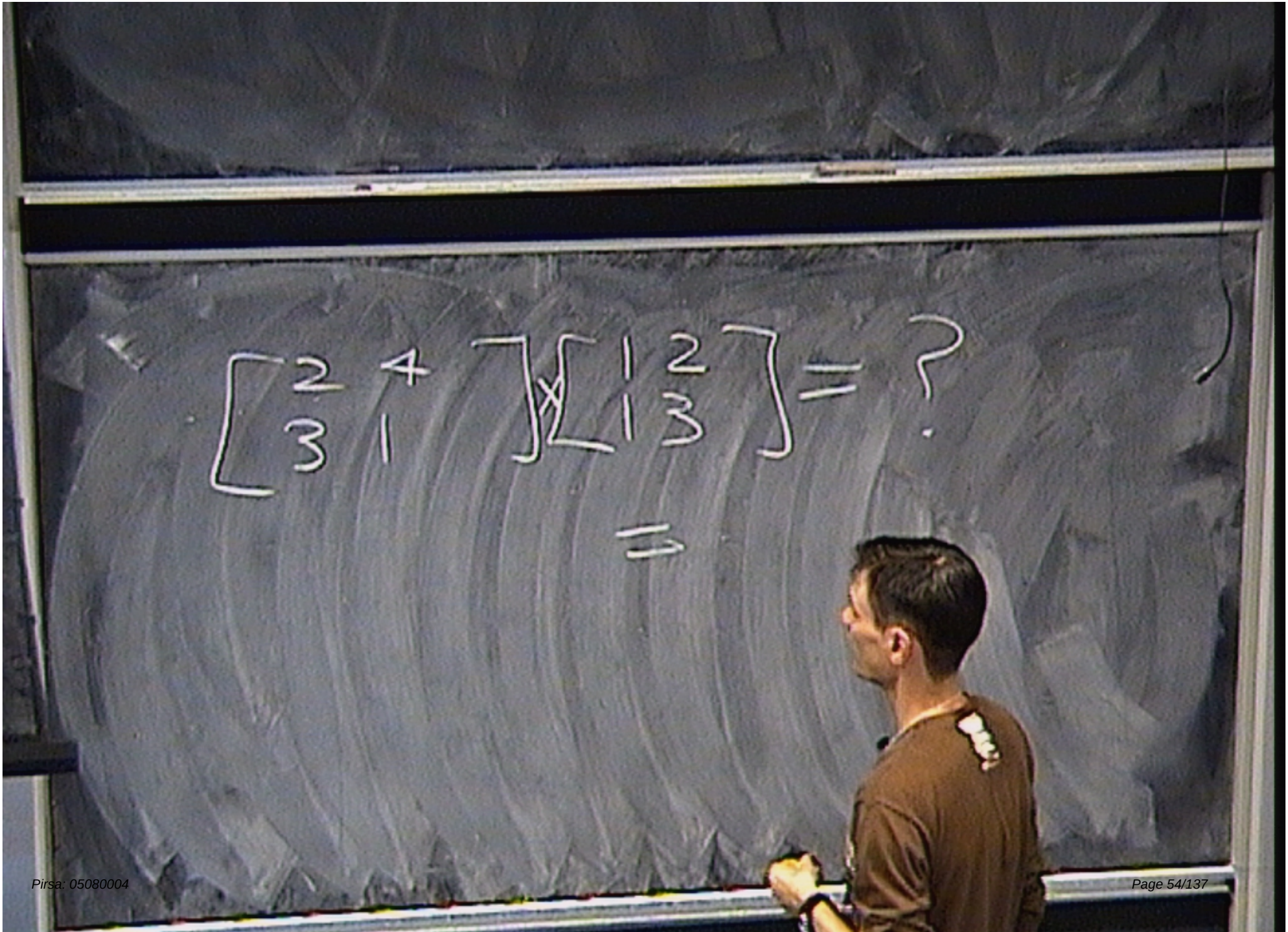
What actually is quantum mechanics?

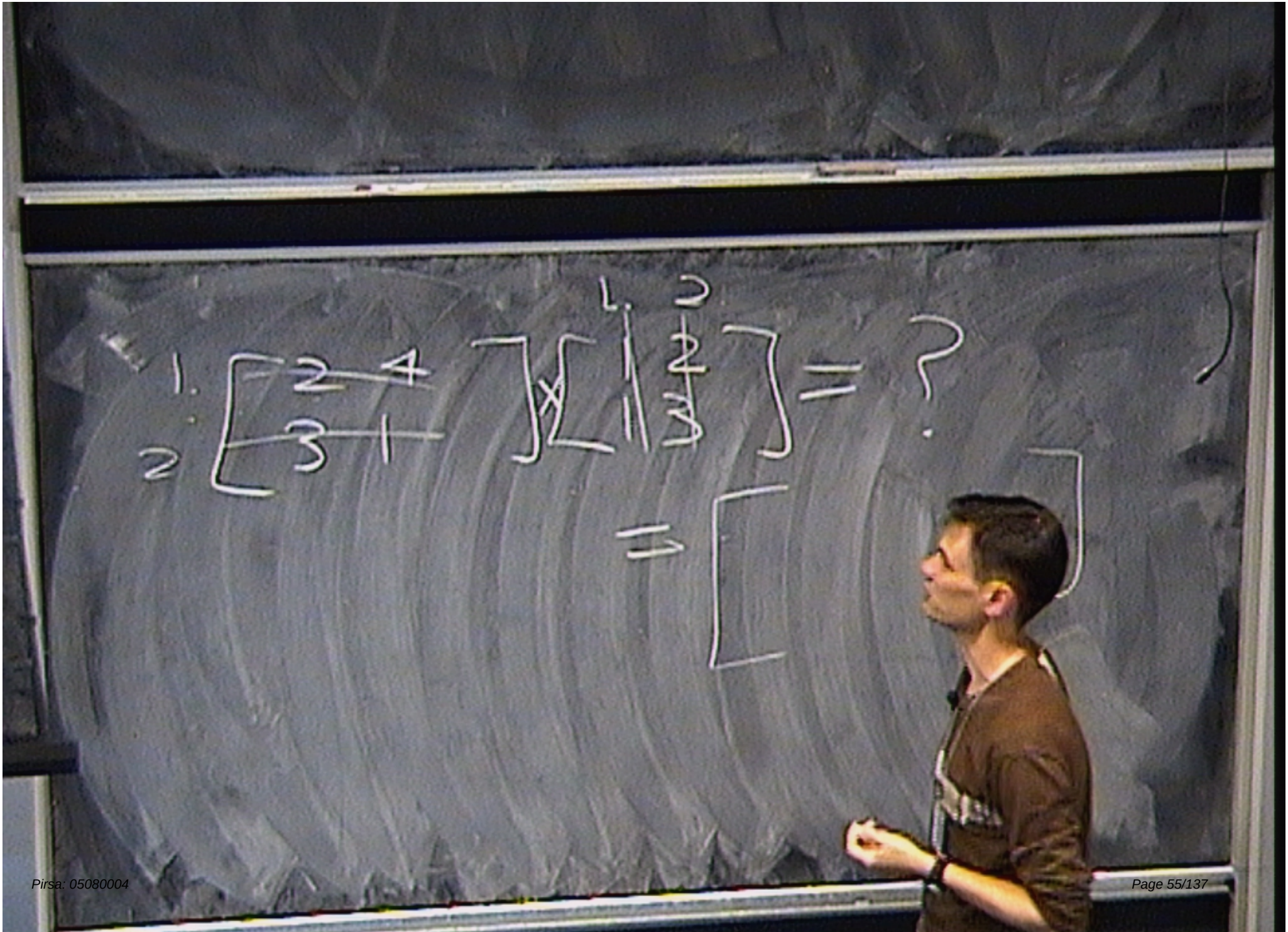


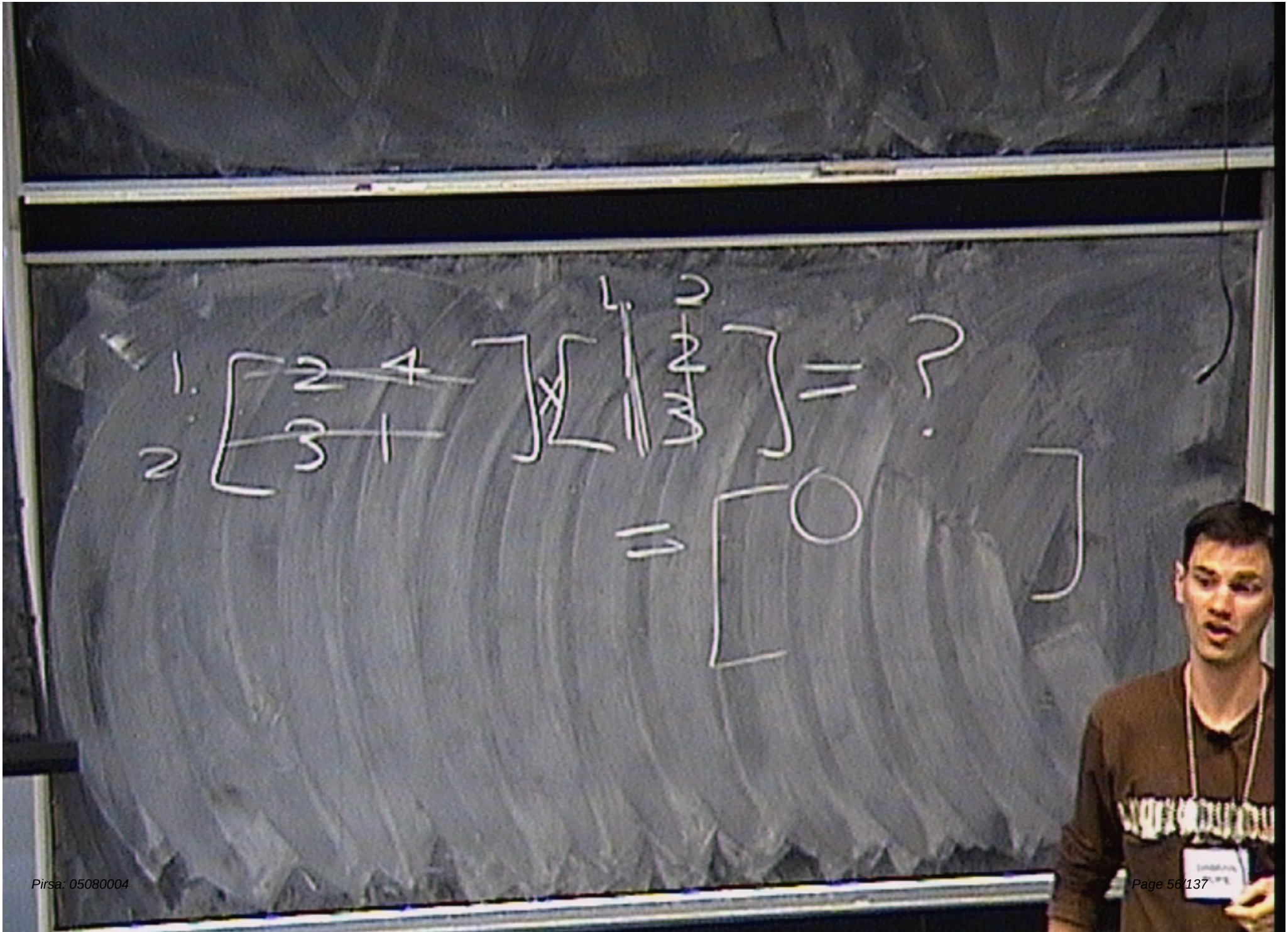


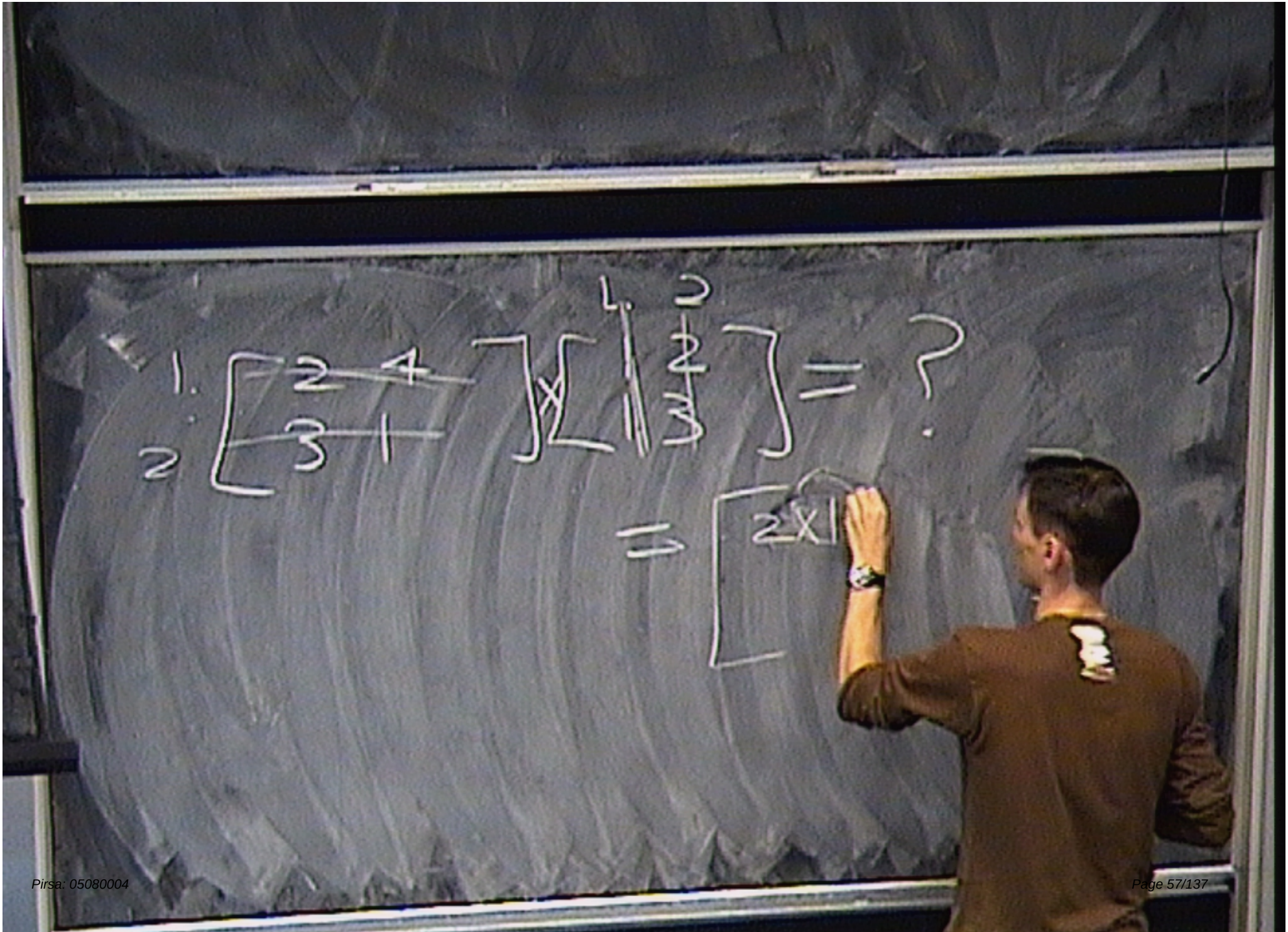
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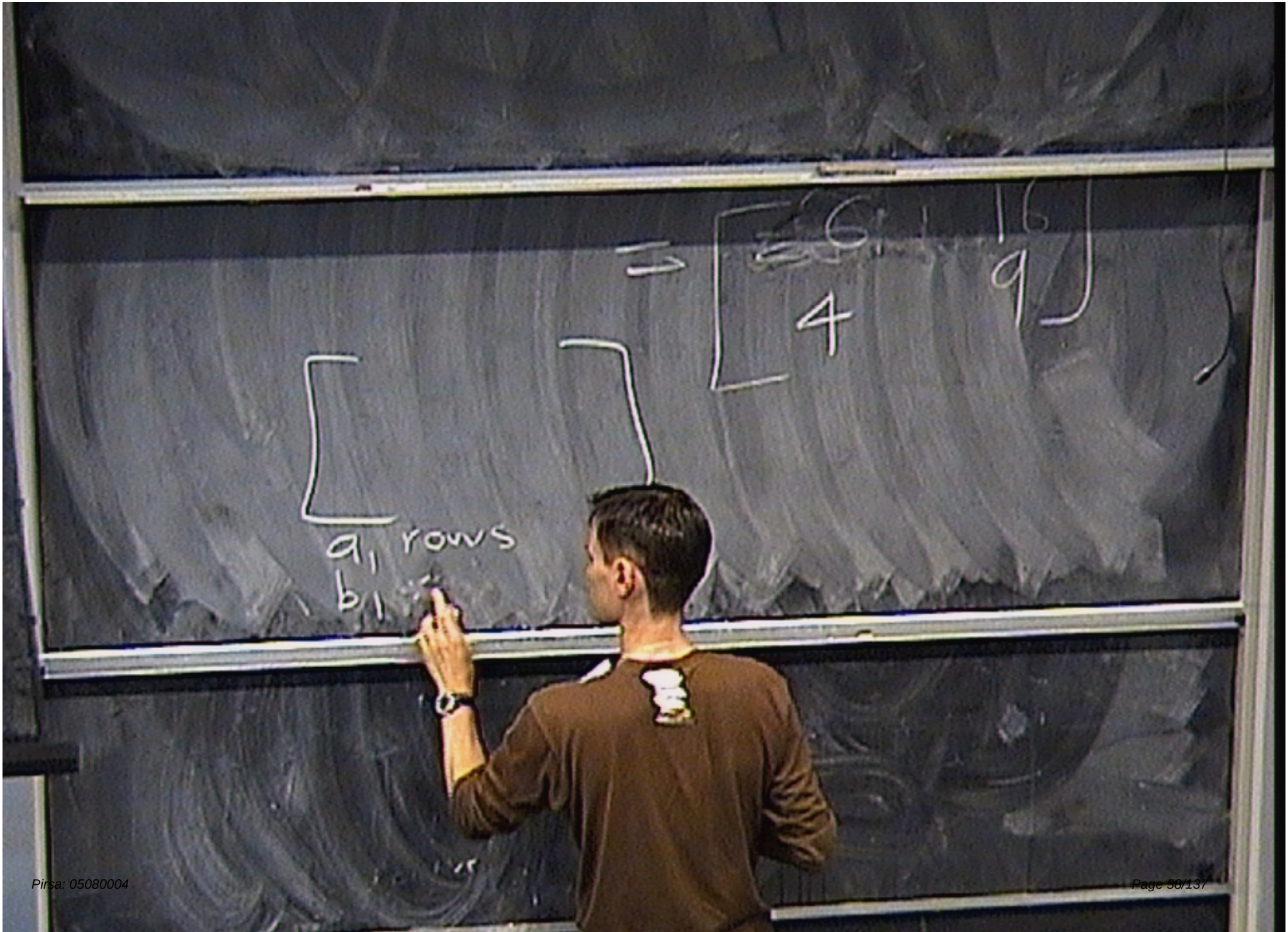
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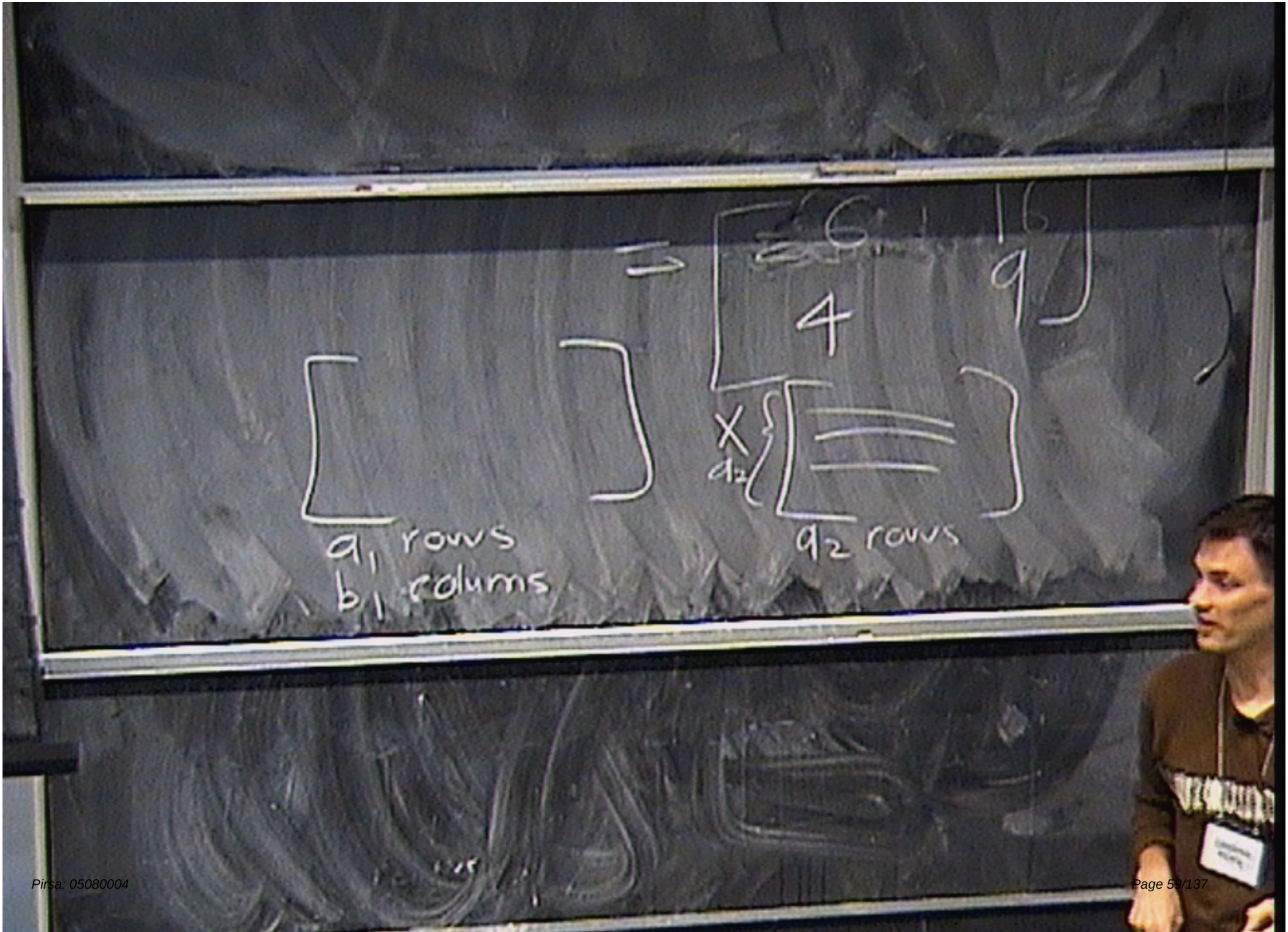

$\begin{bmatrix} 2 & 4 \\ 3 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 2 \\ 1 & 3 \end{bmatrix} = ?$
=

