

Title: Quantum 1

Date: Jul 24, 2008 10:30 AM

URL: <http://pirsa.org/08070035>

Abstract:

Single Slit Expt.

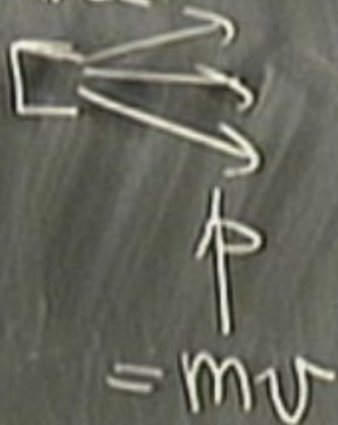
Single Slit Expt.

electron
source



Single Slit Expt.

electron
source



Single Slit Expt.

electron
source



Single Slit Expt.

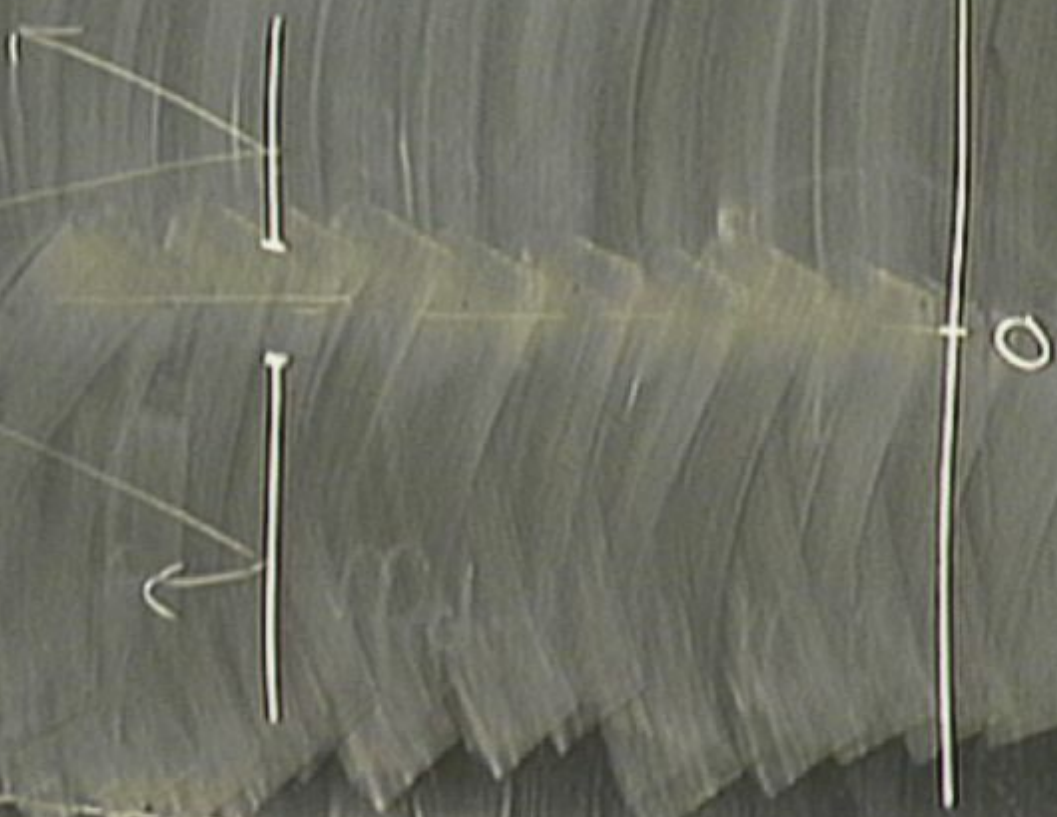
electron
source



Single Slit Expt.