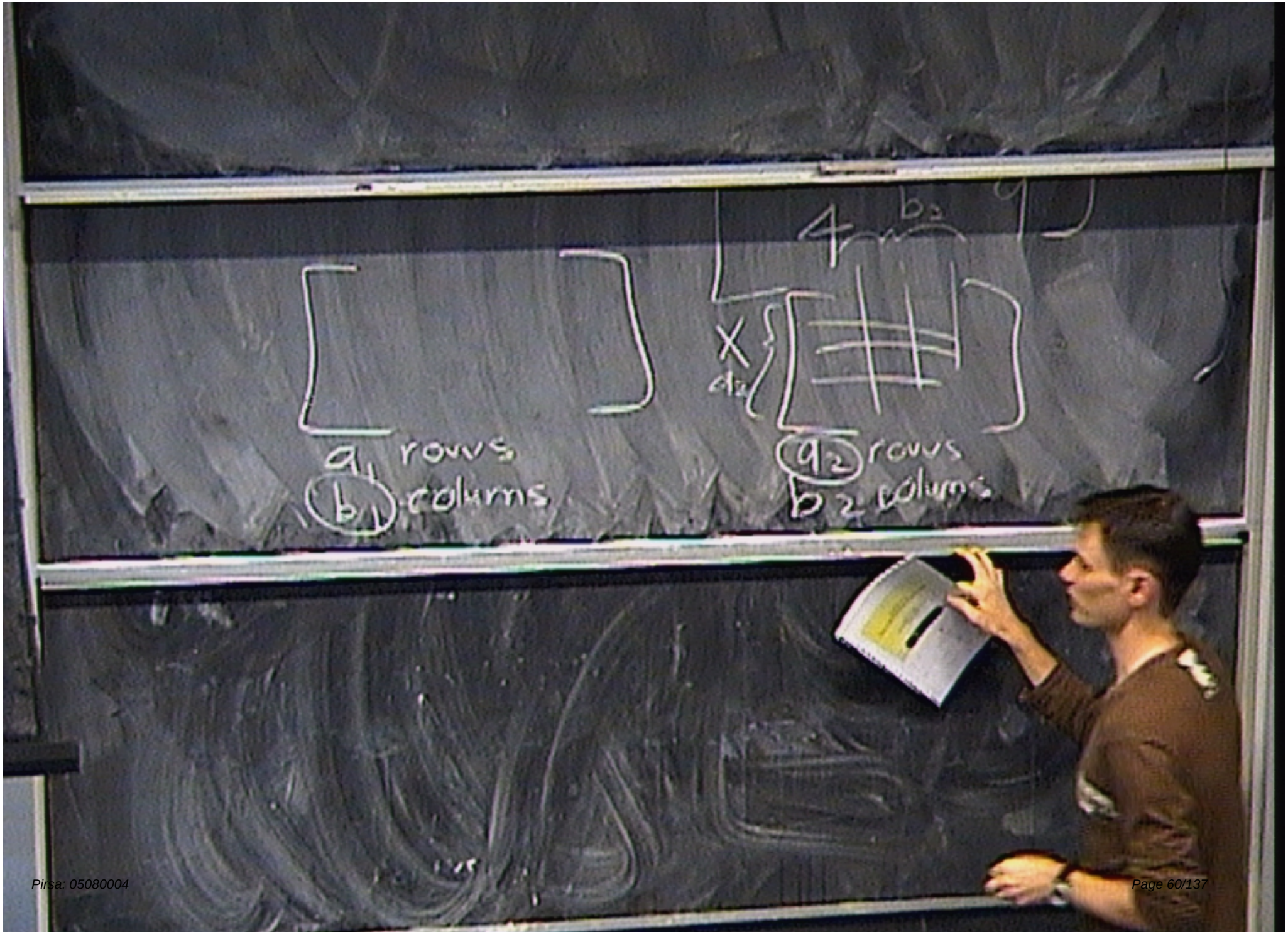

1.
2
2 4
3 1
1. 2
1 2
3 4
=?
=

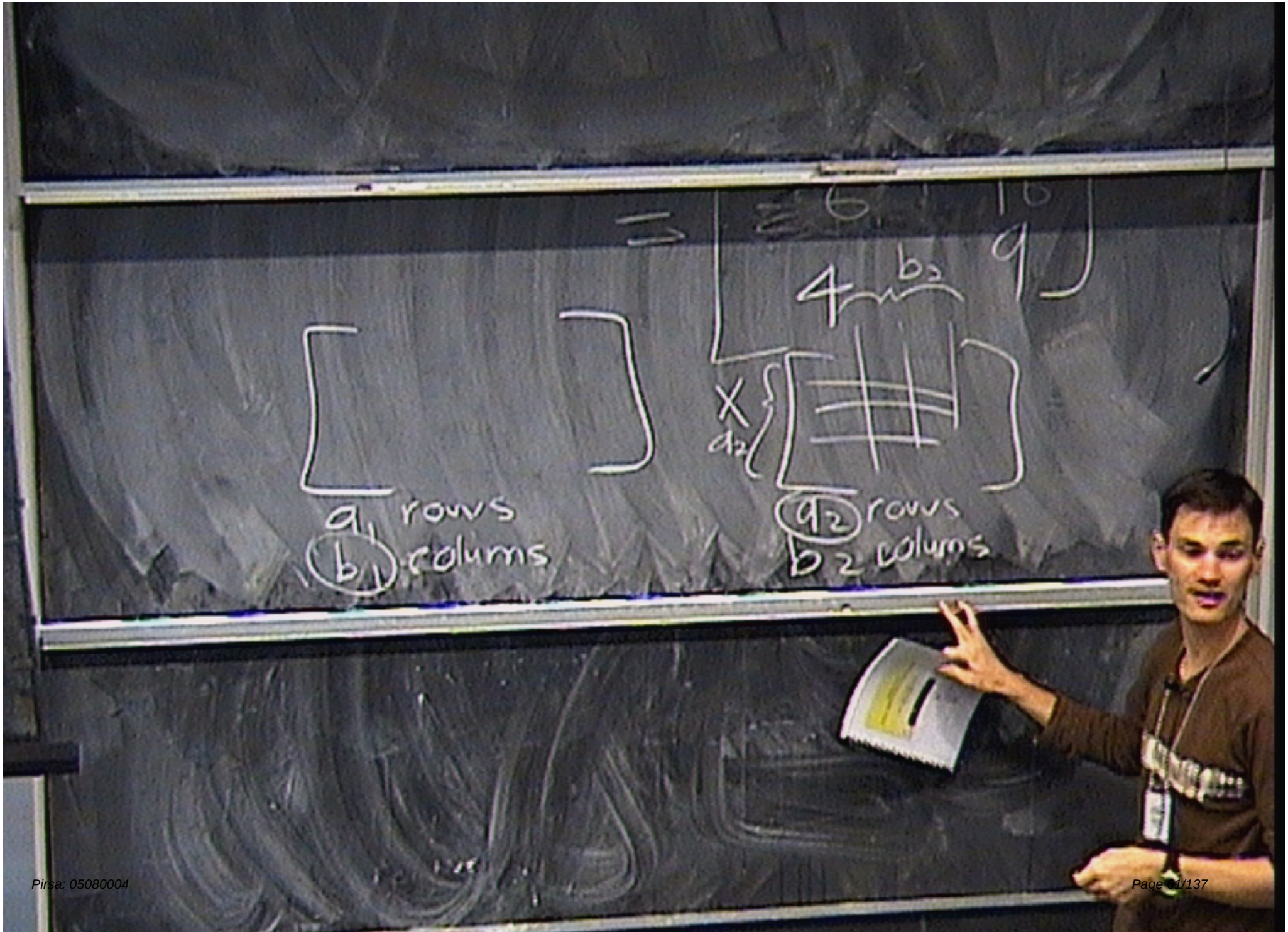

1.
2
=?
=

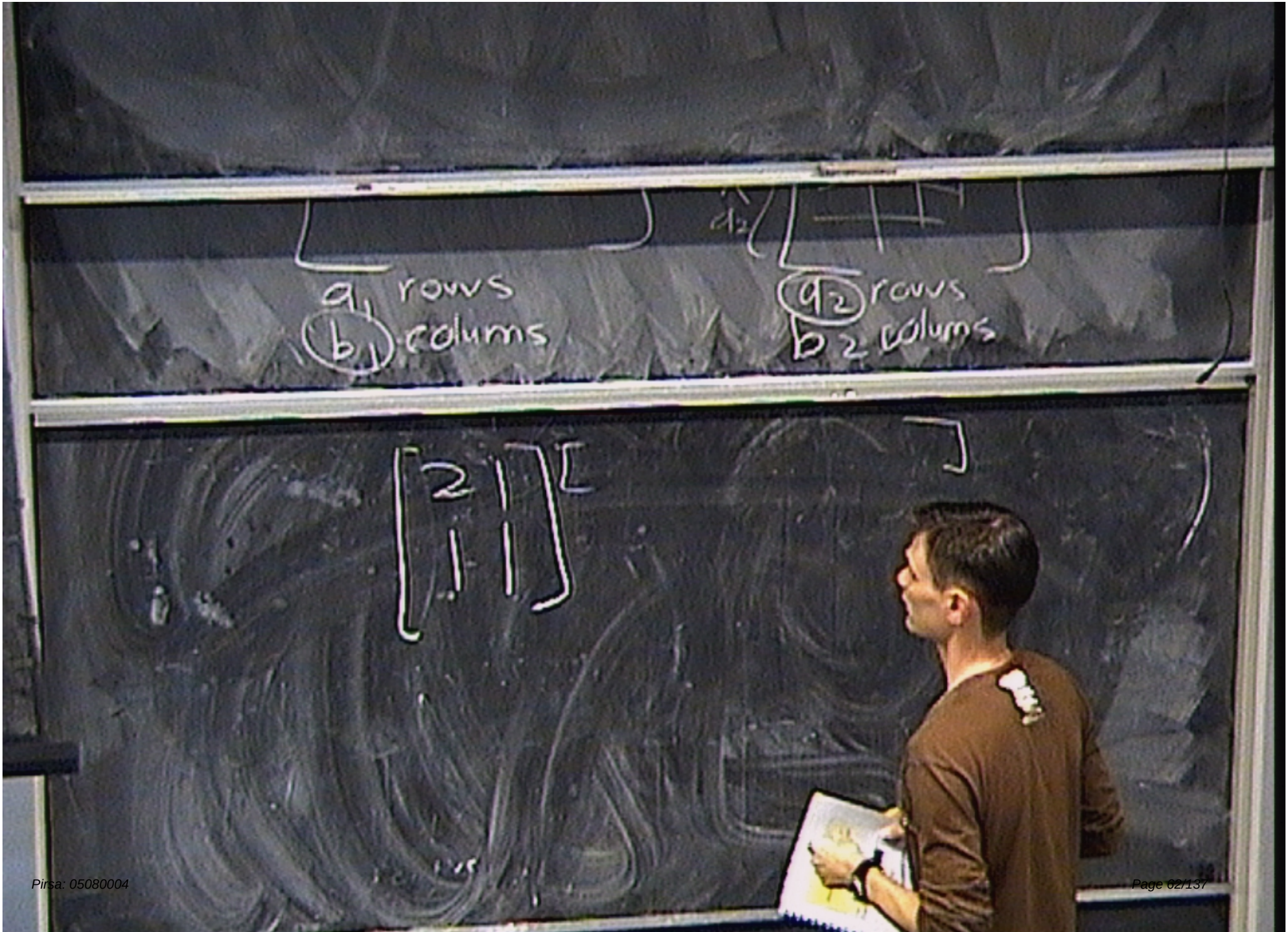

1. [2 4] [1 2] = ?
2 [3 1] [3 4]
2X1

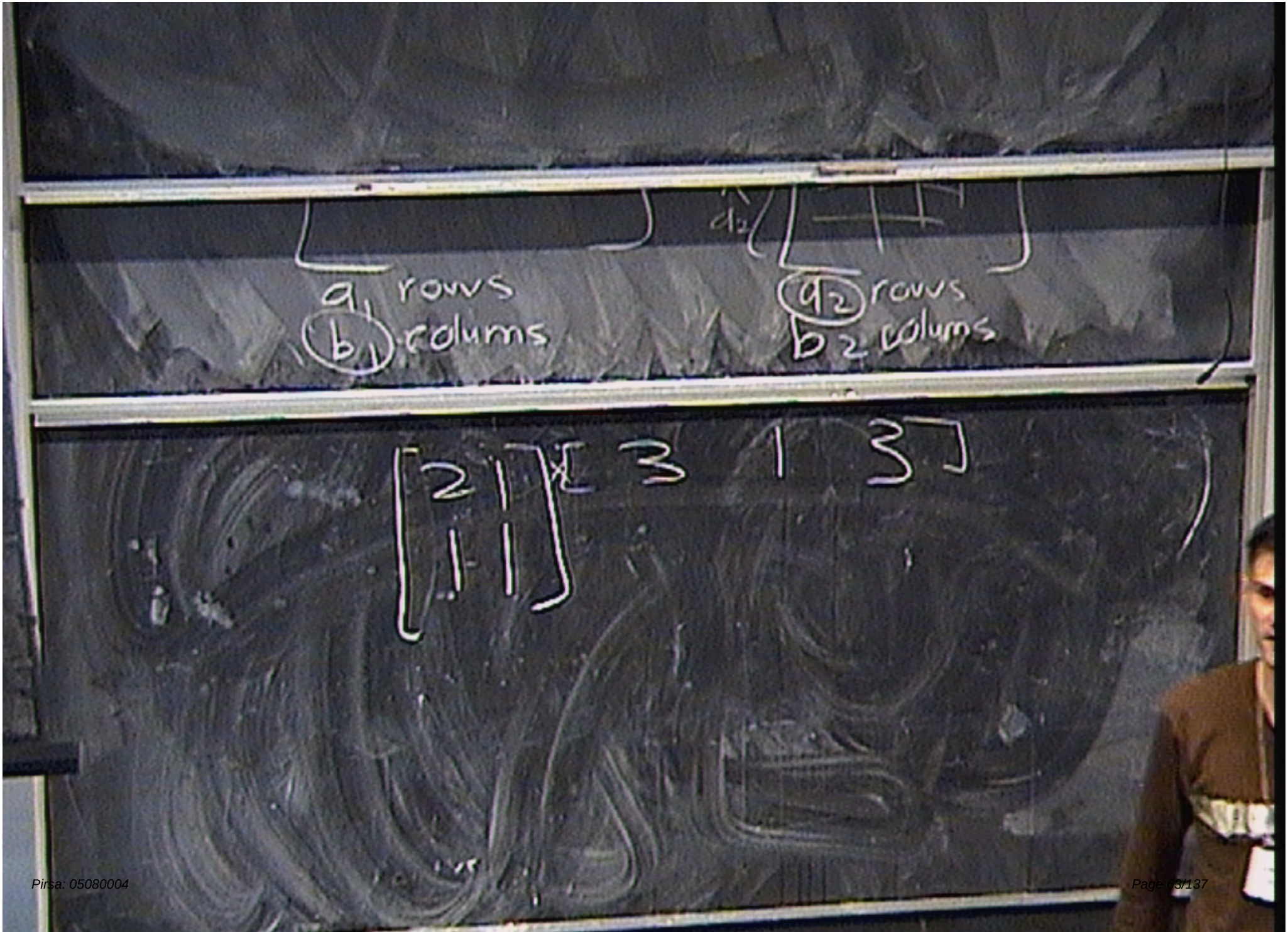

=
4
9
a, rows
b,

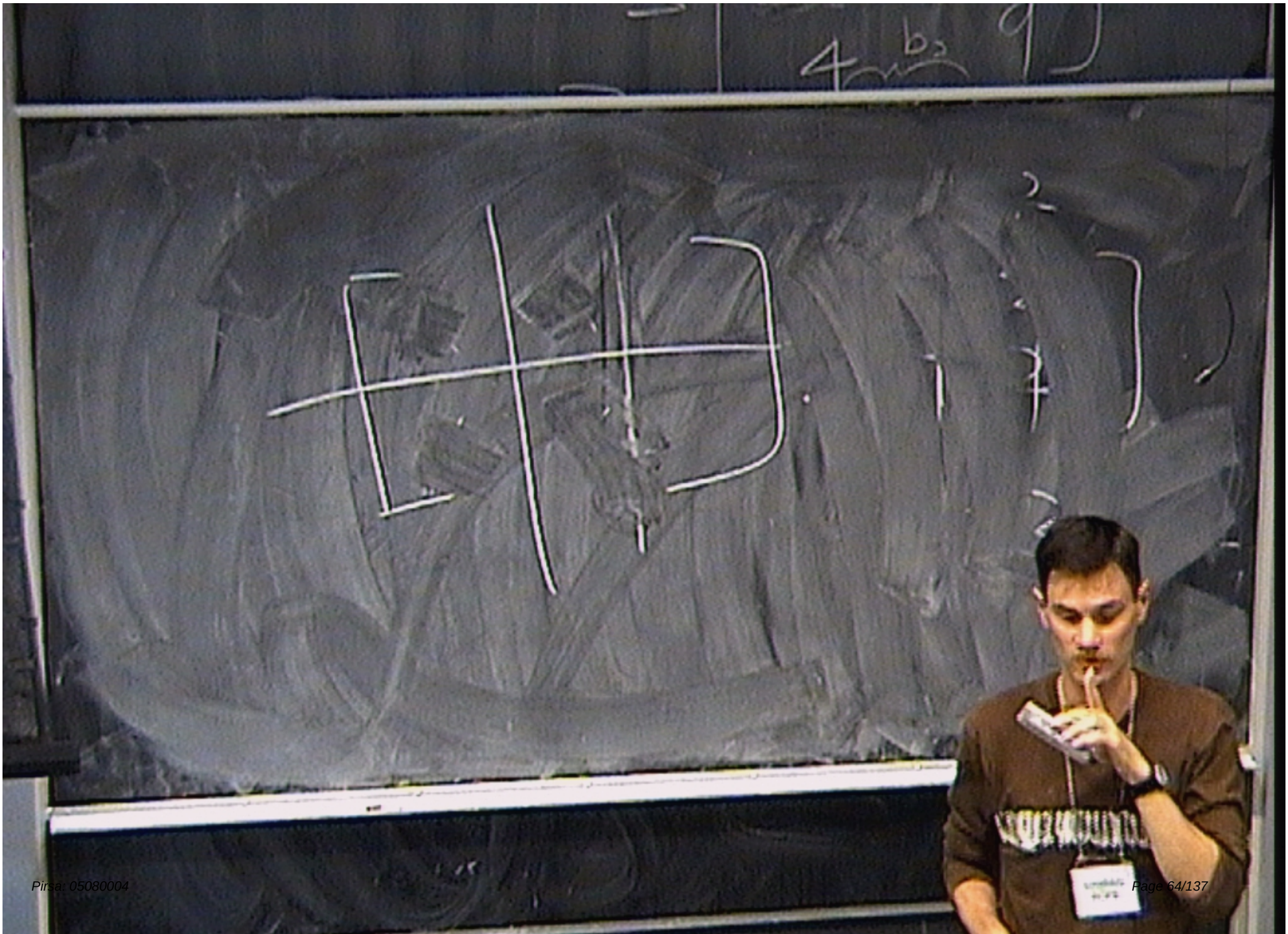

4
a_1 rows
b_1 columns
a_2
a_2 rows

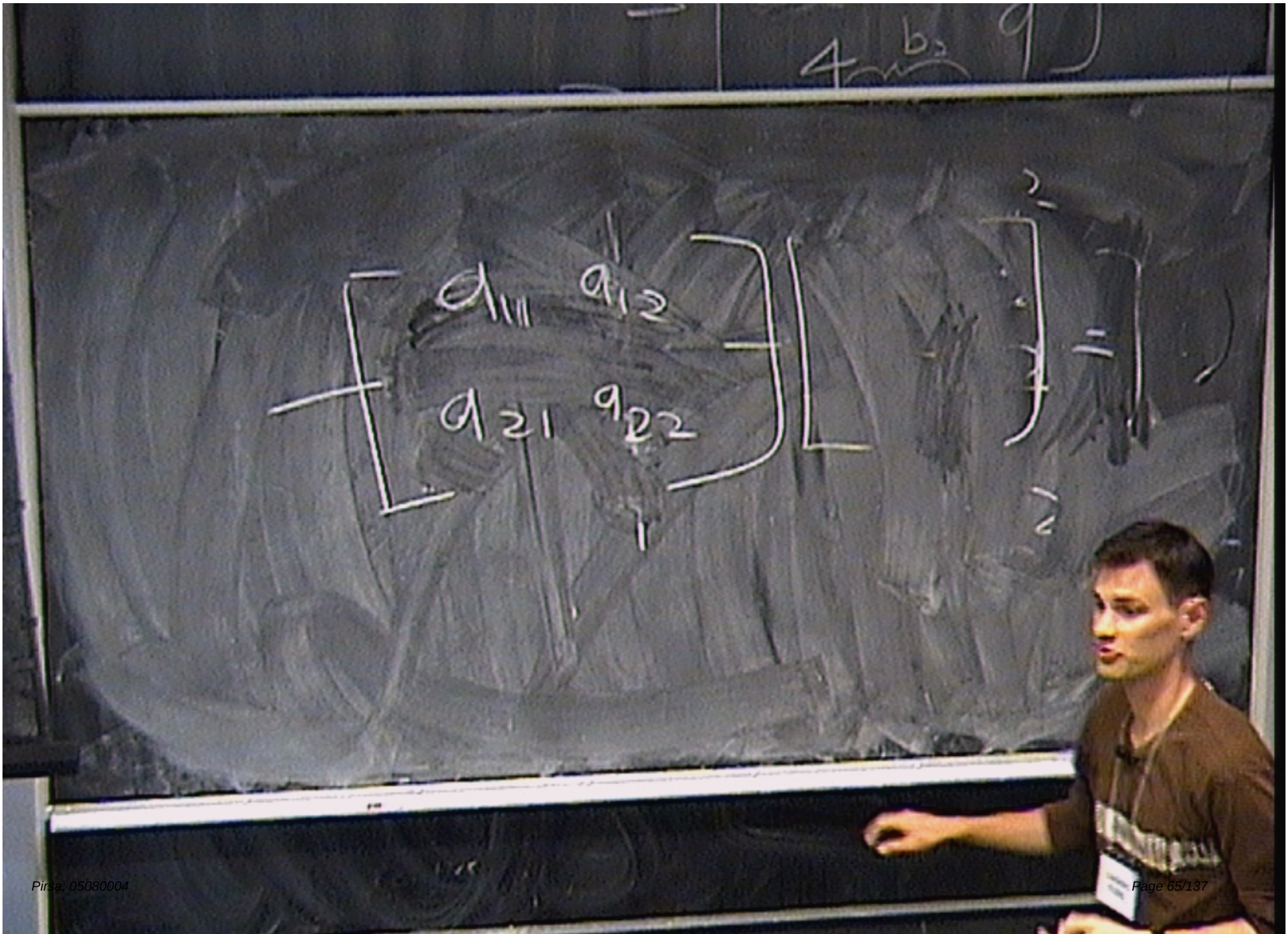

a1 rows
b1 columns
X
a2
q2 rows
b2 columns

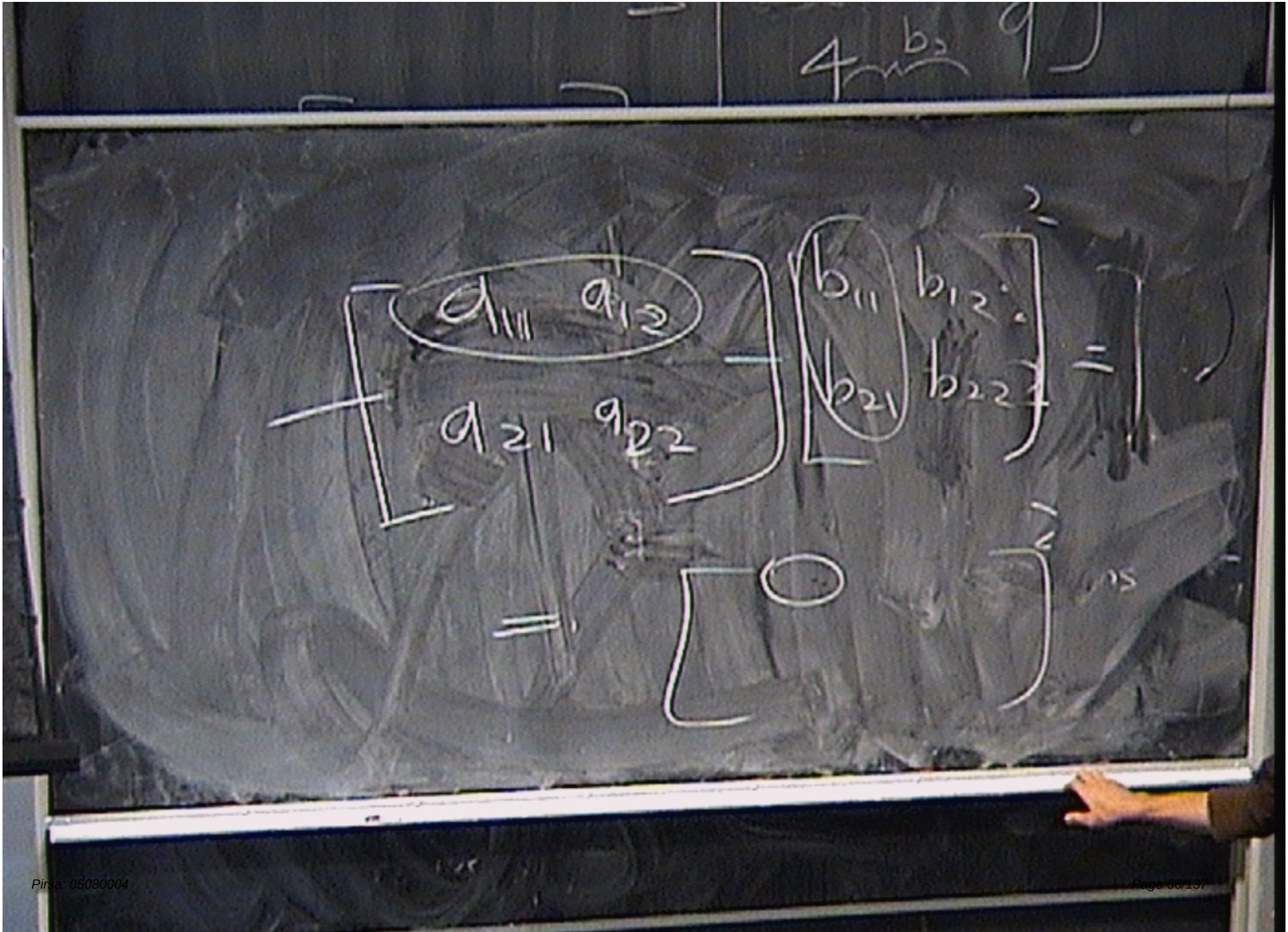

a1 rows
b1 columns
q2 rows
b2 columns

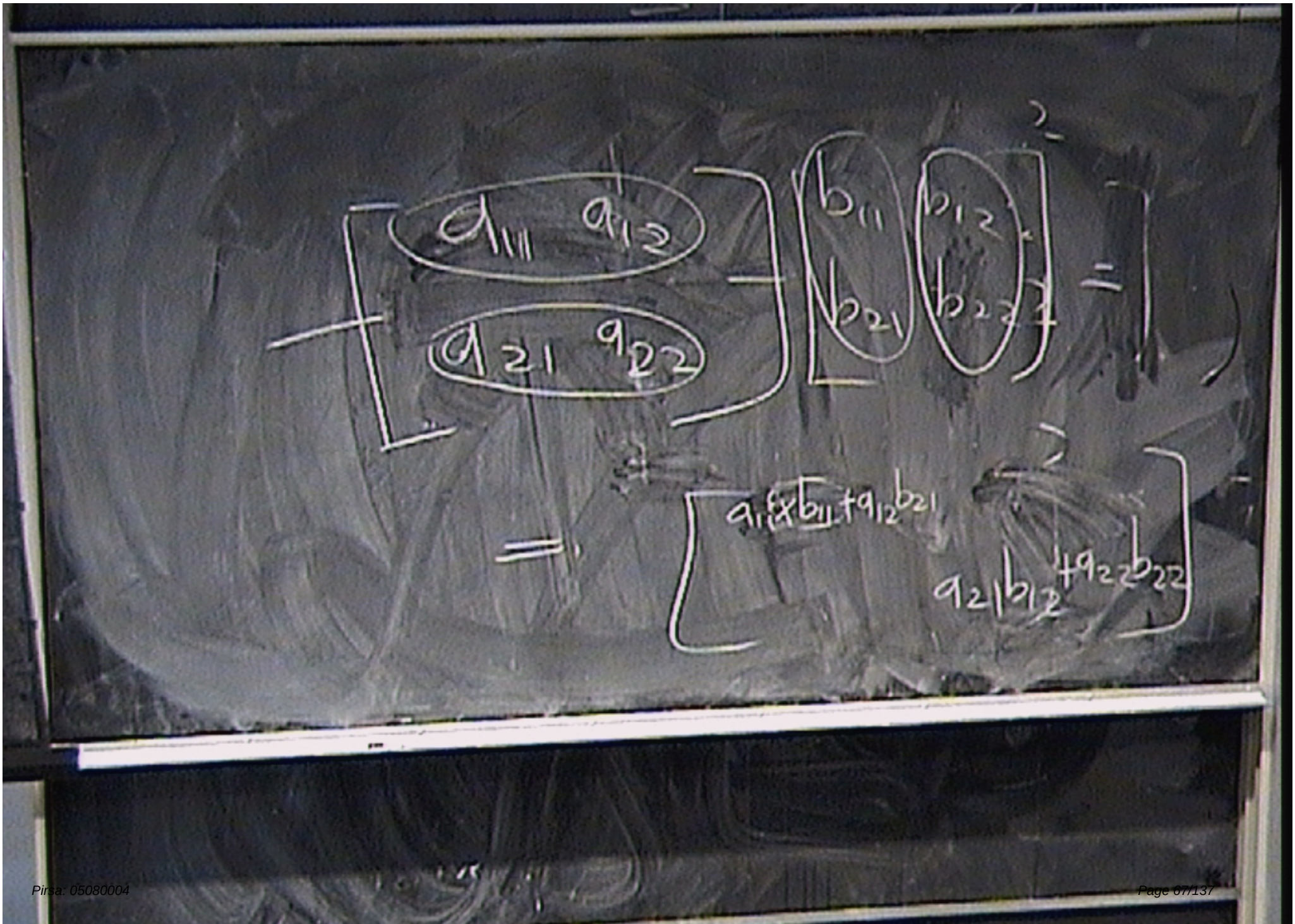