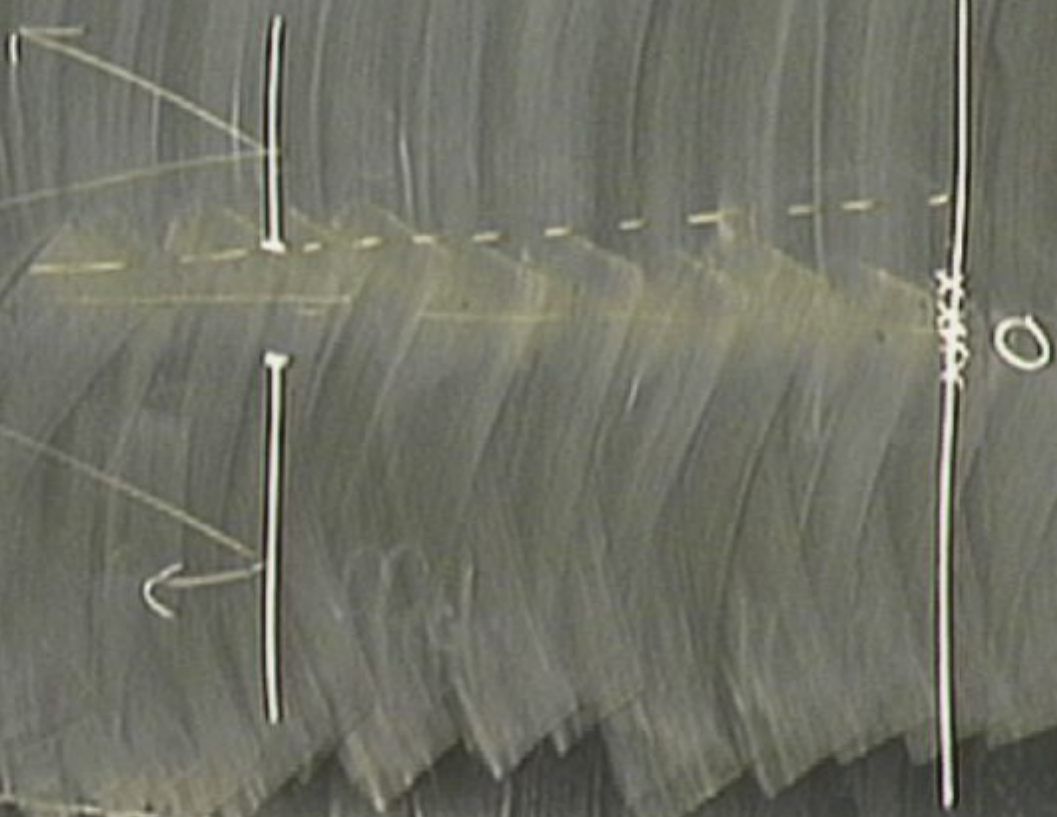
electron
vrce

$$p = mv$$



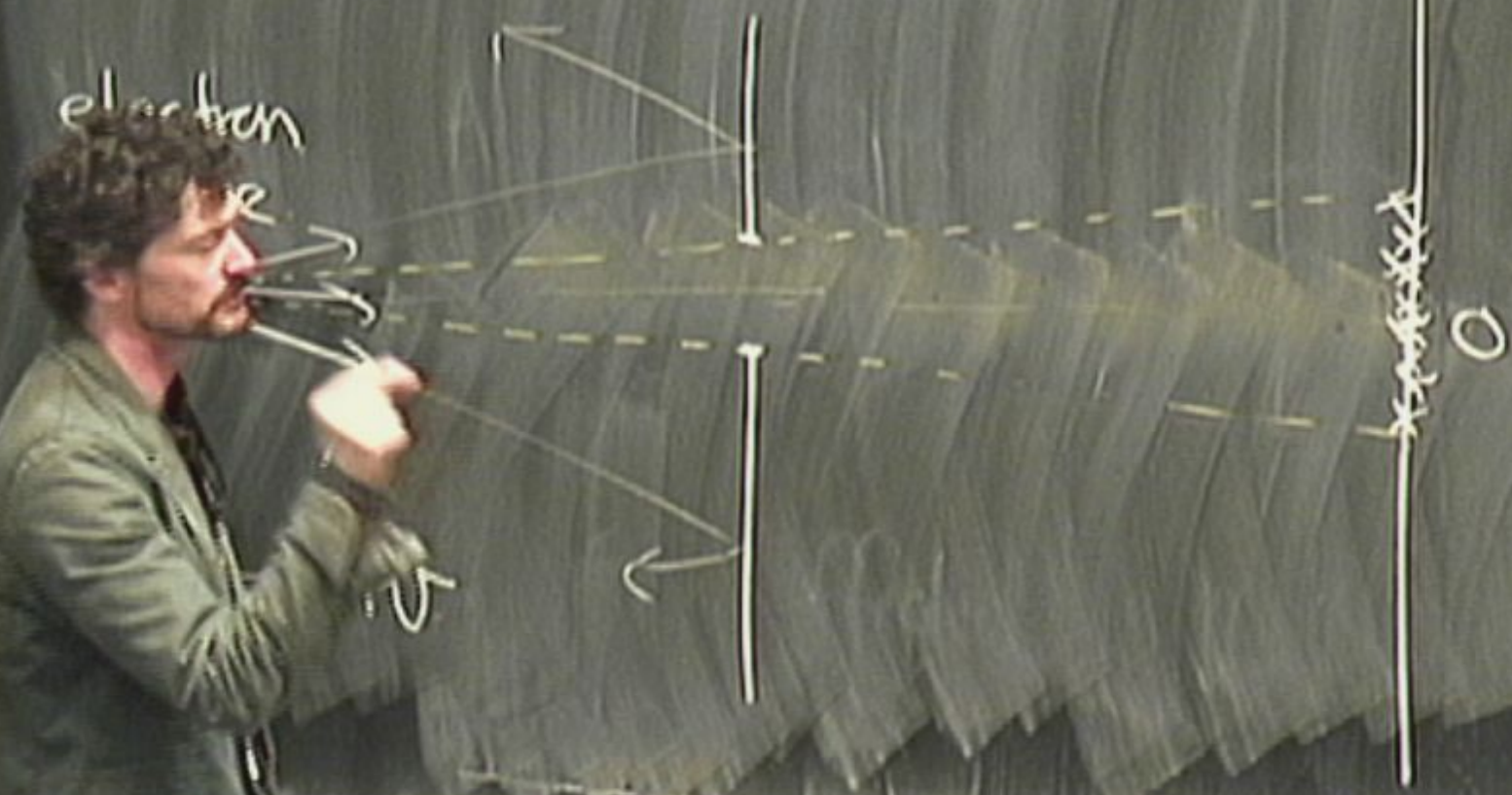
Single Slit Expt.

electron source



Single Slit Expt.

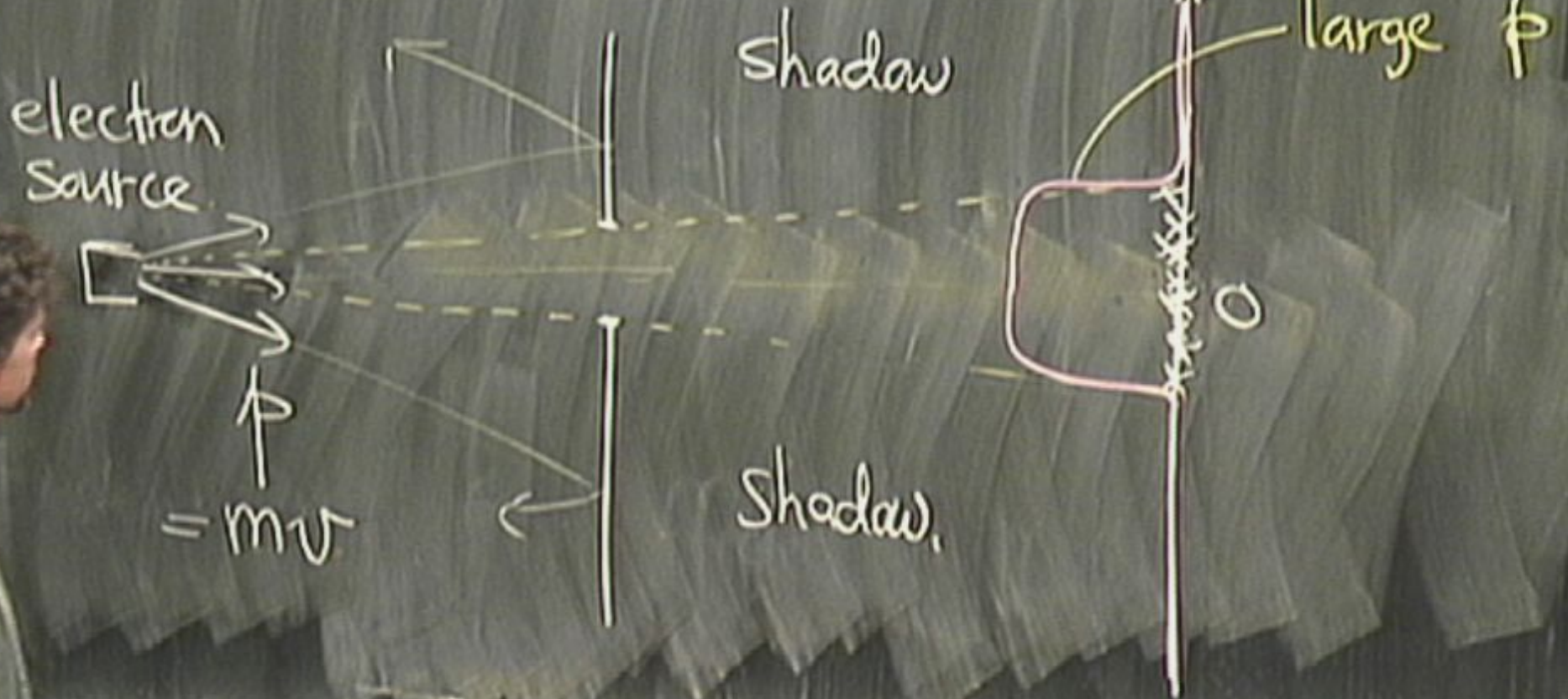
electron



Single Slit Expt.



Single Slit Expt.

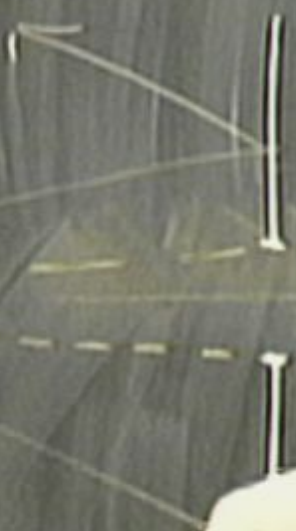


Single Slit Expt.

electron source



p
 $= mv$

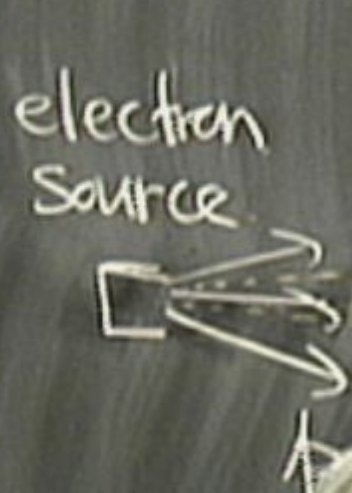


Shadow



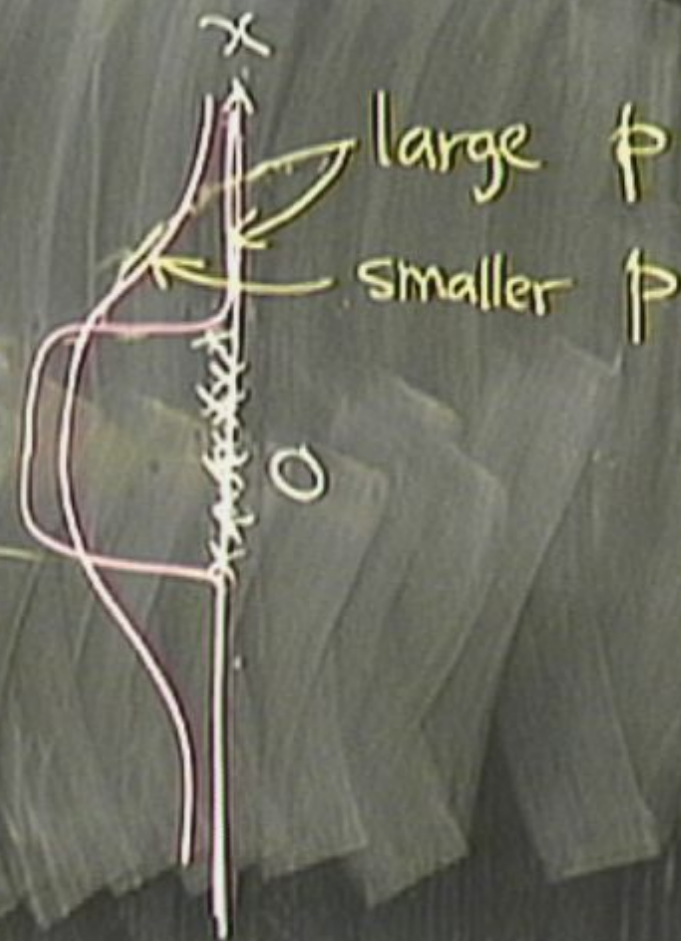
large p

Single Slit Expt.