a1 rows
b1 columns
q2 rows
b2 columns
2 1
1 1

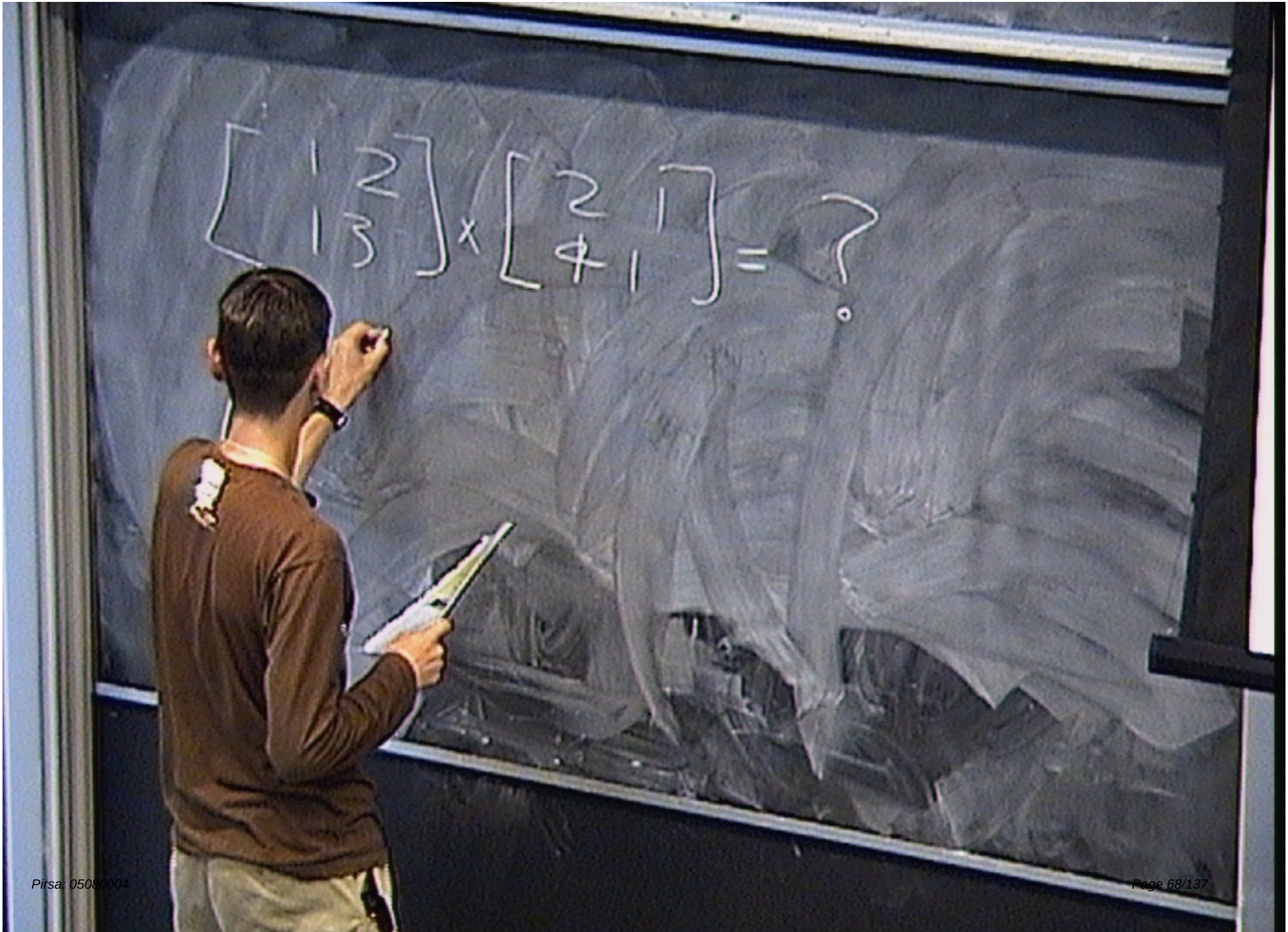

a1 rows
b1 columns
a2 rows
b2 columns
[2 1
1 1] [3 1 3]

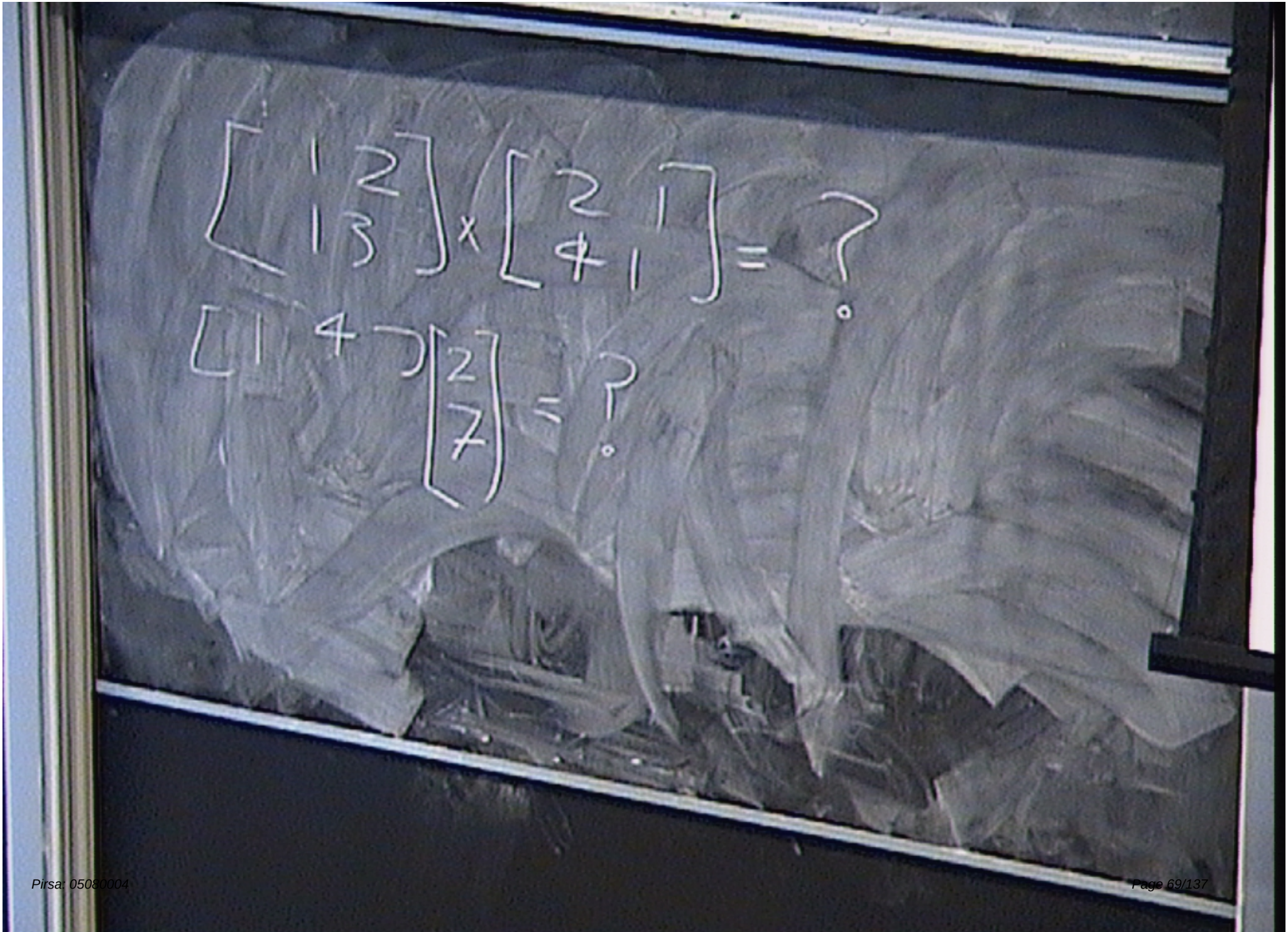




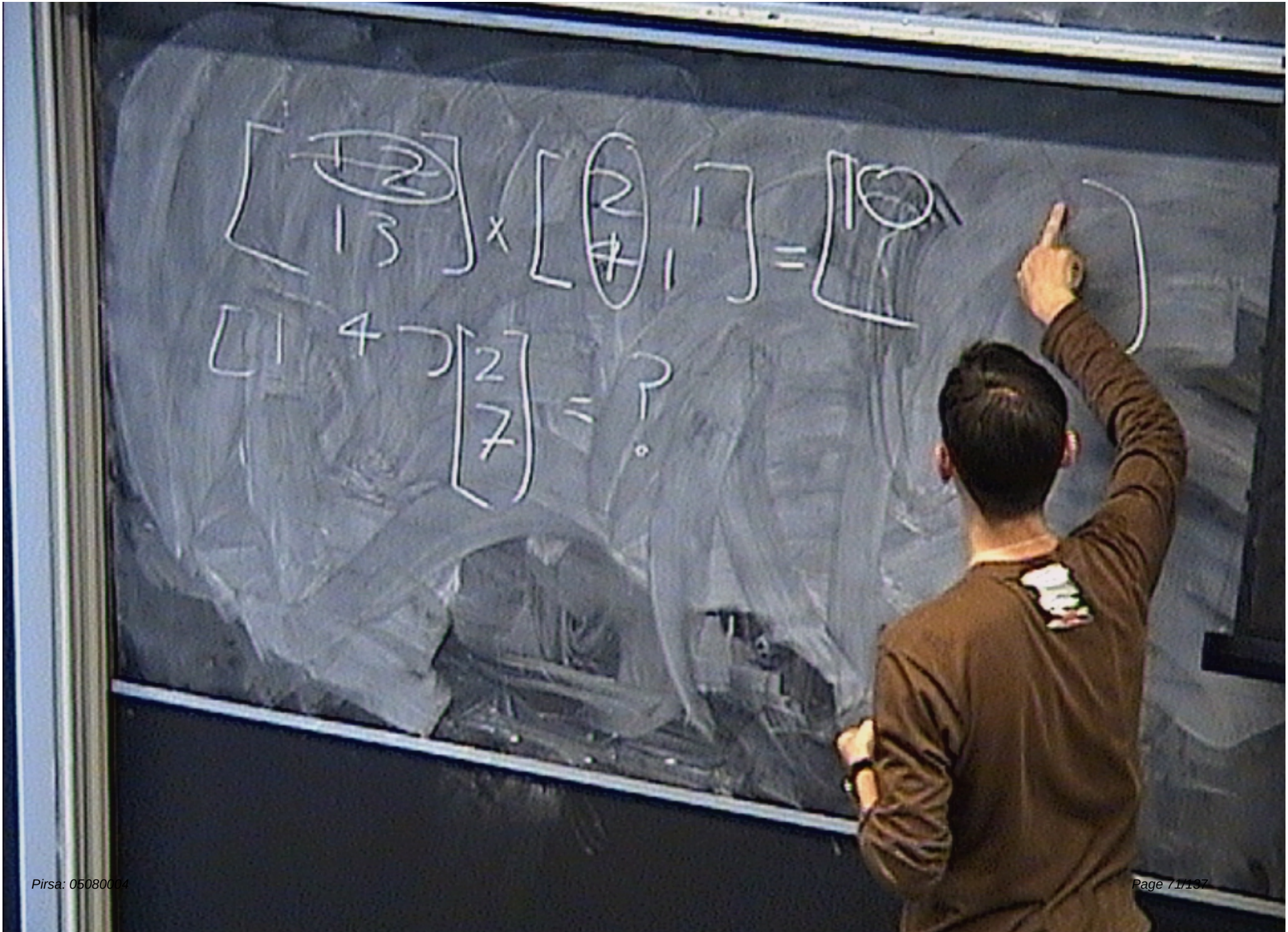

$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} 0 & \\ & \end{bmatrix}$

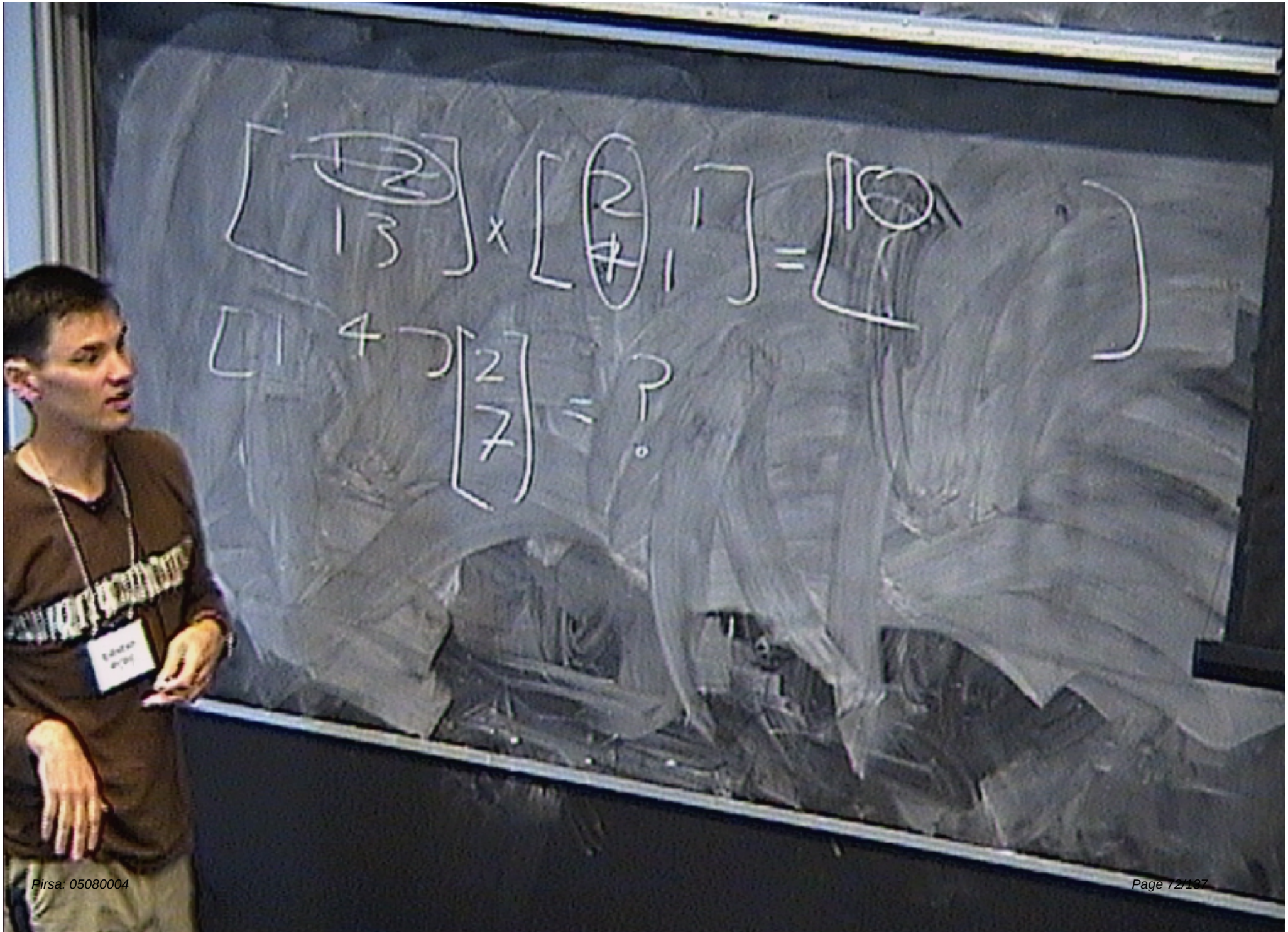

$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = I$
$= I \begin{bmatrix} a_{11}b_{11} + a_{12}b_{21} & \\ & a_{21}b_{12} + a_{22}b_{22} \end{bmatrix}$