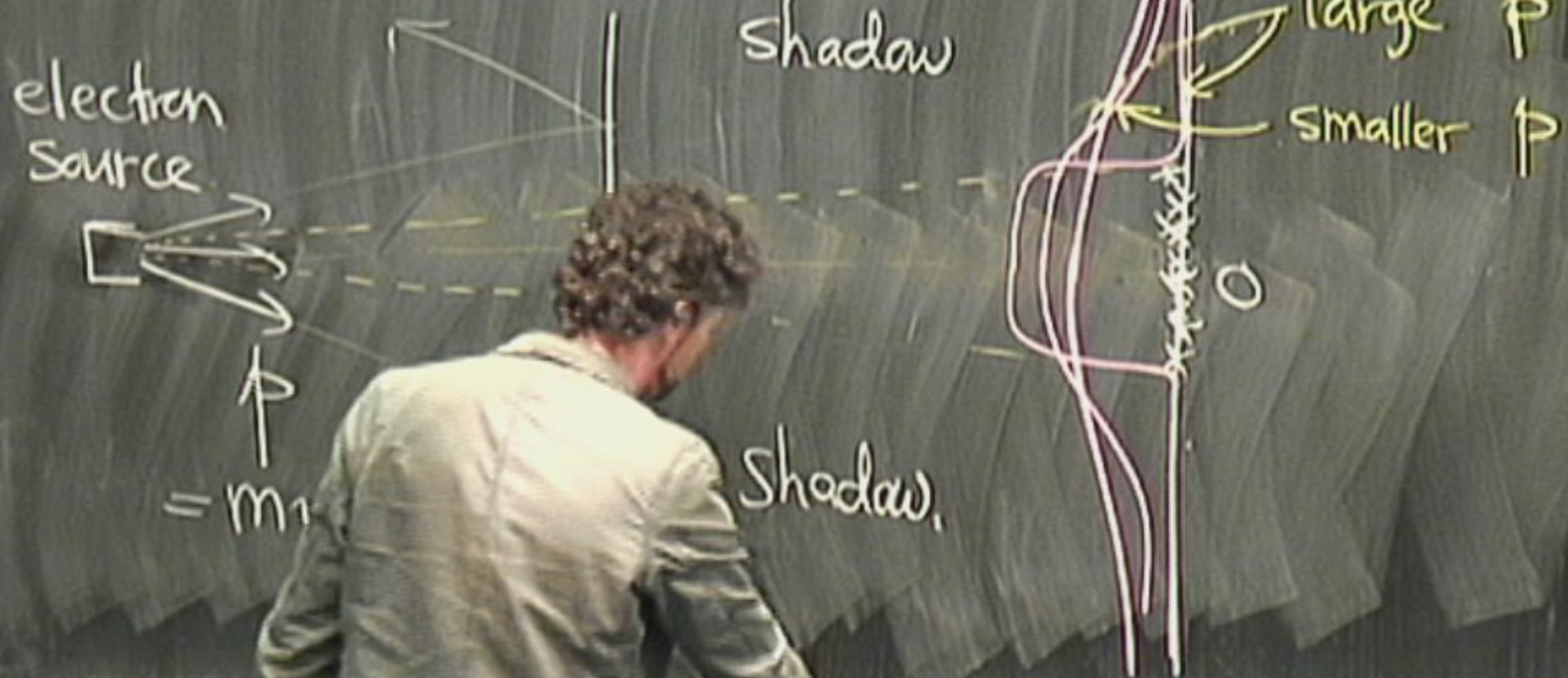


Shadow

Shadow



Single Slit Expt.

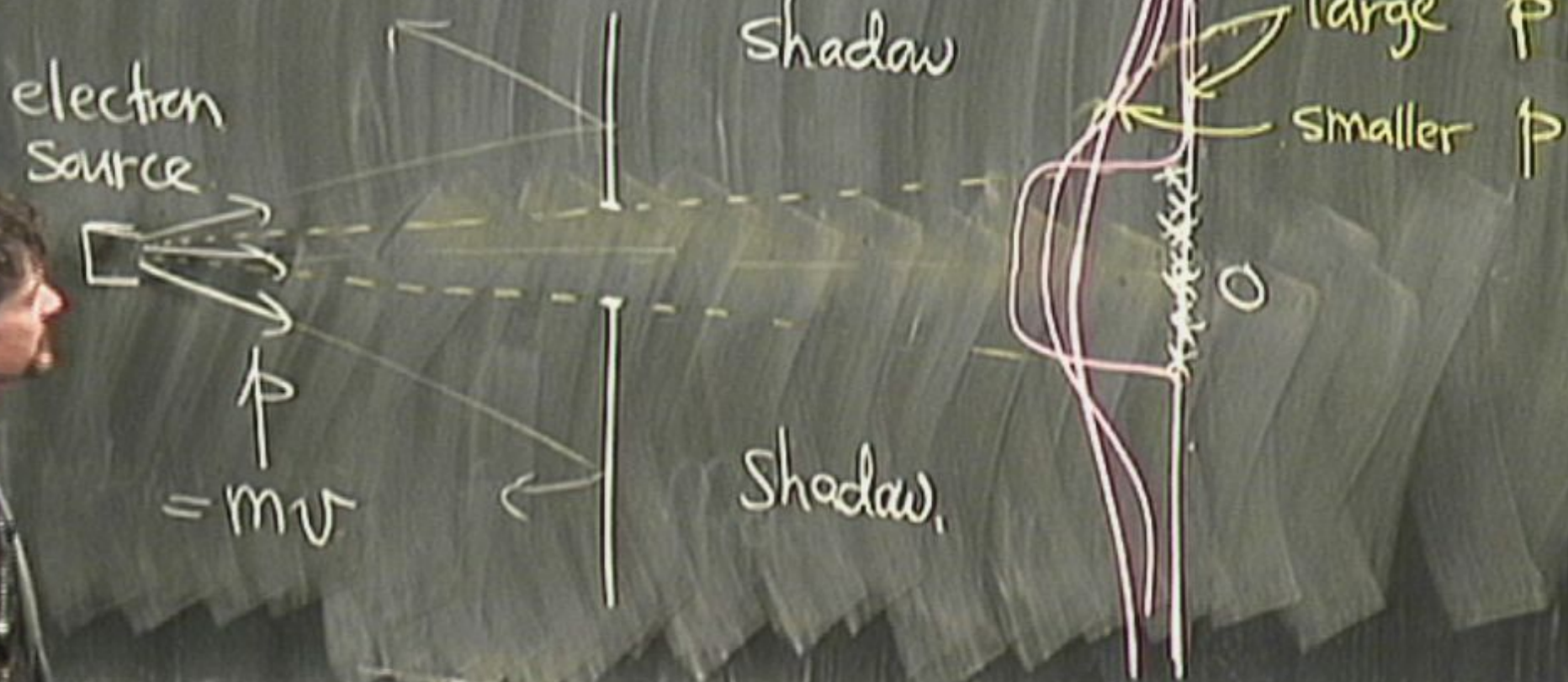


electron source
 p
 $= m_1$

Shadow
Shadow

large p
smaller p

Single Slit Expt.



Single Slit Expt.



Single Slit Expt.

electron source

Shadow

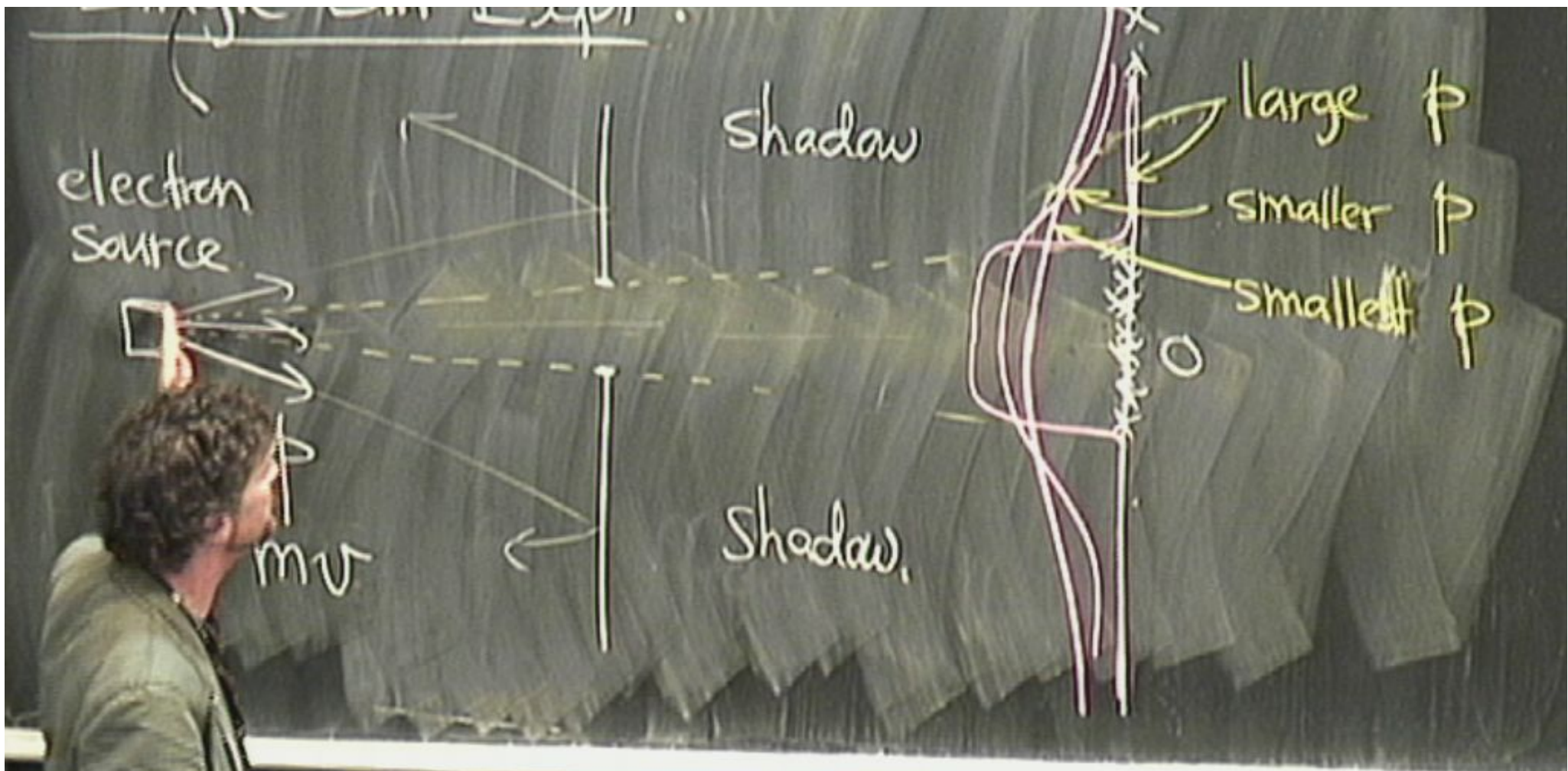
Shadow

large p

smaller p

smallest p

0