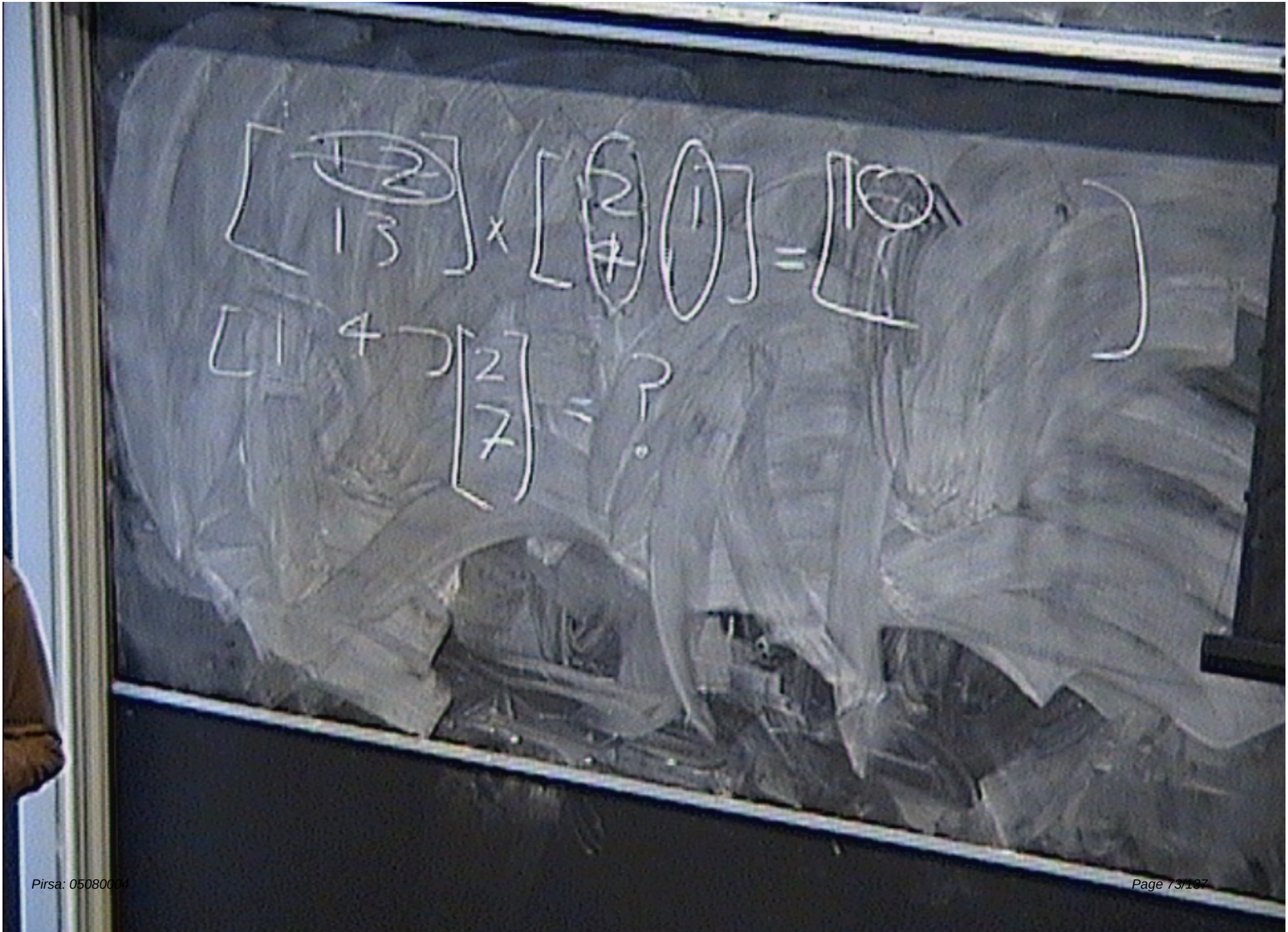

[1 2]
[1 3]
x
[2 1]
[4 1]
=
?

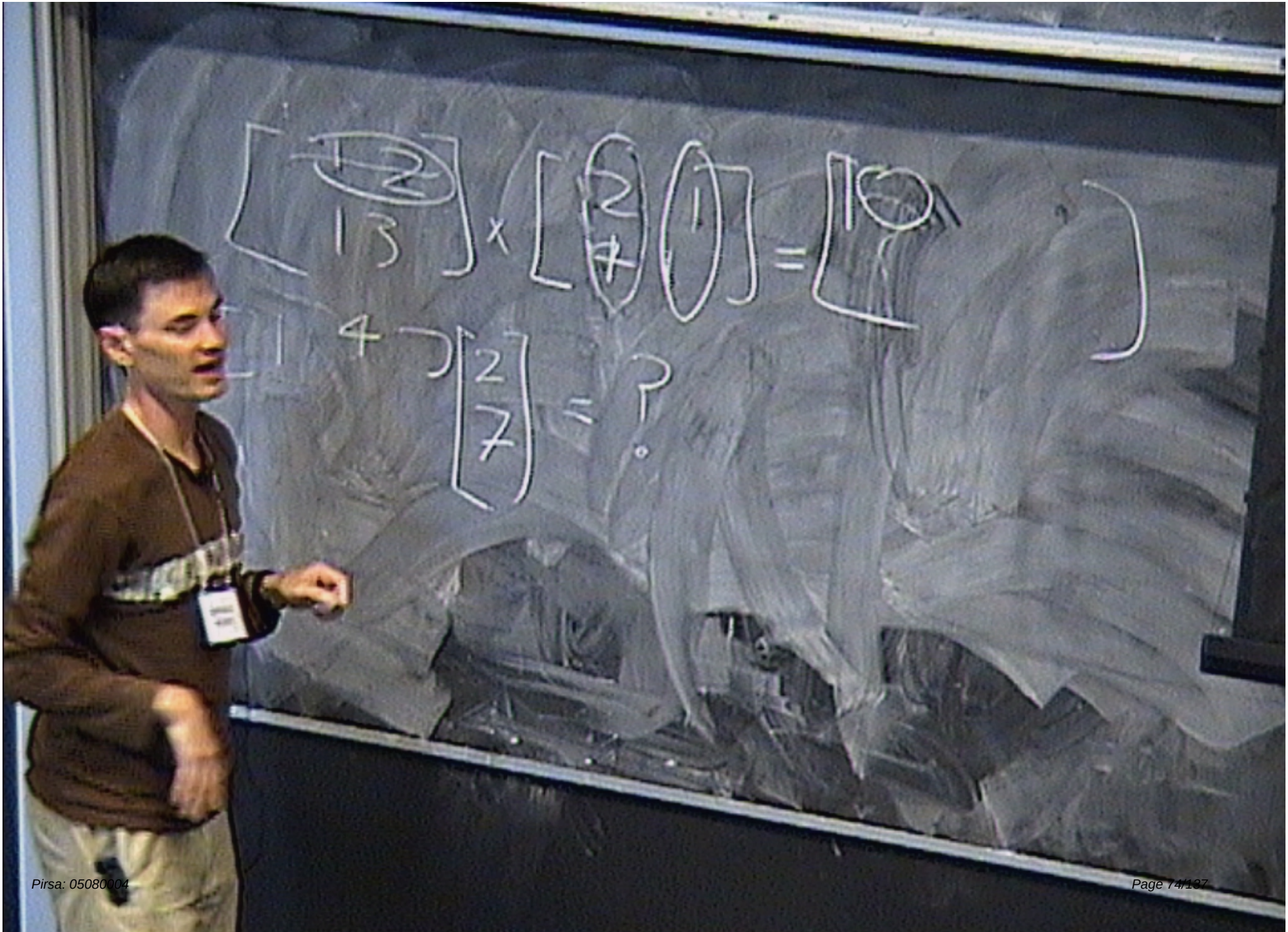

[1 2 / 1 3] x [2 1 / 4 1] = ?
[1 4] [2 / 7] = ?

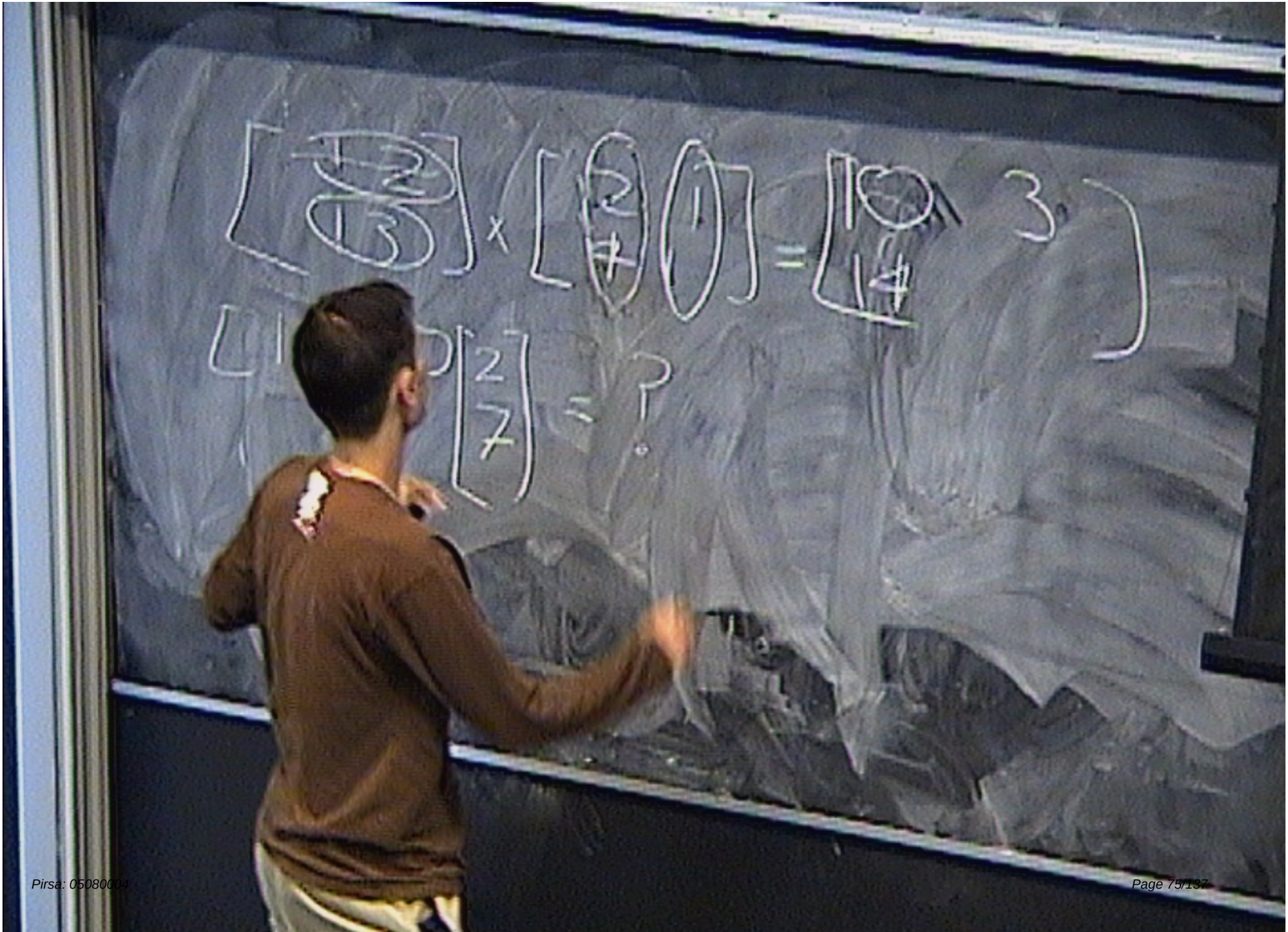


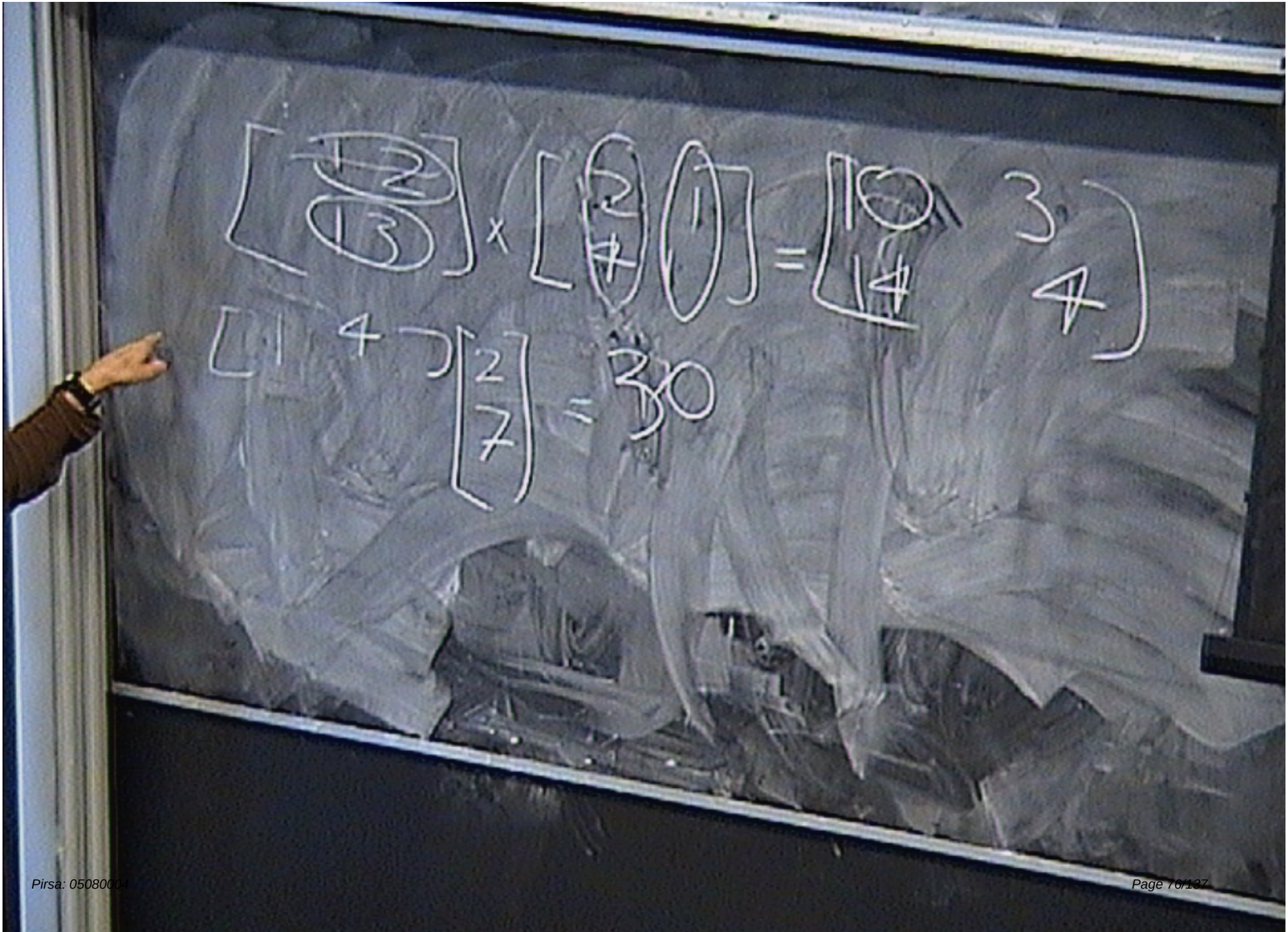

[1 2 / 1 3] x [2 1 / 0 1] = [ ]
[1 4] [2 / 7] = ?

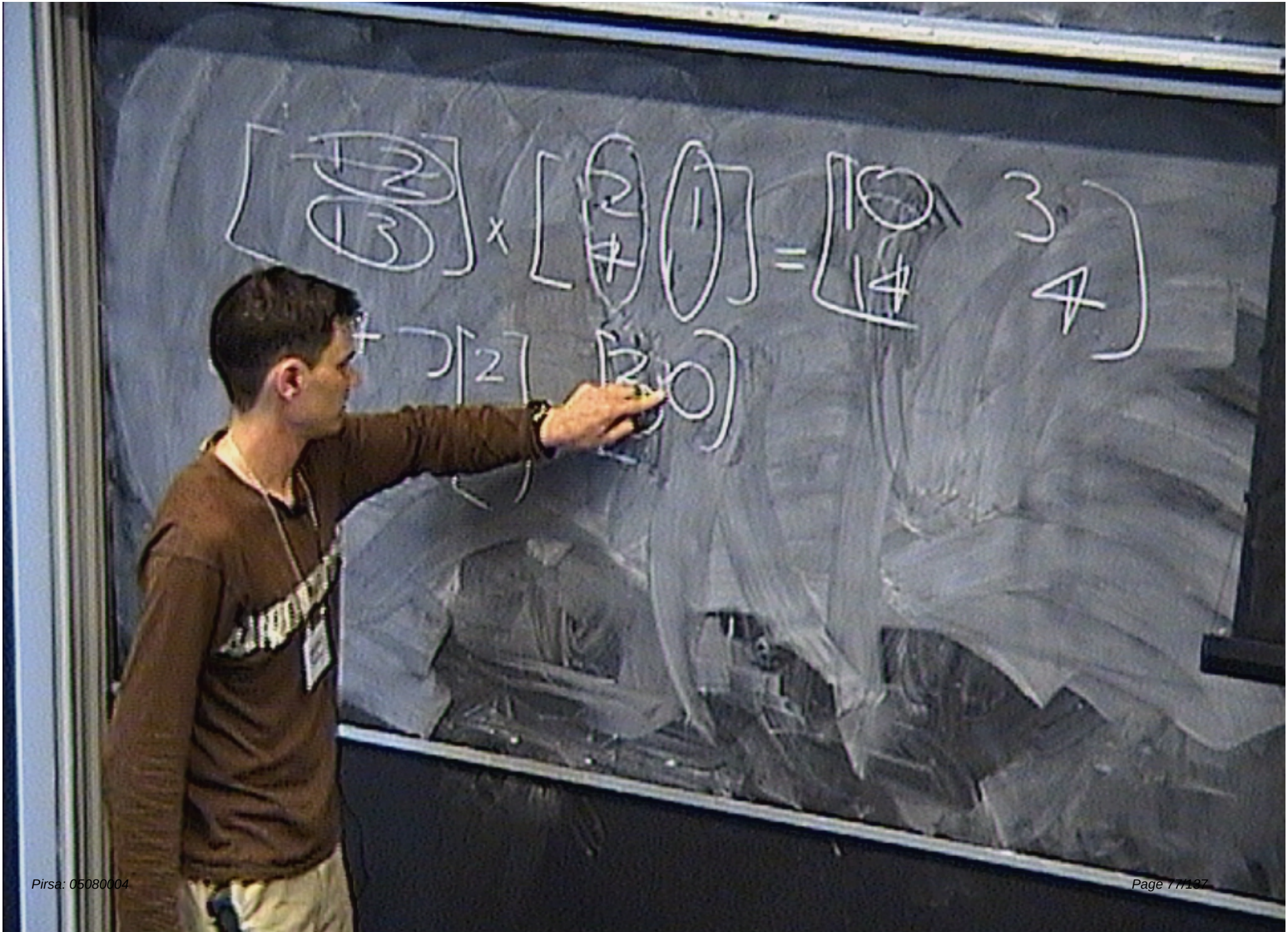

[1 2 / 1 3] x [2 1 / 0 1] = [ ]
[1 4] [2 / 7] = ?

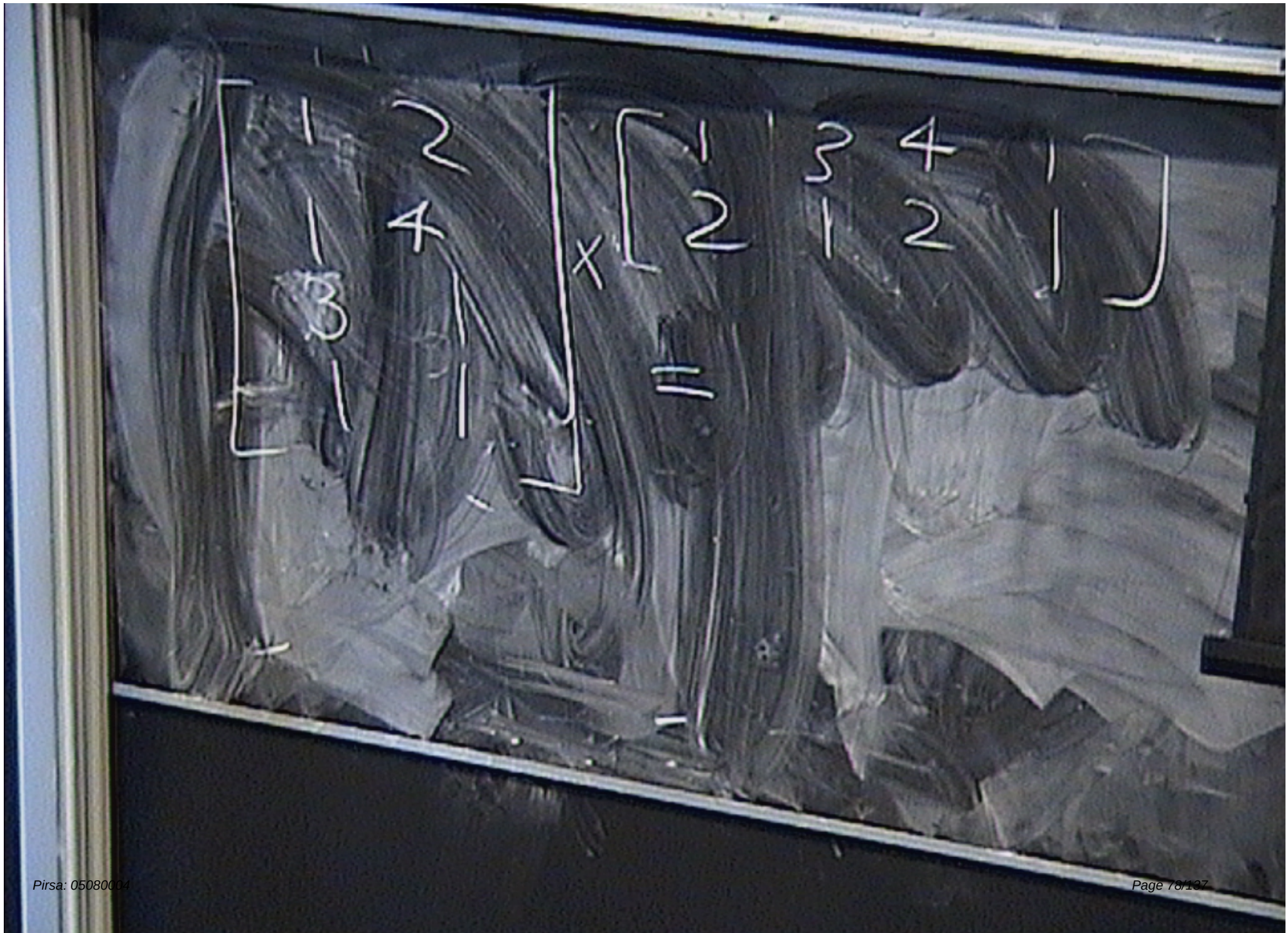

[1 2 / 1 3] × [2 1 / 1 0] = [ ]
[1 4] [2 / 7] = ?

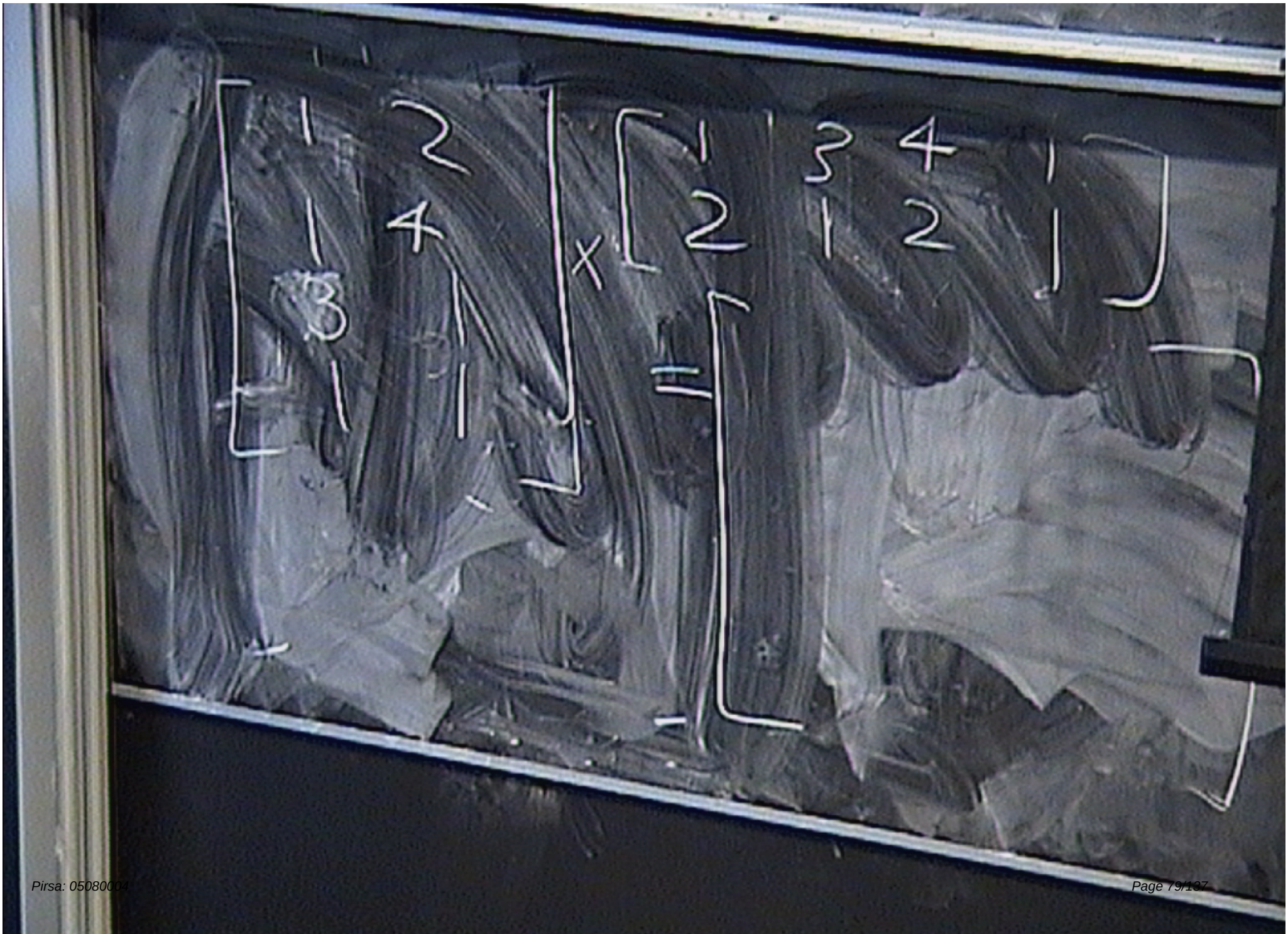

[1 2 / 1 3] x [2 1 / 1 0] = [ ]
[1 4] [2 / 7] = ?

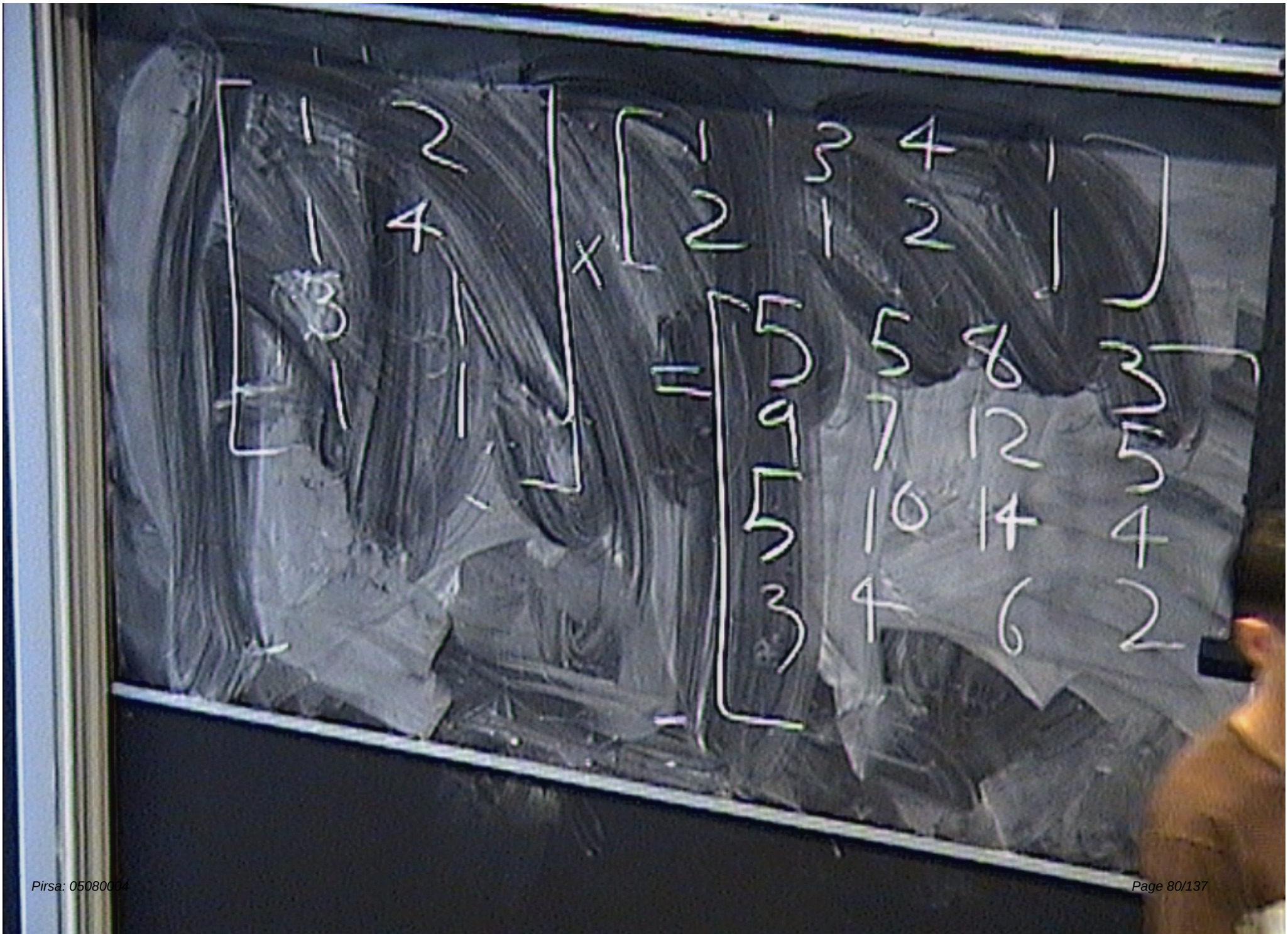



[1 2 / 3]
[2 1]
[10 3 / 14 4]
[1 4]
[2 / 7]
30

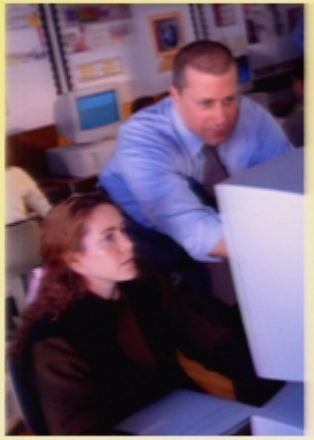



1 2
1 4
3 1
1 1
x
1 3 4 1
2 1 2 1
=


1 2
1 4
1 3
1 1
x
1 3 4 1
2 1 2 1
=


1 2
1 4
3 1
1 1
x
1 3 4 1
2 1 2 1
=
5 5 6 3
9 7 12 5
5 10 14 4
3 4 6 2

How should we teach quantum physics in Grade 12?

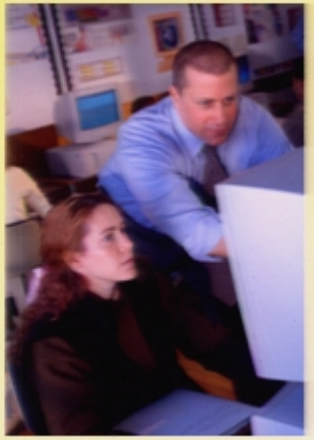


What is the essence of quantum physics?



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How should we teach quantum physics in Grade 12?

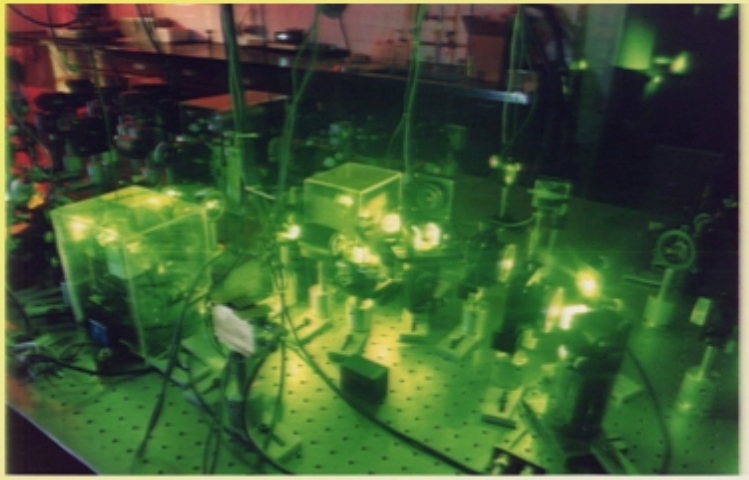


What is the essence of quantum physics?



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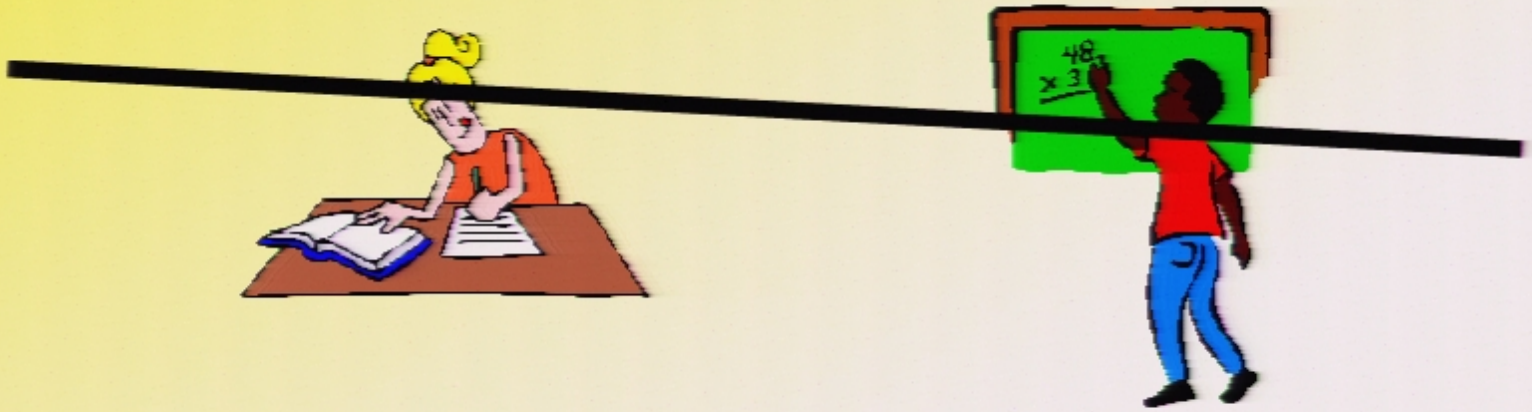
What actually is quantum mechanics?





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FOR TEACHERS ONLY



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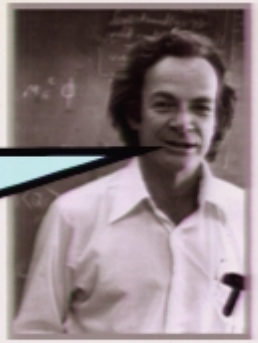
- To most, quantum mechanics is incredibly puzzling

'If you do not get dizzy sometimes when you think about these things [within quantum physics] then you have not really understood it.'



Niels Bohr

'I think I can safely say that nobody understands quantum mechanics'



Richard Feynman

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- Am I missing something about it?
- Am I not understanding the 'trick' behind it?

"If you find the theory difficult to understand, this is the theory's fault --- not yours." --- Professor Jim Baggot.

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A mathematical framework

- Quantum mechanics is a mathematical framework for calculating the results of experiments involving subatomic particles, atoms and molecules.
- For example, imagine electrons emitted by a very hot piece of metal (metal filament or electron gun)

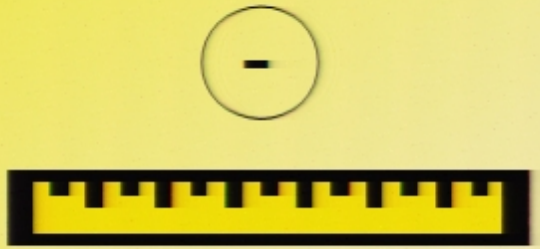


FILAMENT ELECTRON ELECTRON DETECTOR

- quantum mechanics provides a way to calculate *probability* of detecting the electron to be at various locations.

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- Eg. Probability(x is between 1.5 and 2 metres) = 0.4



- Use the wavefunction ψ to calculate such probabilities
- Quantum mechanics does not provide an account or picture of what each electron was doing before we looked at it.
- Just a calculational tool

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A mathematical framework

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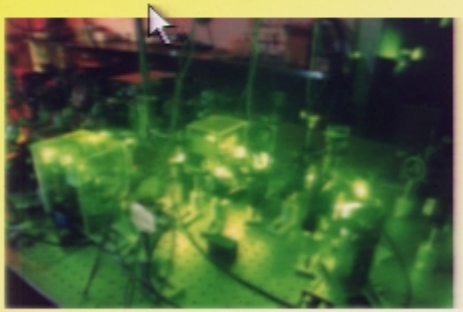
- c.f. an instruction manual for a DVD player.



- It tells us what buttons to press to play a DVD, but does not explain the underlying electronics.
- It does not explain things at a fundamental level.
- Quantum mechanics only tells us 'what buttons to press' (i.e. math calculations to do) to determine the probability of finding an electron here or there.
- It is silent as to what is really going on 'out there' in the world (if anything).

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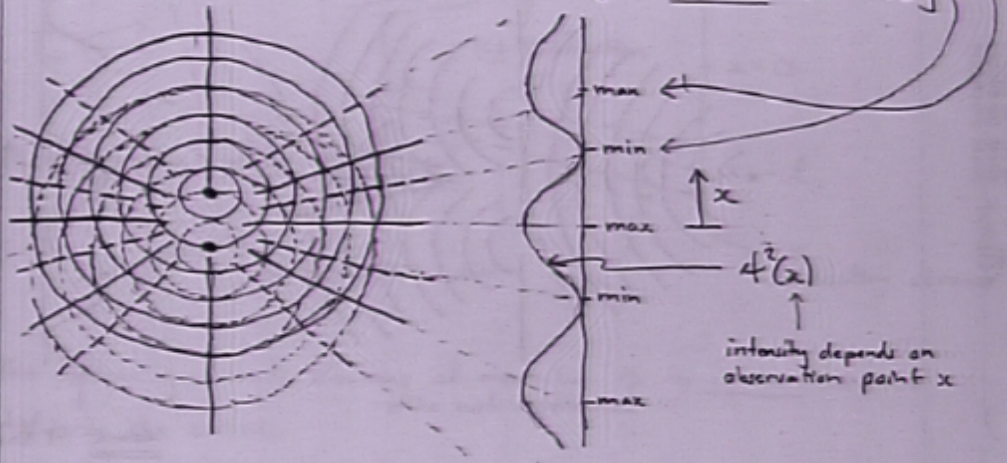
What actually is quantum mechanics?





Intro To Quantum Theory

Interference of Water Waves



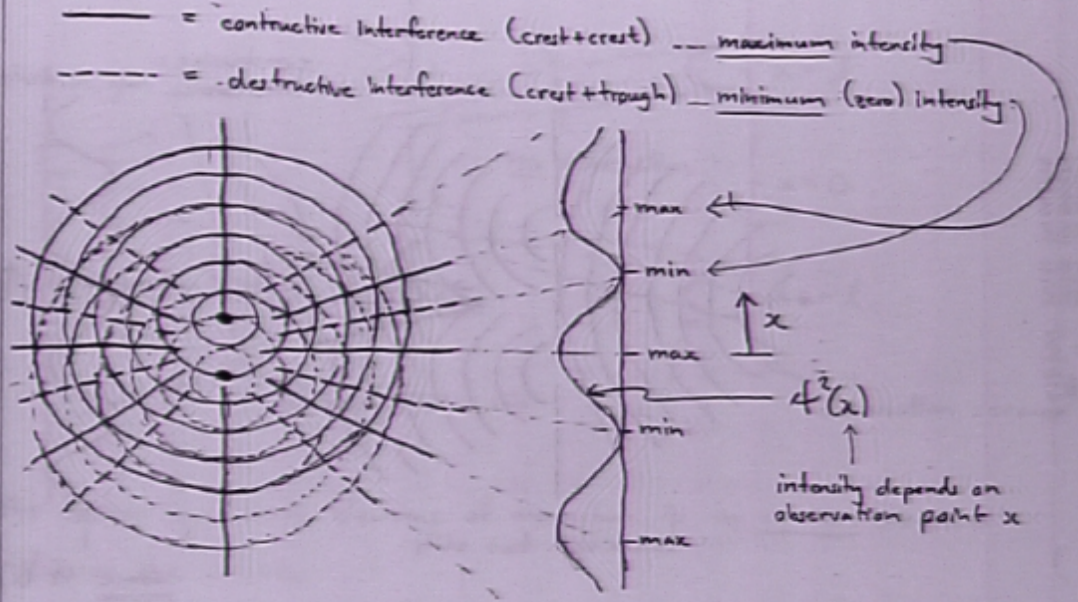
wave intensity $\equiv$ (wave amplitude)^2 $= \psi^2$

note: at any observation point x, the wave vibrates up (crest, or positive) and down (trough, or negative) with respect to still-water level. A crest represents as much energy as a trough. Therefore square this +/- amplitude to get a strictly positive number representing the wave intensity (or energy).

Pirsa: 05080004

Intro To Quantum Theory

Interference of Water Waves



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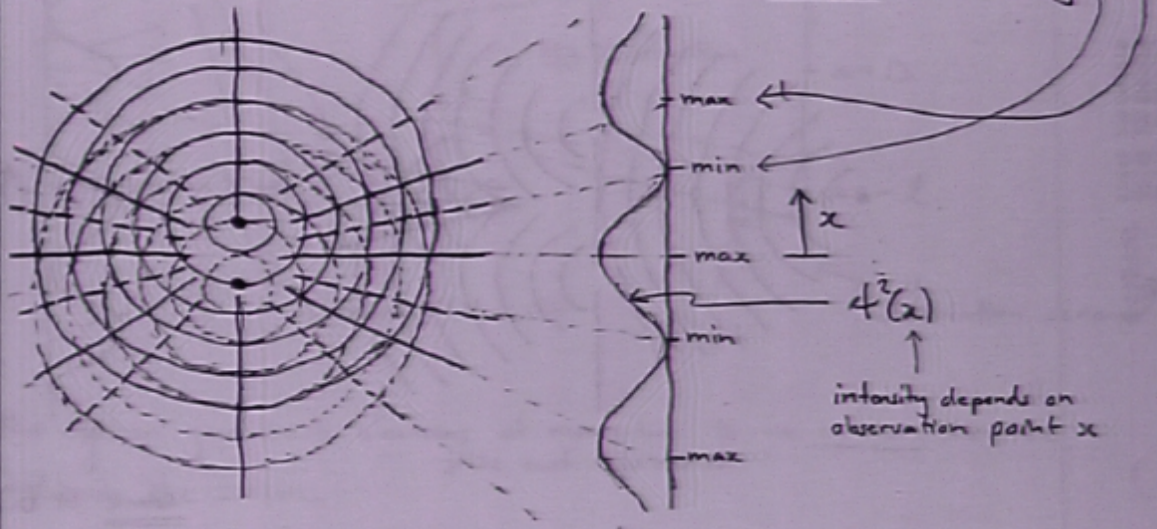
22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
EMBALO

Intro To Quantum Theory

Interference of Water Waves

——— = contructive interference (crest+crest) __ maximum intensity

– – – – – = destructive interference (crest+trough) _ minimum (zero) intensity



wave intensity ≡ (wave amplitude)^2 ≡ ψ^2

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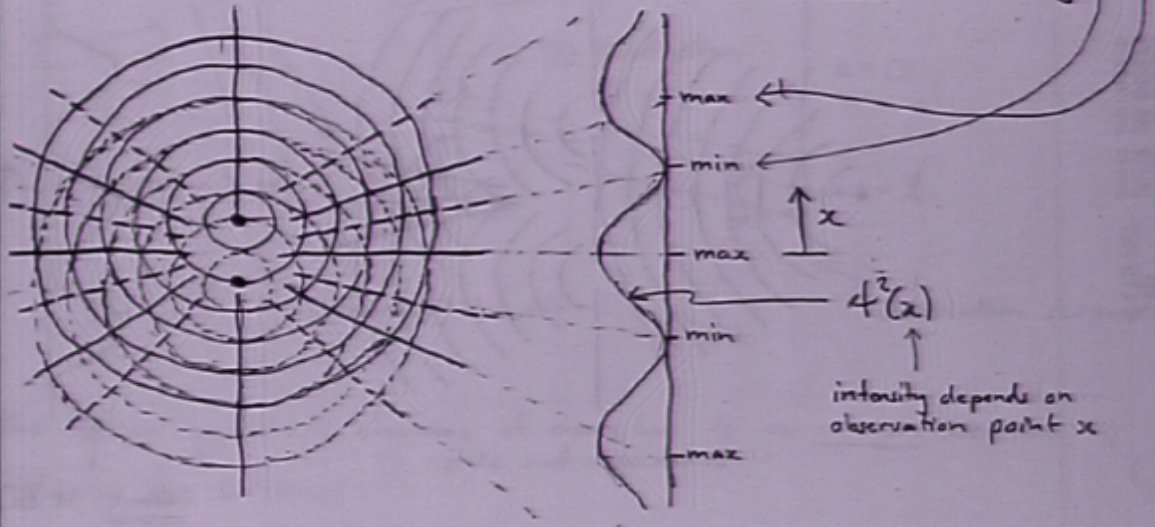
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Intro To Quantum Theory