electron source

$$p = mv$$

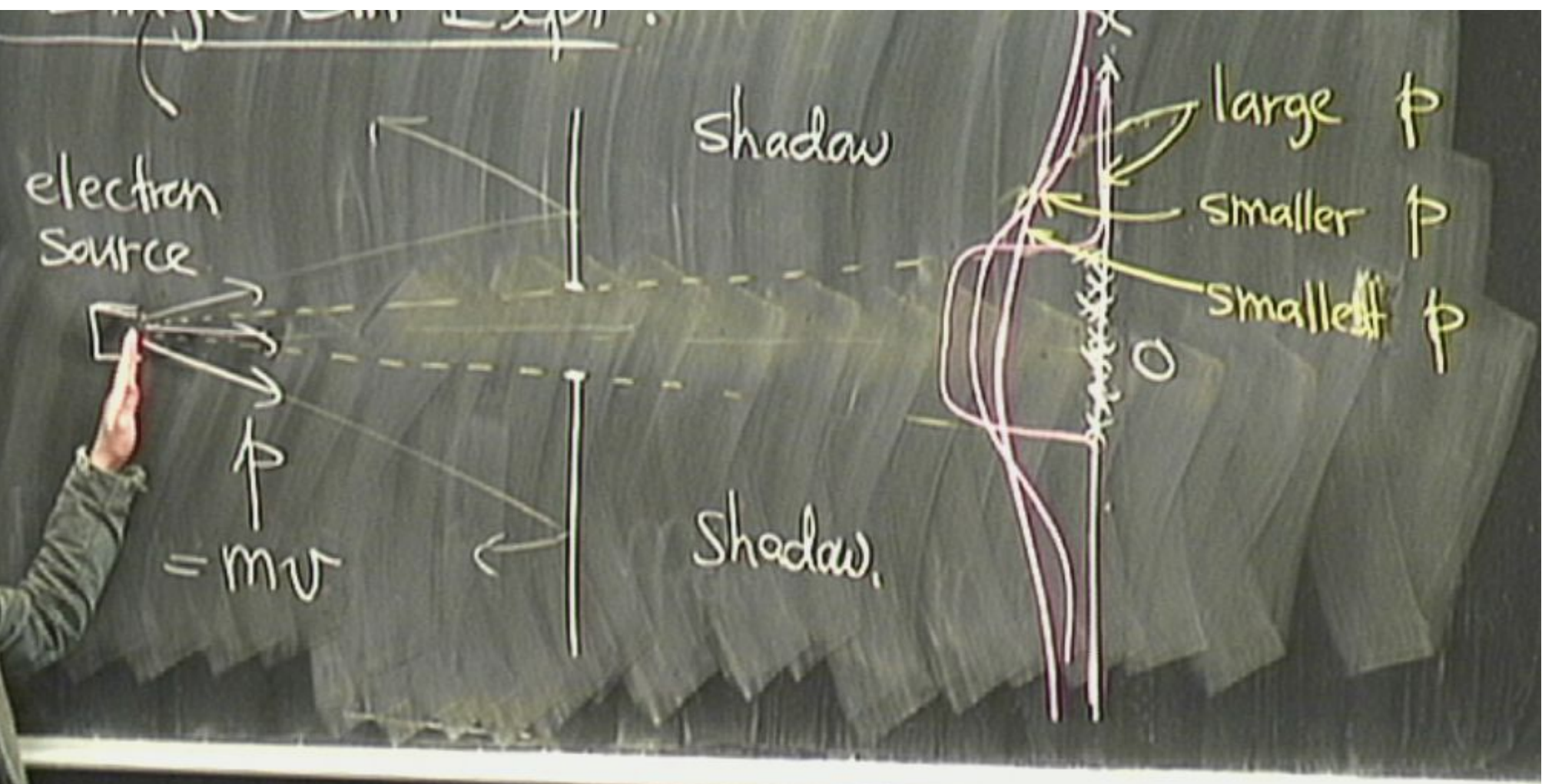
Shadow

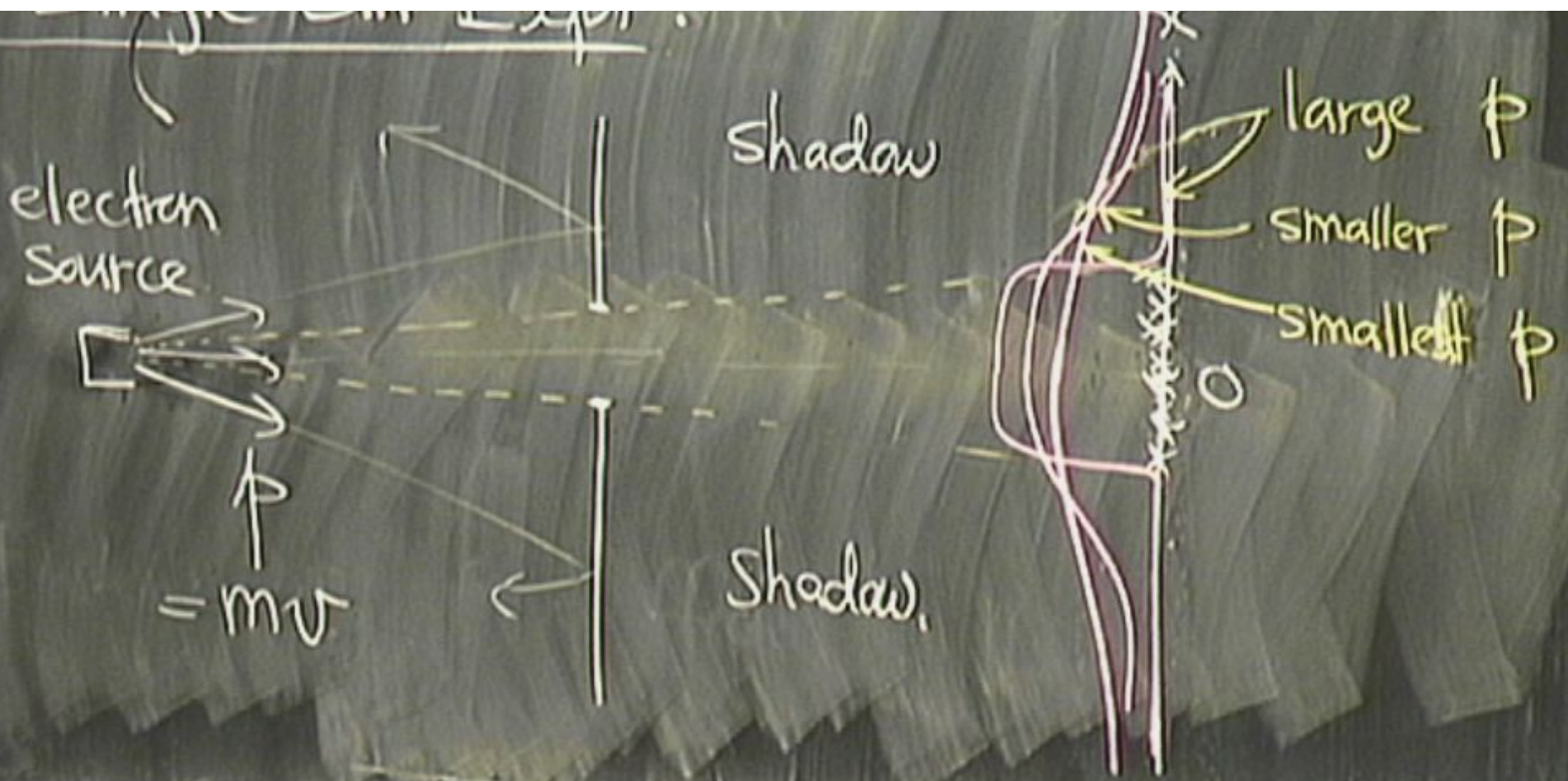