Interference of Water Waves

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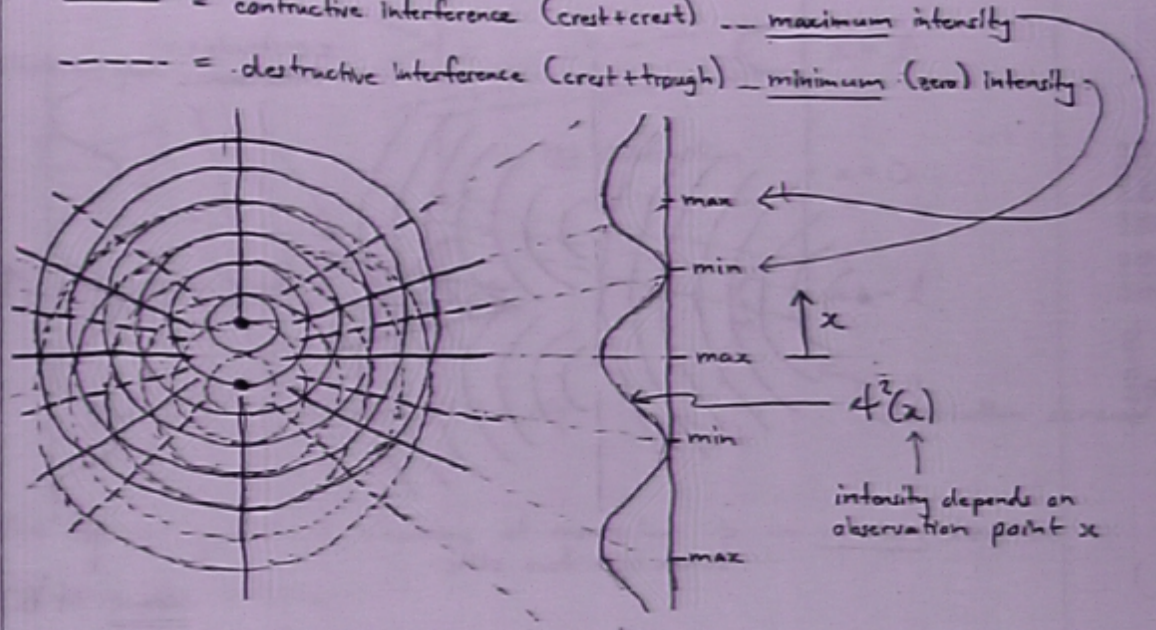
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22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
EMBOSSED

Intro To Quantum Theory

Interference of Water Waves



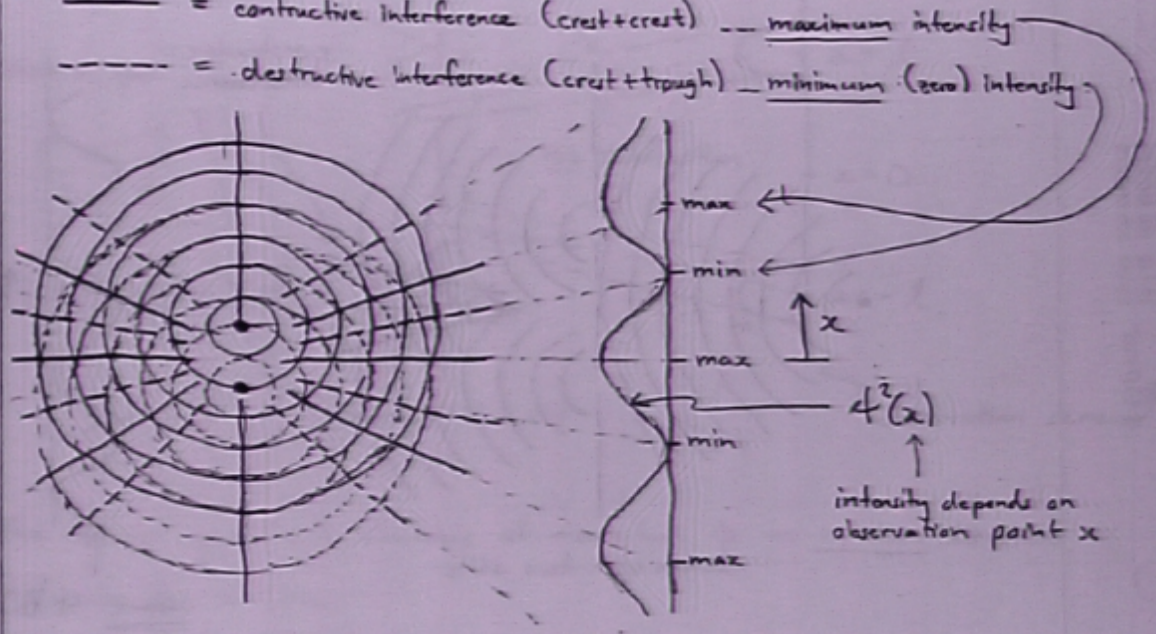
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Intro To Quantum Theory

Interference of Water Waves

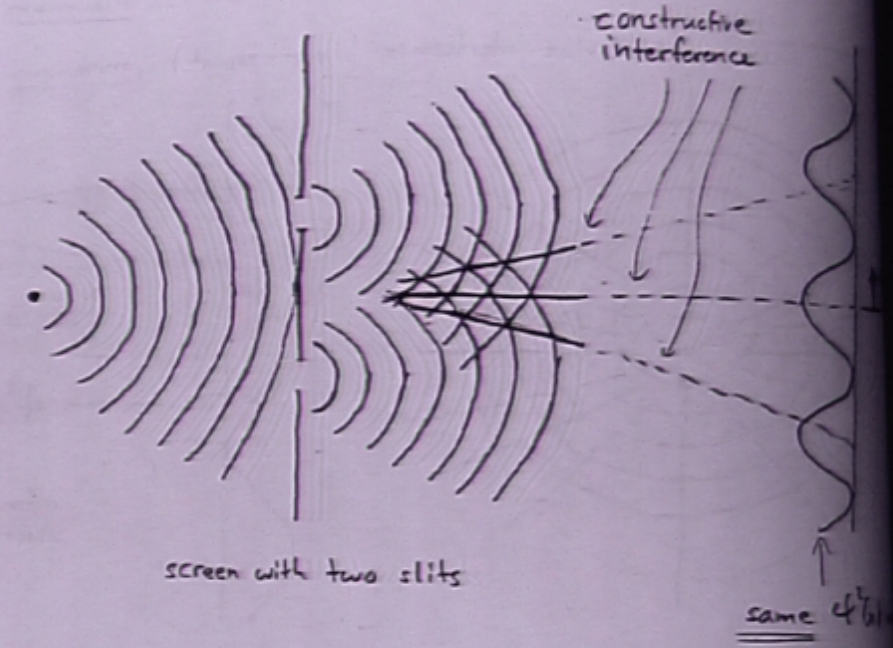


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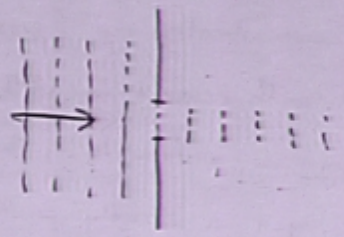
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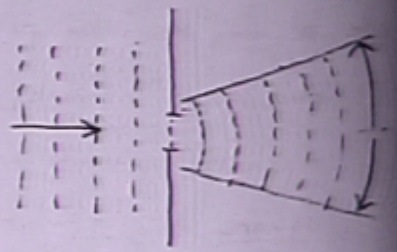
How to Make a Water Wave Interfere with Itself



NB: waves passing through each slit undergo diffraction: [Huygens pri



no diffraction



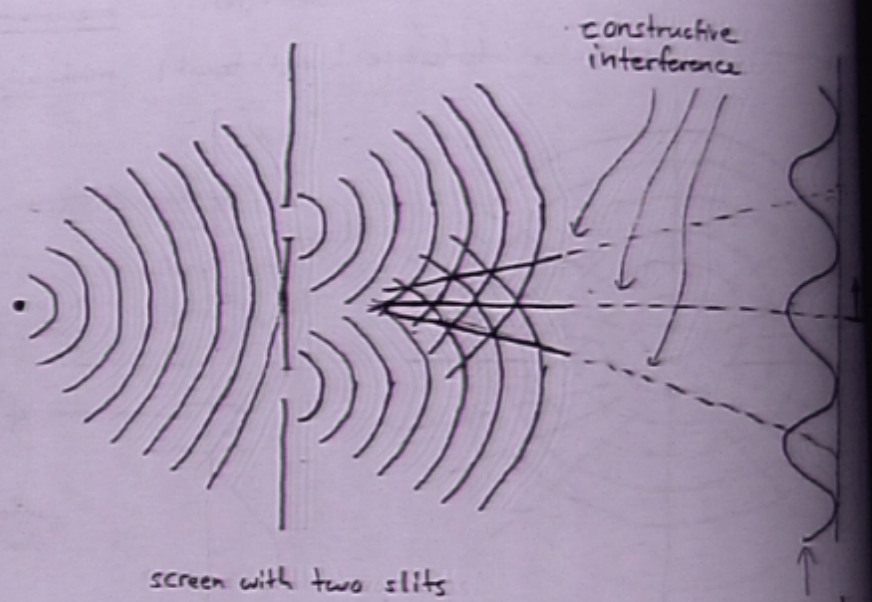
diffraction

This makes each slit act almost like a "point source" of waves, and the resulting pair of waves on the right hand side of the screen can then interfere

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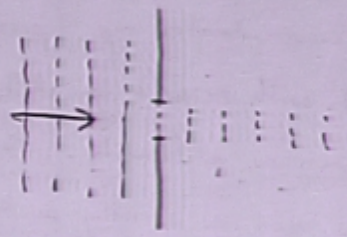
22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
CAMPAD

How to Make a Water Wave Interfere with Itself

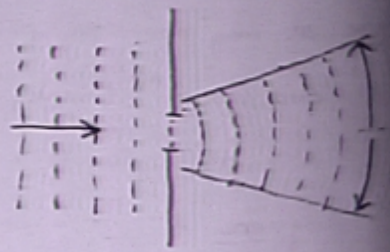


same ef[illegible]

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no diffraction

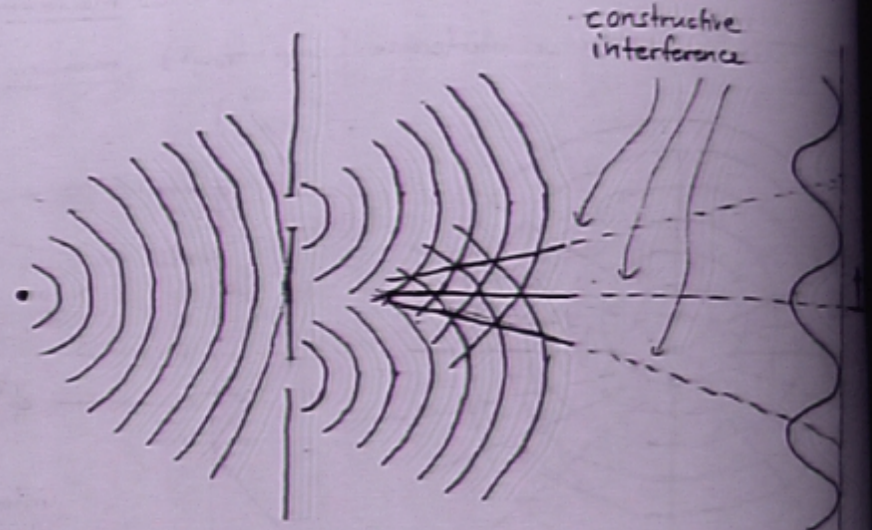


diffraction

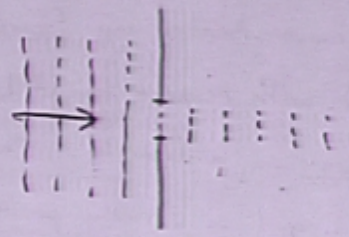
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Print: 05080004

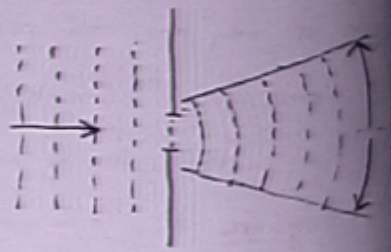
How to Make a Water Wave Interfere with Itself



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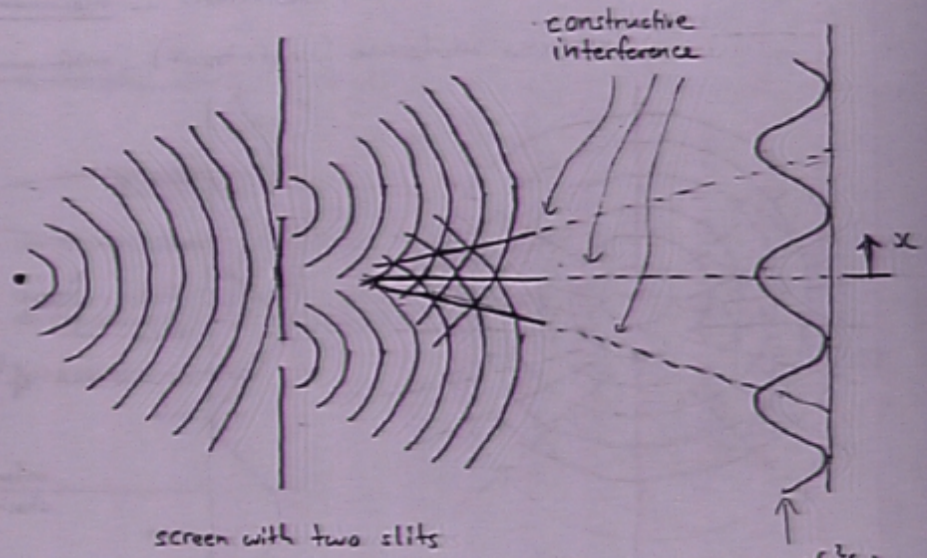


diffraction

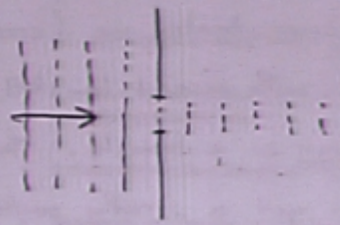
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Pirsa: 05080004

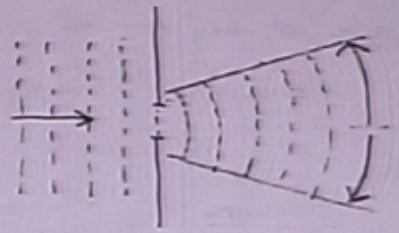
How to Make a Water Wave Interfere with Itself



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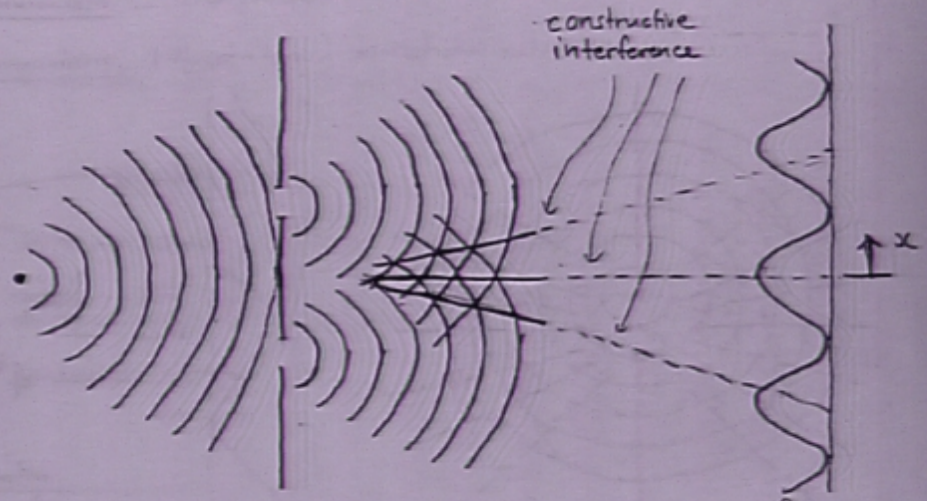


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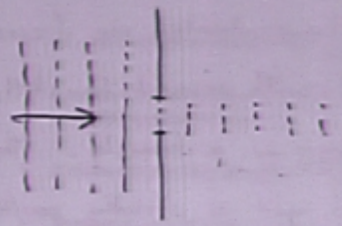
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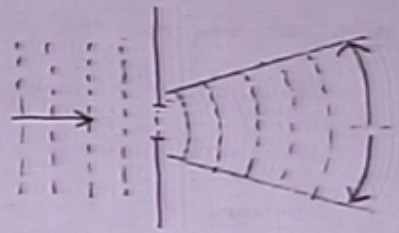
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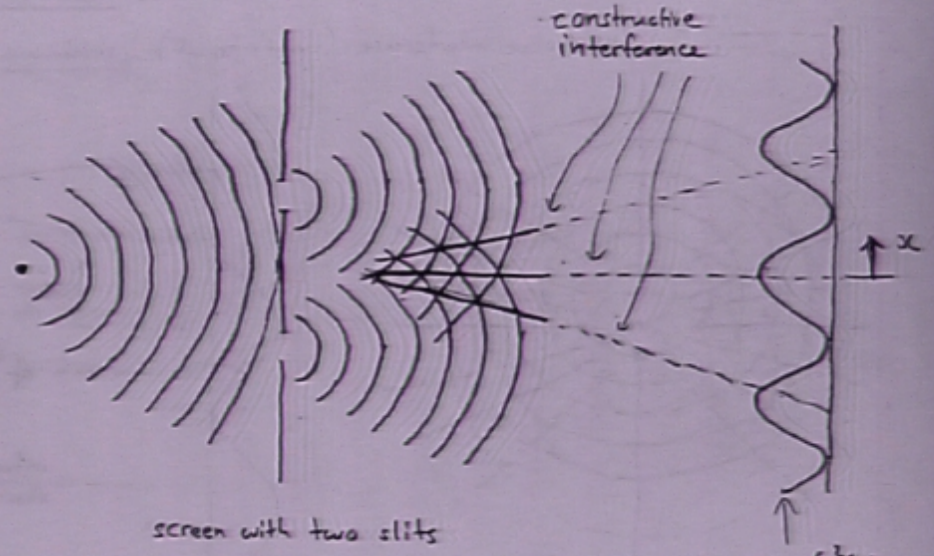


diffraction

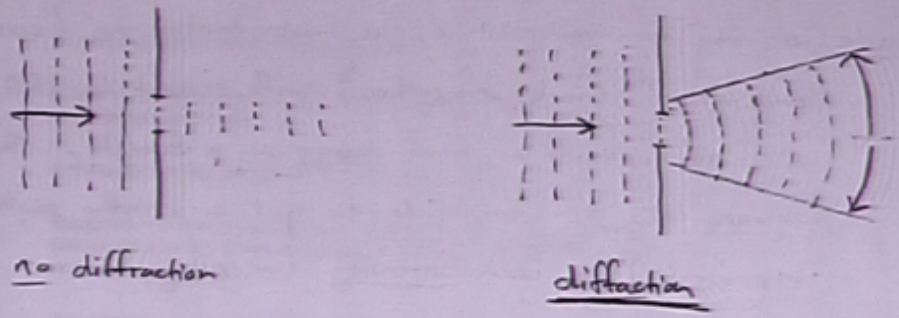
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How to Make a Water Wave Interfere with Itself

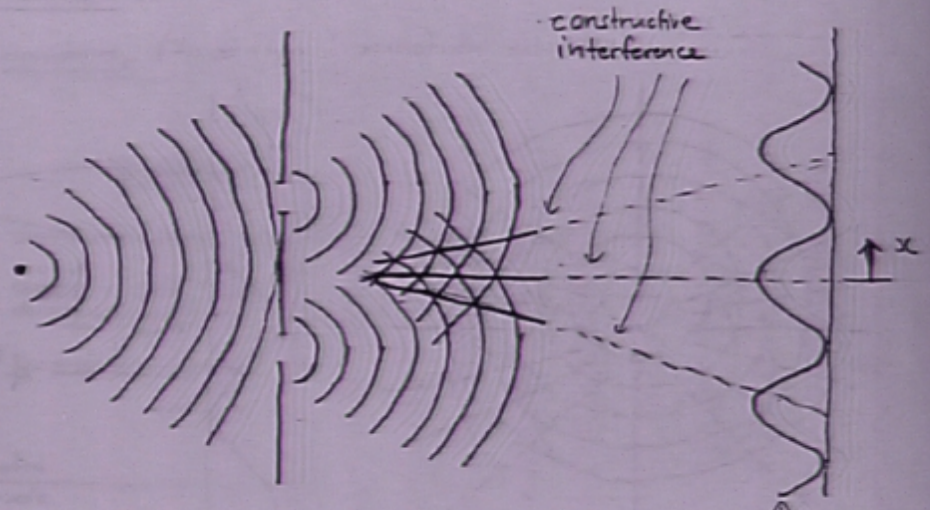


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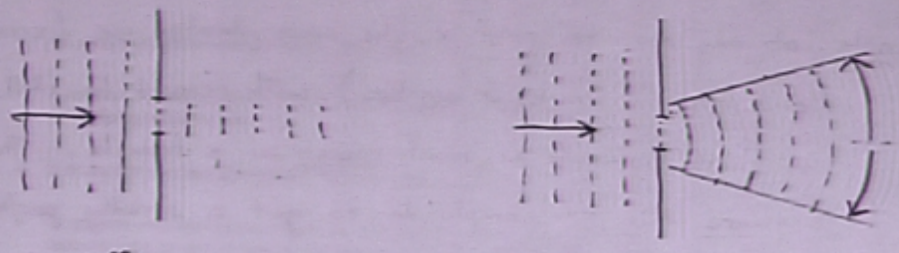


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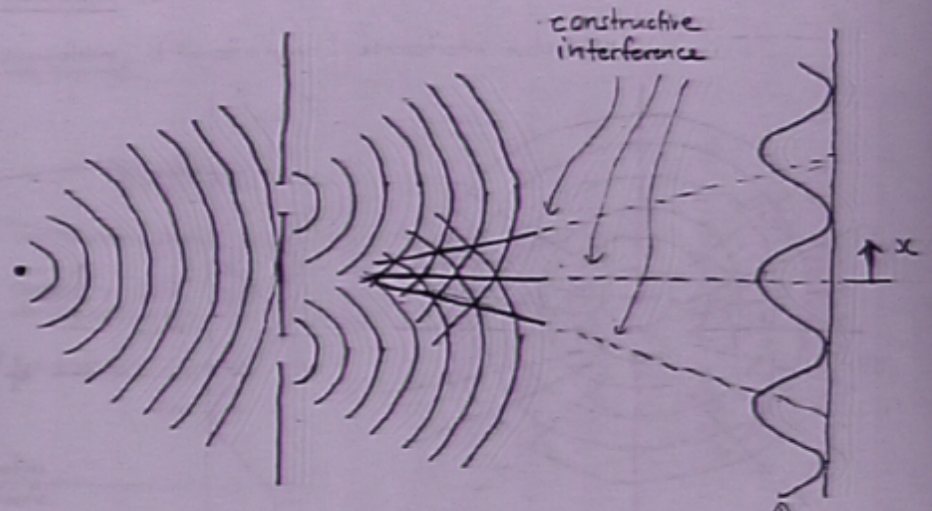


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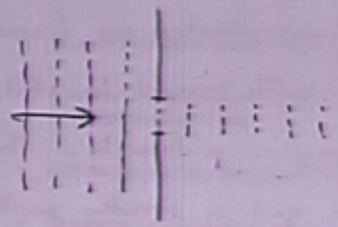


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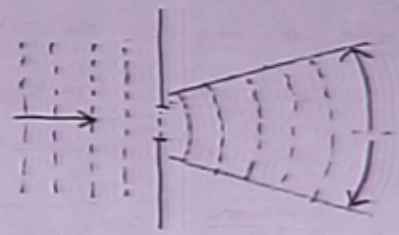
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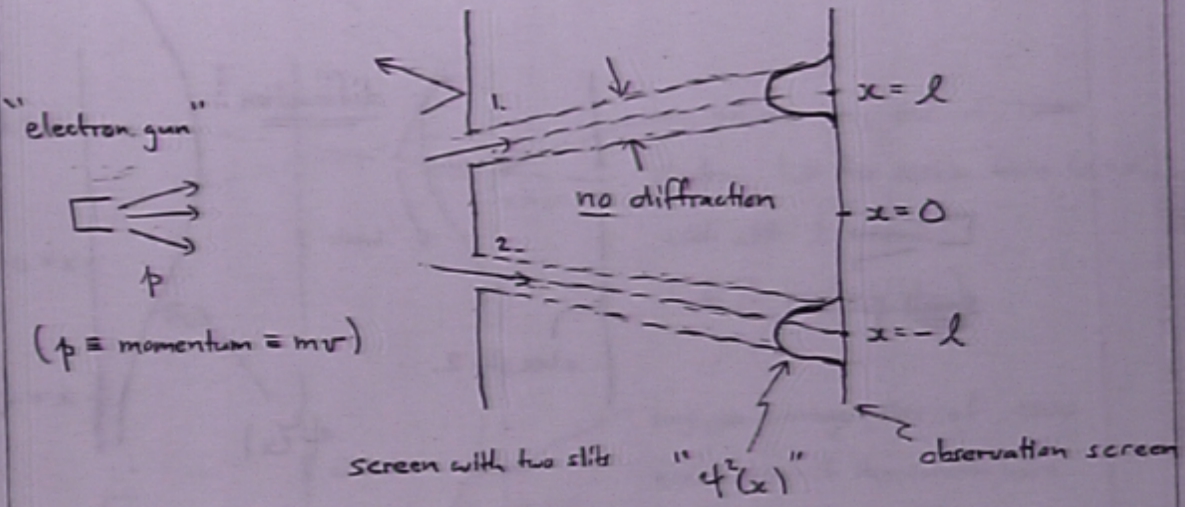


diffraction

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Pirsa: 05080004

Double Slit Experiment with Electrons (or any other "elementary particle")

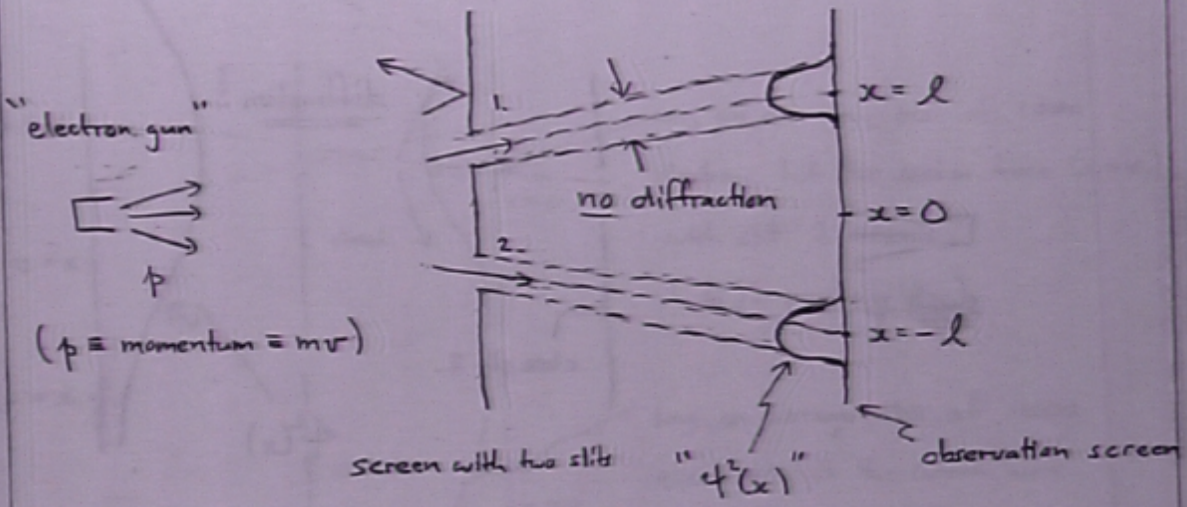


- The electron gun emits electrons of momentum p in random directions towards the screen.
- Of those electrons that pass through the screen, on average, half will pass through slit 1. (and hit the second screen near $x = +\ell$), the other half through slit 2. (hitting near $x = -\ell$) ---this is how we expect particles to behave, and this is what we observe (under "usual" circumstances)

NB: In this case "$\psi^2(x)$" can be thought of as a measure of the probability an electron will hit the observation screen at point x: basically, zero probability except near $x = \pm\ell$, and equal probability near $x = +\ell$ or $-\ell$. (Probability will be very important in what follows).

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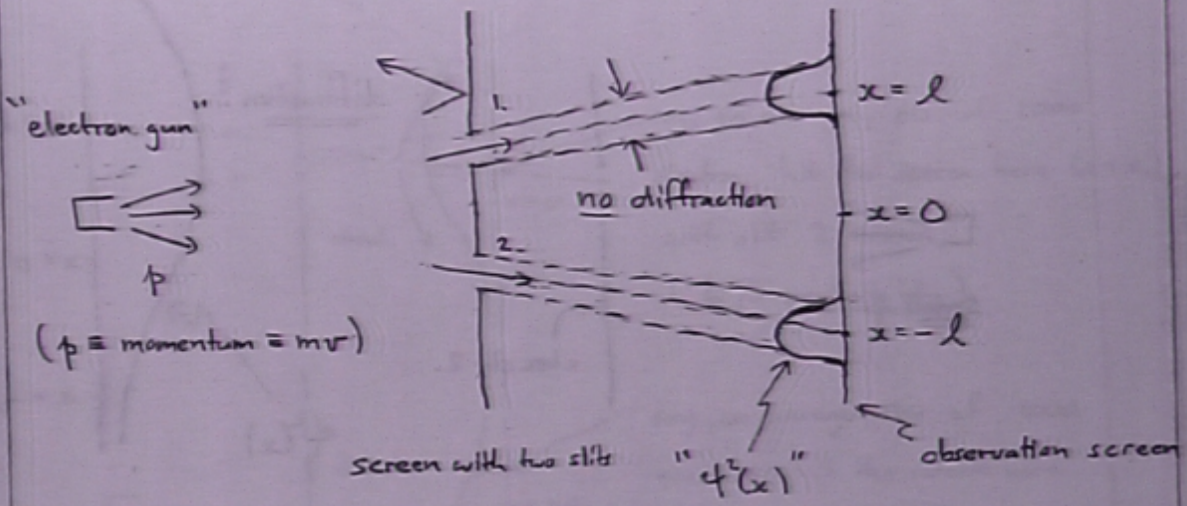


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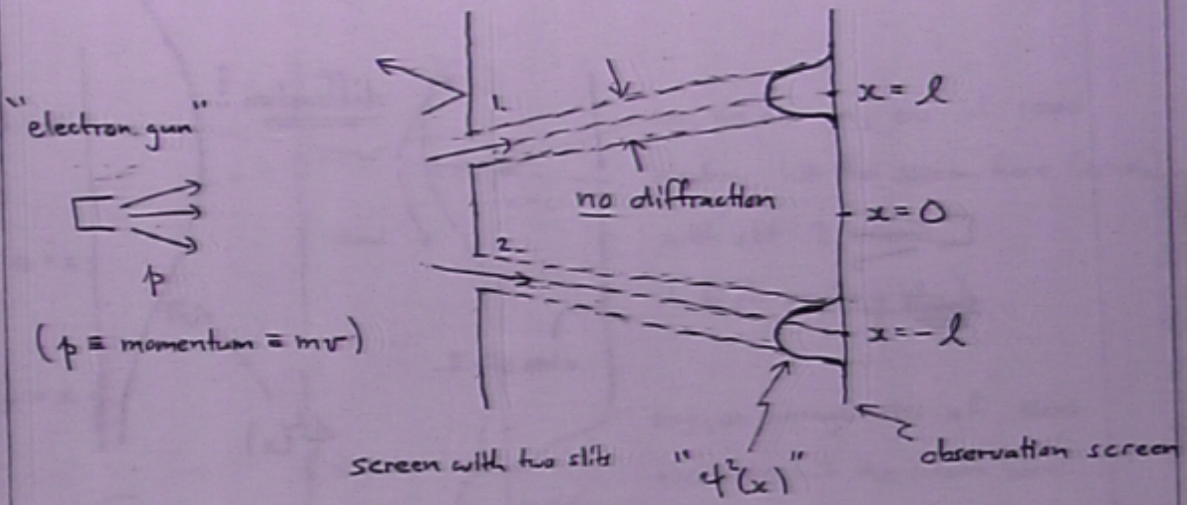


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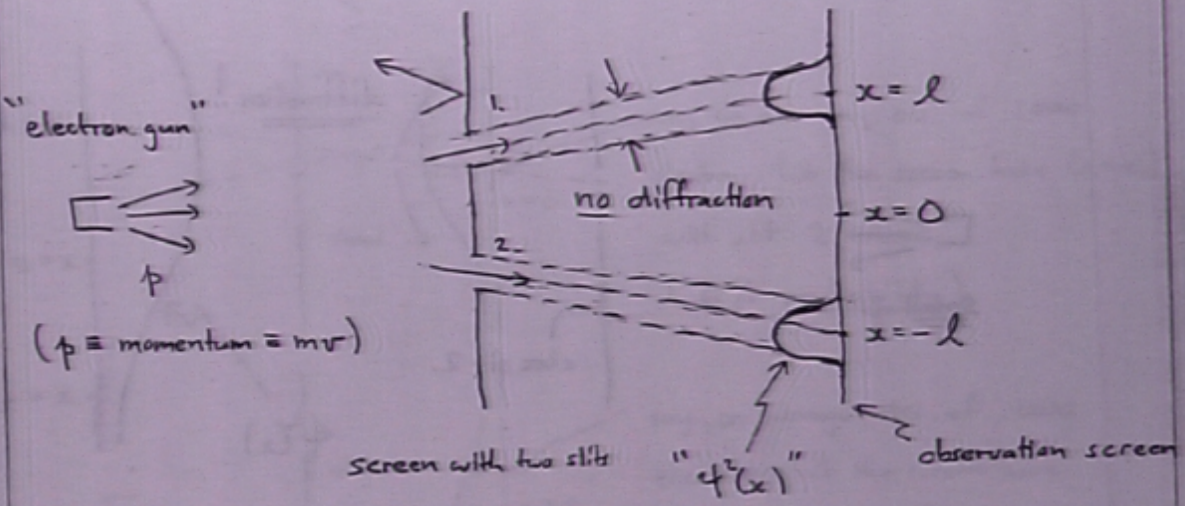


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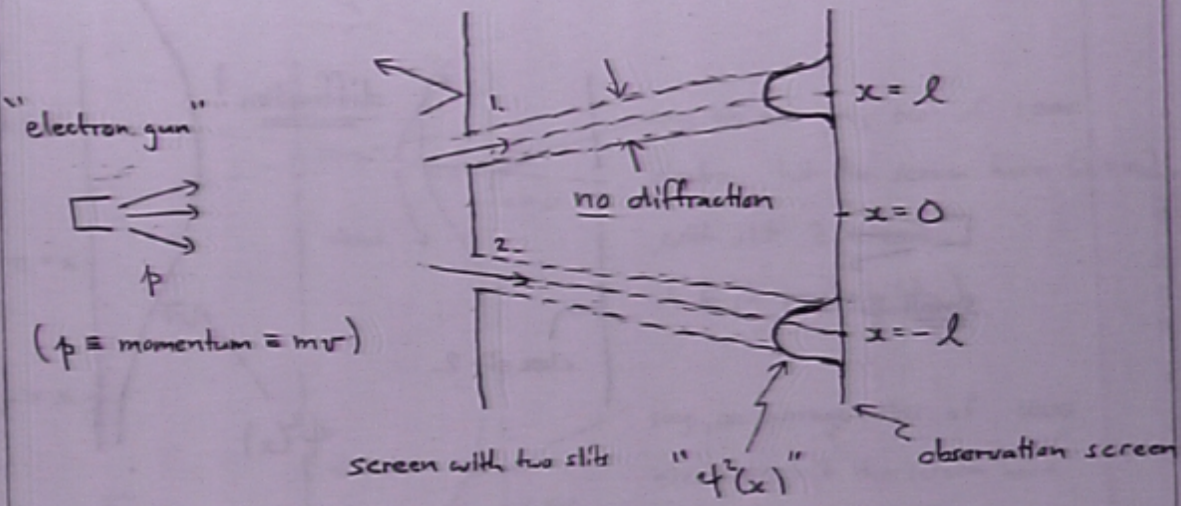


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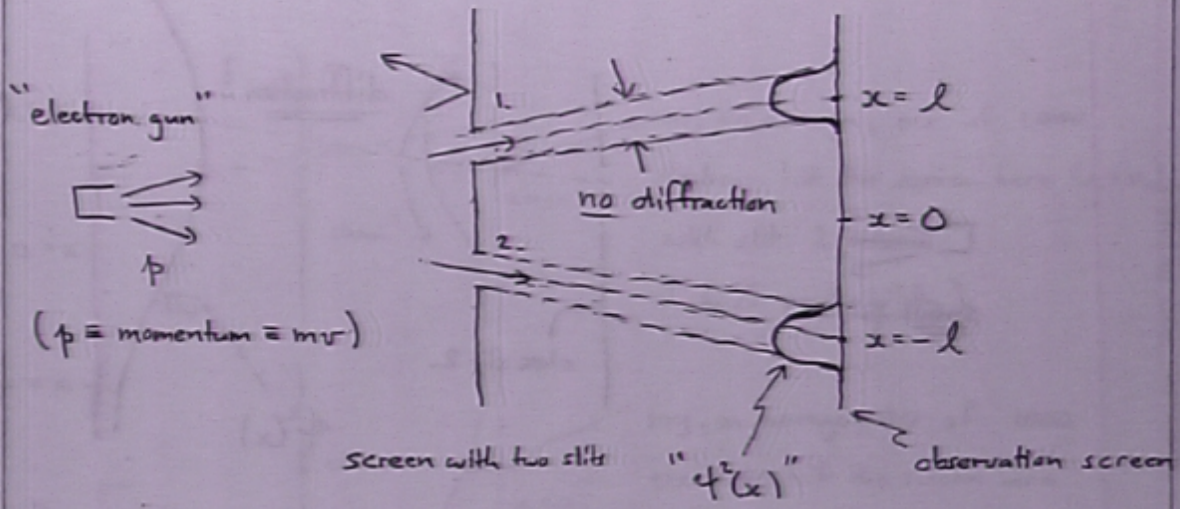


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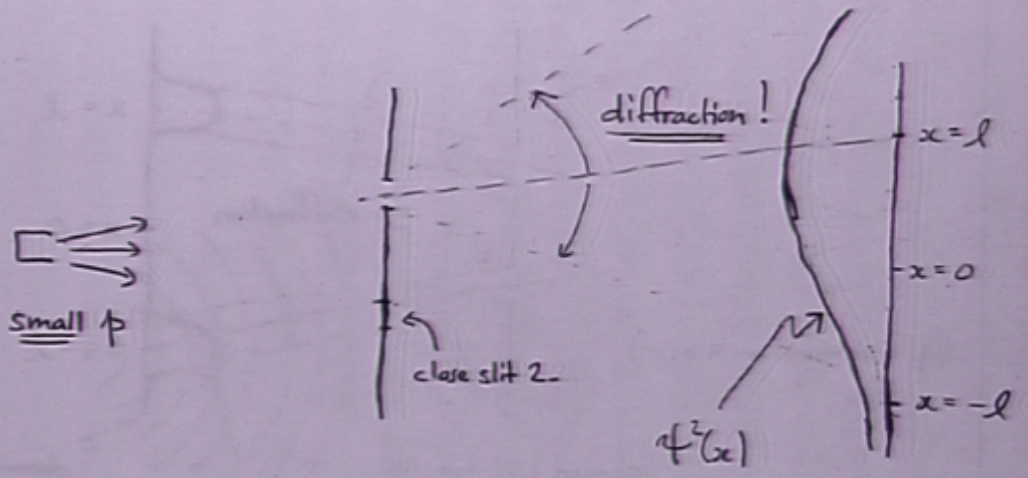


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Pirsa: 05080004

Turn the Momentum Down (smaller p), and Close One Slit

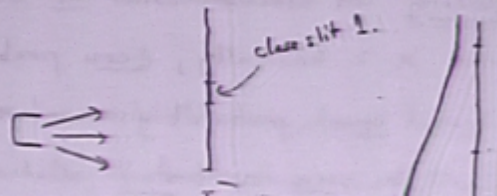


The electrons randomly hit the observation screen, but now over a wider range (than expected)
— they still hit most often near $x = +\ell$ (expected particle behaviour)
— but with smaller p they now frequently hit points quite far away from $x = +\ell$ (unexpected behaviour for particles)

— very reminiscent of wave diffraction (!?)

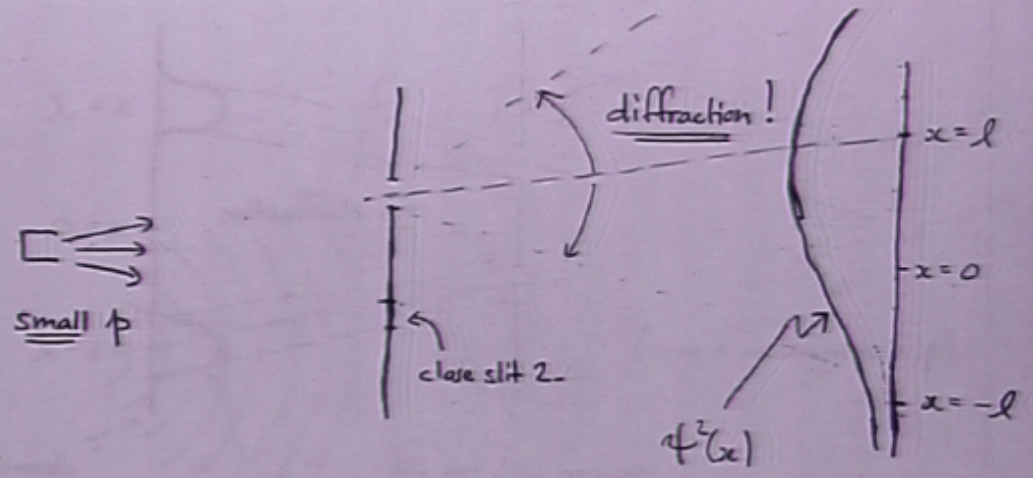
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Similarly, repeating with slit 1 closed we get:



Page 113/137

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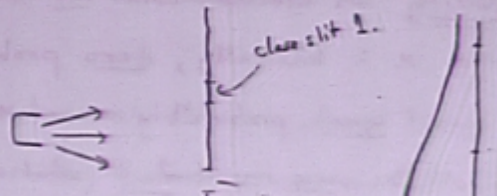


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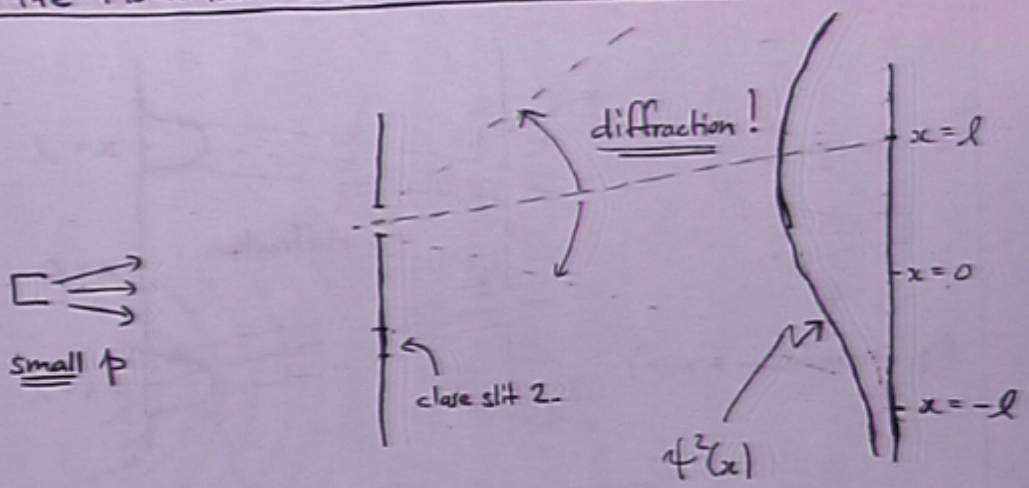
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Pirsa: 05080004

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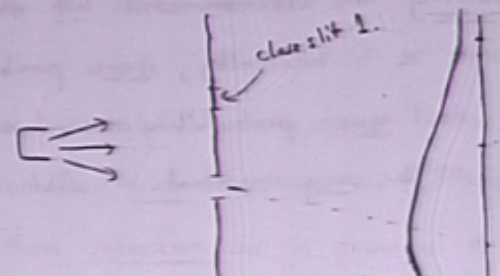
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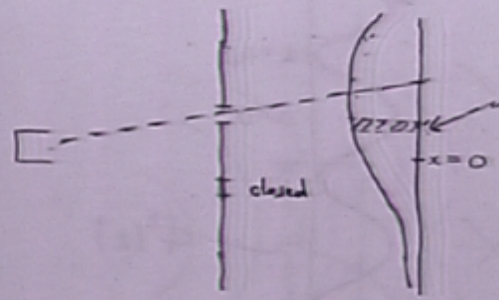
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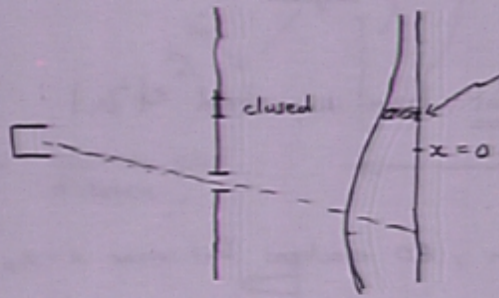