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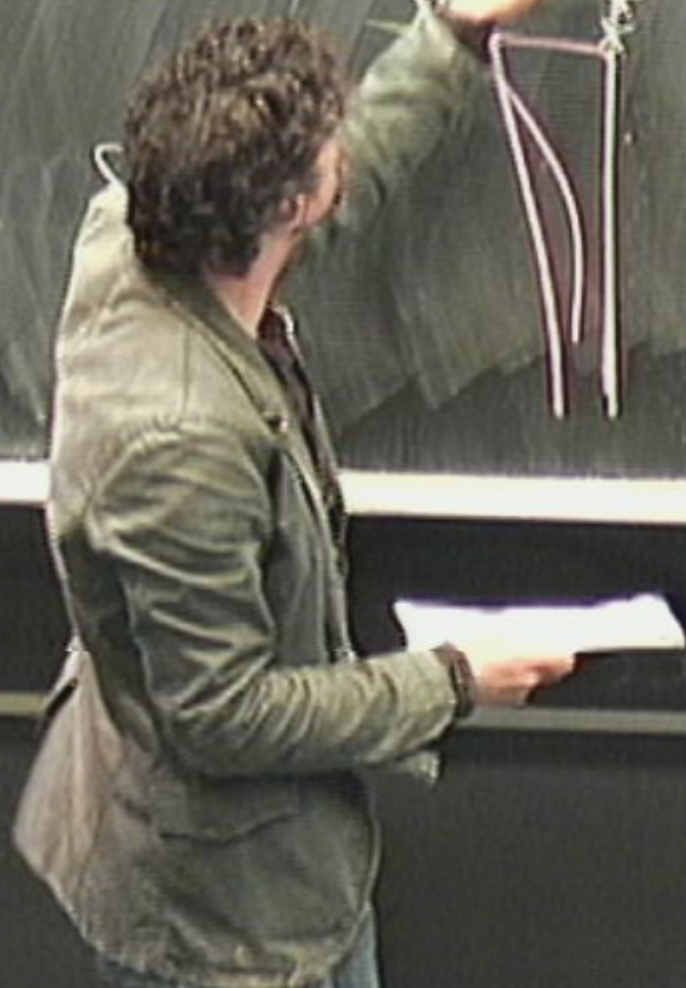
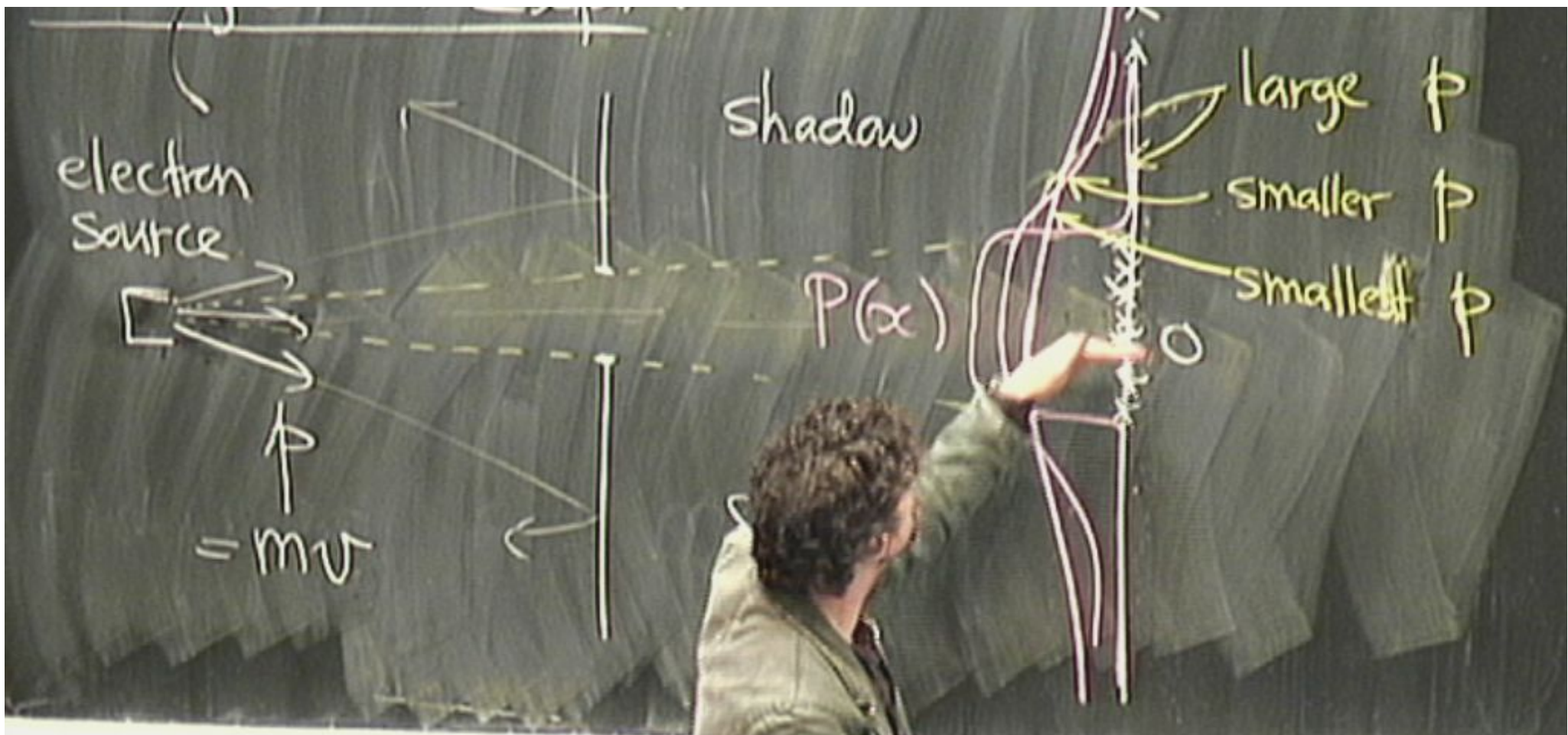
large p