Prsa: 05080004

Probability In More Detail : Counting Electrons



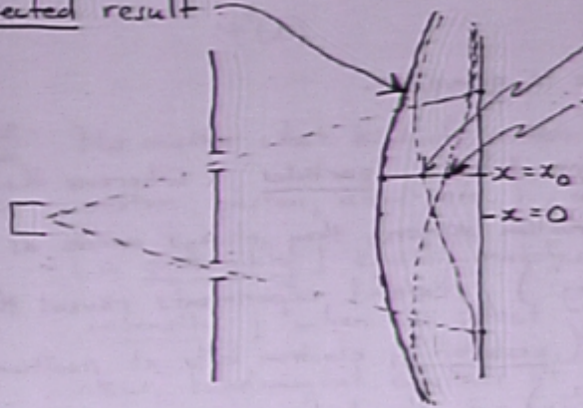
say, on average, 60 of 1000 electrons hit the screen here ($x = x_0$) with slit 2 closed. (6% probability)



say, on average, 40 of 1000 electrons hit the screen here (same point: $x = x_0$) with slit 1 closed. (4% probability)

Now Open BOTH Slits

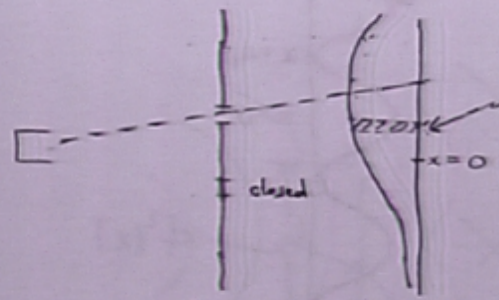
expected result



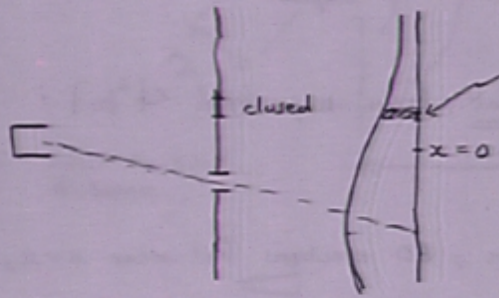
60 passing through slit 1.
+ 40 passing through slit 2.
= 100 electrons total hitting near $x = x_0$

ie. let 2000 electrons total pass through the first screen. About half (1000) will pass through slit 1, of which 6% (60) will hit x_0,

Probability in More Detail: Counting Electrons



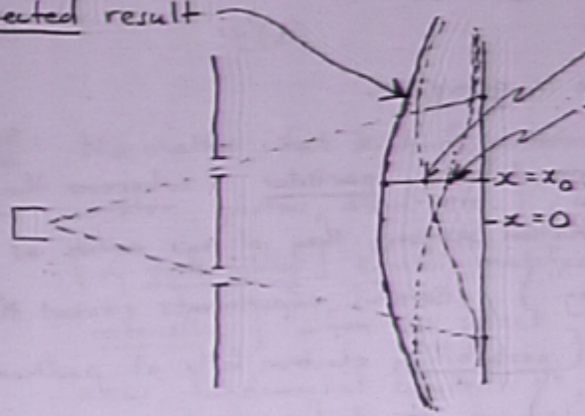
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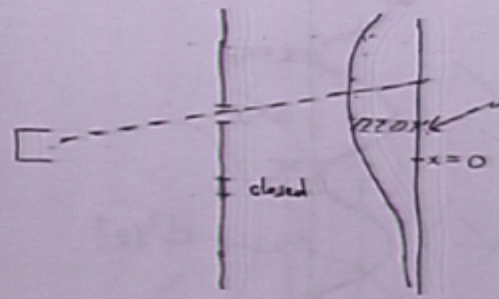


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Pirsa: 05080004

Probability in More Detail : Counting Electrons



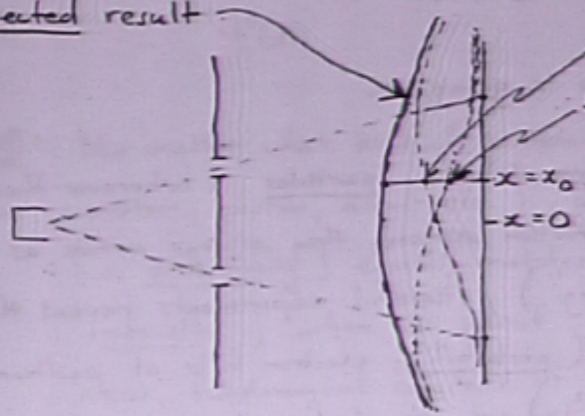
say, on average, 60 of 1000 electrons hit the screen here ($x = x_0$) with slit 2 closed. (6% probability)



say, on average, 40 of 1000 electrons hit the screen here (same point: $x = x_0$) with slit 1 closed. (4% probability)

Now Open BOTH Slits

expected result

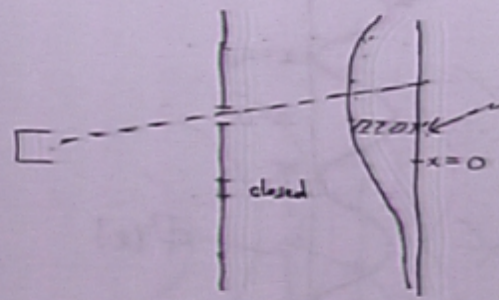


60 passing through slit 1.
+ 40 passing through slit 2.
= 100 electrons total hitting near $x = x_0$

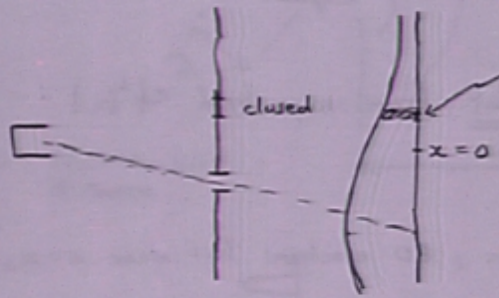
i.e. let 2000 electrons total pass through the first screen. About half (1000) will pass through slit 1, of which 6% (60) will hit x_0,

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Probability in More Detail: Counting Electrons



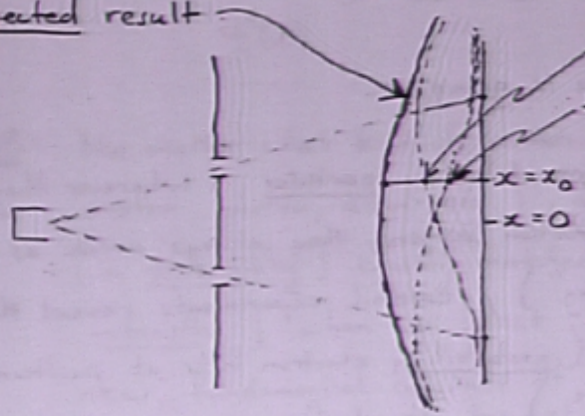
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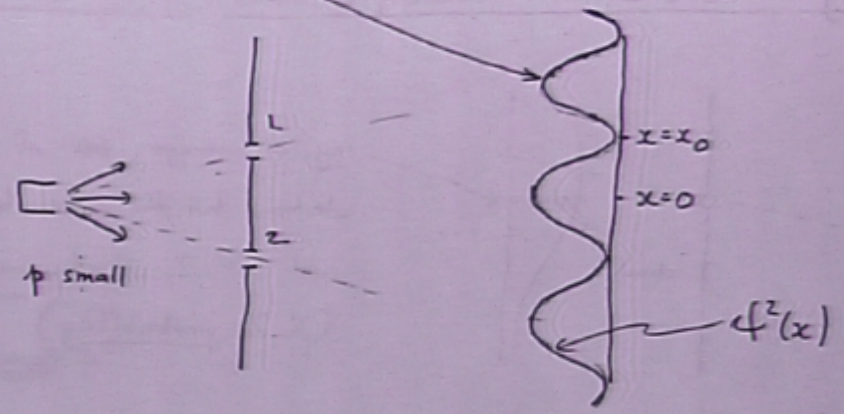


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actual result



- actual $f^2(x)$ is totally different from expected $f^2(x)$!!

Most striking is the fact that:

a) With just slit 1 open, 60 electrons hit near $x = x_0$

b) " " " 2 " , 40 " " " "

c) With both slits open, zero electrons hit near $x = x_0$!?

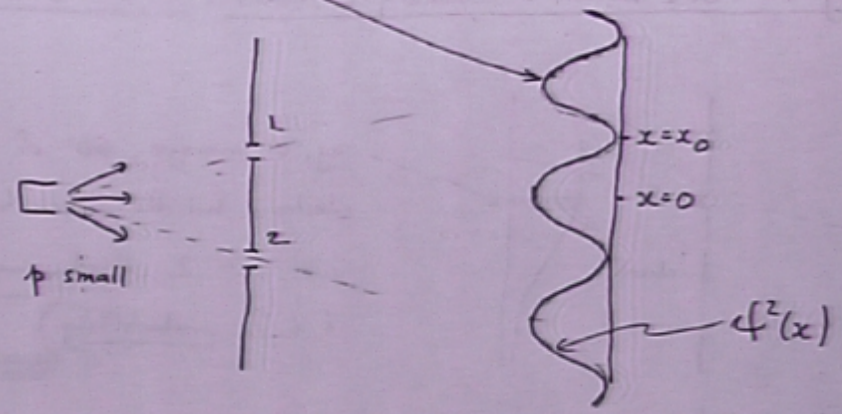
--- shouldn't it be 60+40 = 100 ?

-- something extremely strange is going on.

NB: even though electrons are definitely particles (wherever they happen to hit the observation screen, they always arrive as a tiny lump of "something"), careful experiments reveal that the observed $f^2(x)$ (probability electron hits at position x) is identical to the $f^2(x)$ we found for a water wave (or any other type of wave) interfering with itself !!

Page 120/137

actual result



- actual $\psi^2(x)$ is totally different from expected $\psi^2(x)$!!

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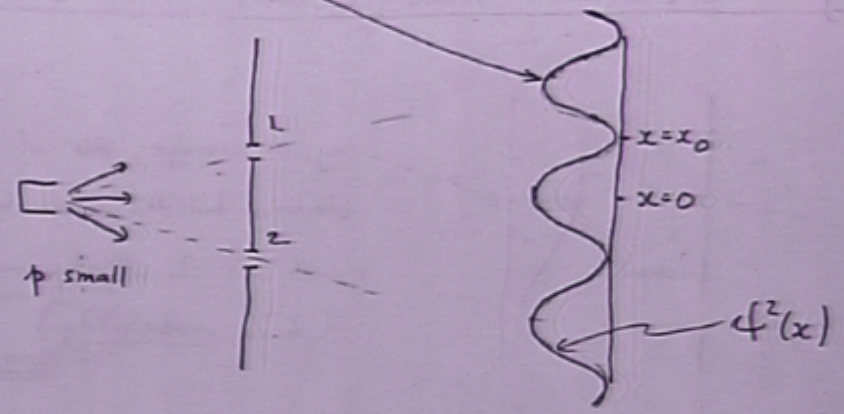
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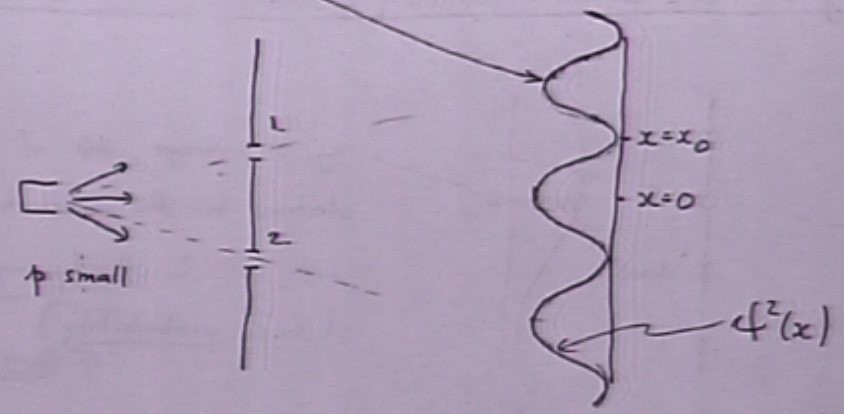
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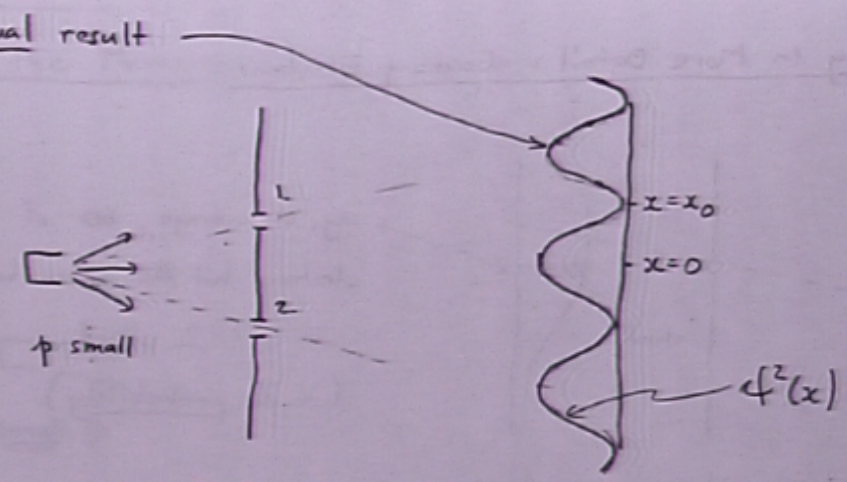
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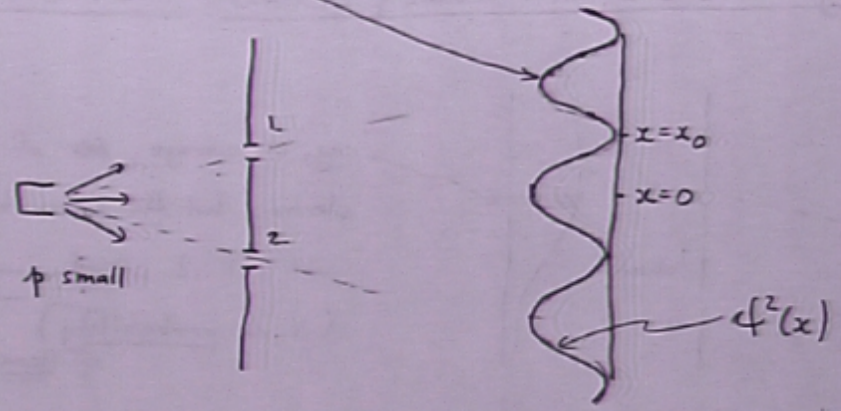
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actual result



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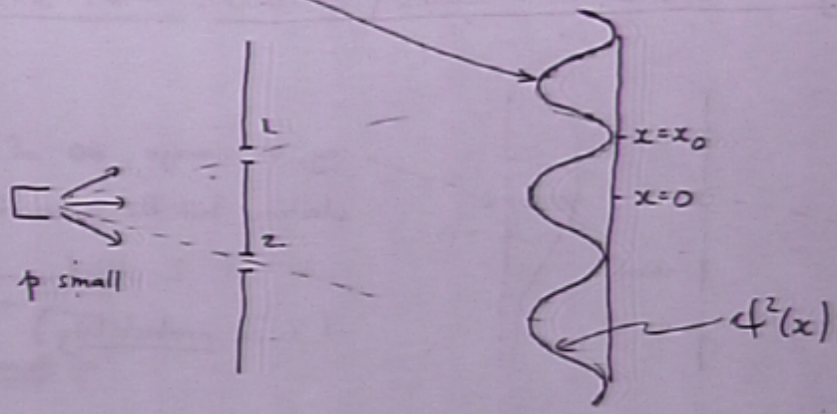
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22·141 50 SHEETS
22·142 100 SHEETS
22·144 200 SHEETS
EXACT

actual result



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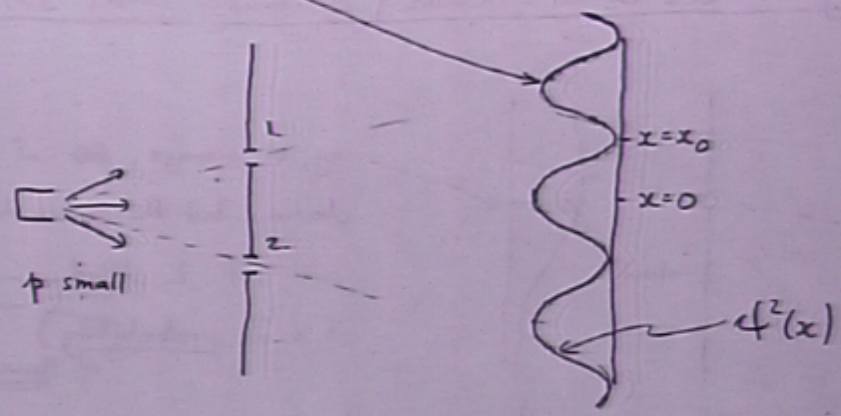
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Pirsa: 05080004



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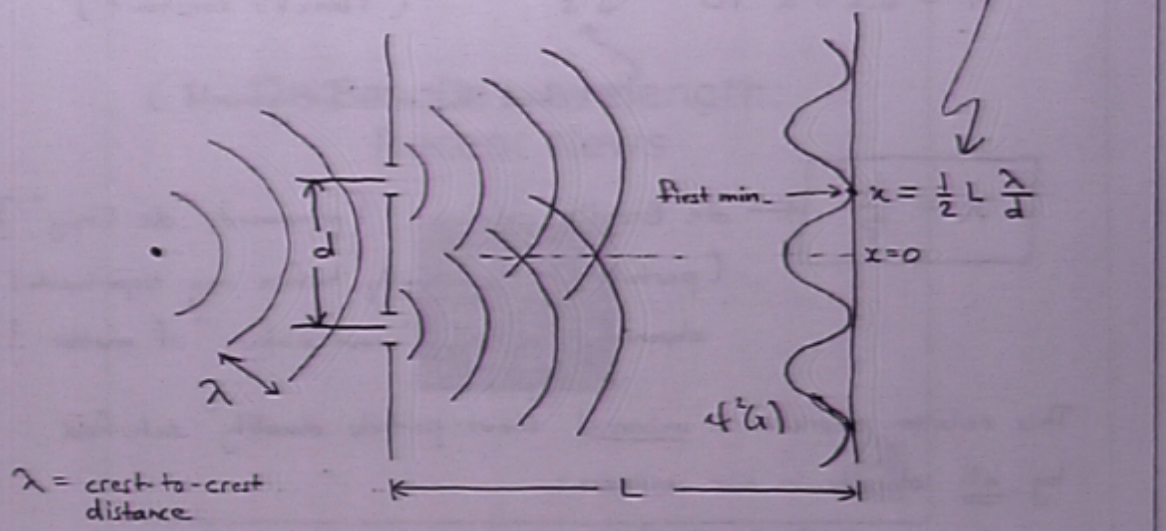
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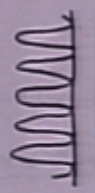
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fact (exercise)



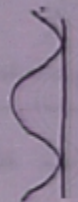
λ = crest-to-crest distance

small λ :



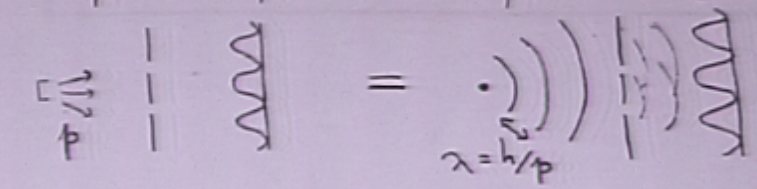
ψ²(x)

large λ :

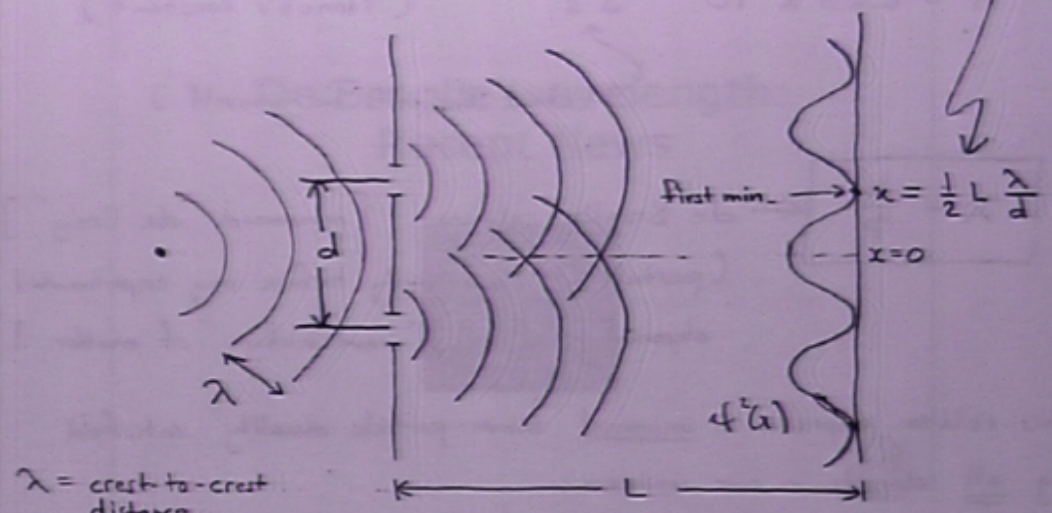


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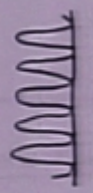


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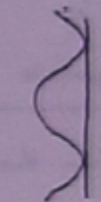
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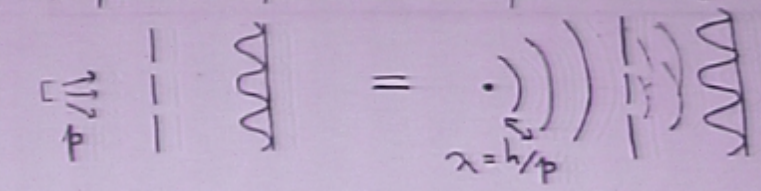
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A huge number of independent experiments reveal that h has the value:

$$h = 6.63 \times 10^{-34} \text{ J·s}$$ (Planck's constant)

(check the units for yourself)

$$\boxed{\lambda = \frac{h}{p}}$$ ← de Broglie relation [pronounced "de Broy"]

(postulated theoretically before any experimental observations of the "wave nature" of matter !)

This relation expresses a universal "wave-particle duality" satisfied by all objects in our universe:

$$\lambda \, p = h$$

wave particle quantum

ie. Quantum theory is a consistent unification of wave and particle concepts.

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GAMPAD 22-144 200 SHEETS

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