smaller p

smallest p







(1) Randomness

$P(x) = \text{Probability}$

(1) Randomness

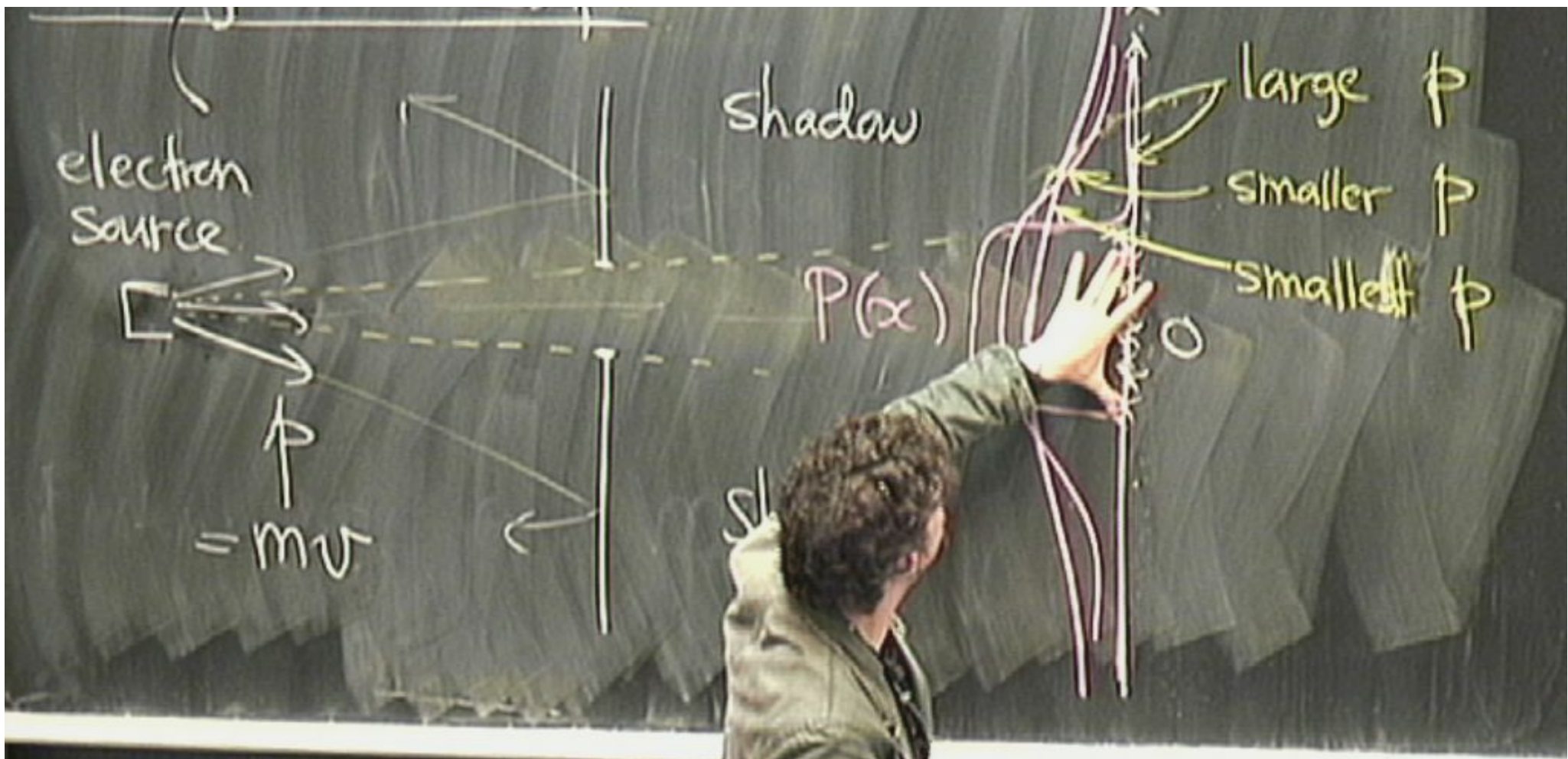
$P(x) =$ Probability

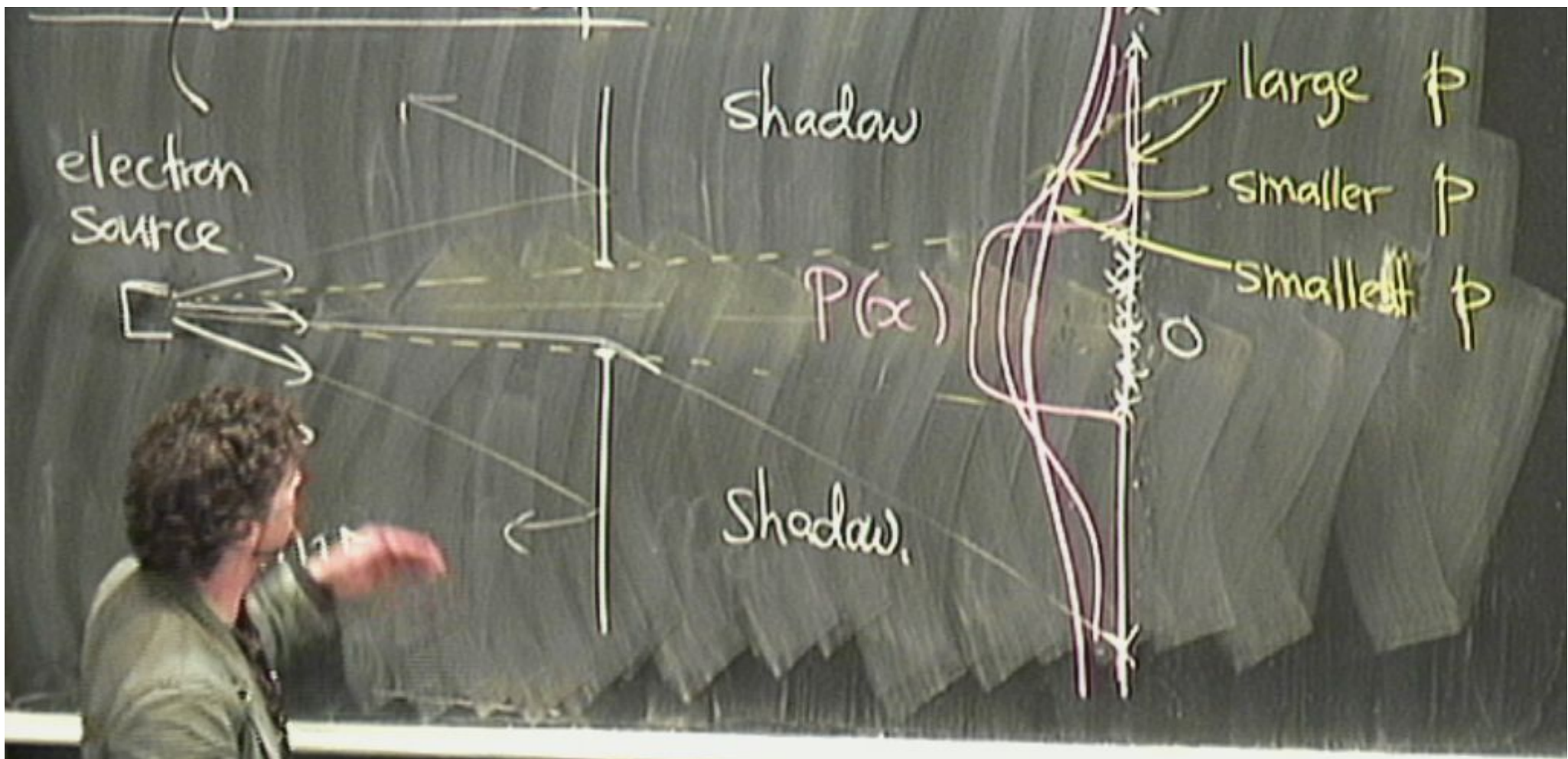
(2)

(1) Randomness

$P(x)$ = Probability

(2) Spreading of $P(x)$ as p decreases.





electron source

Shadow

$P(x)$

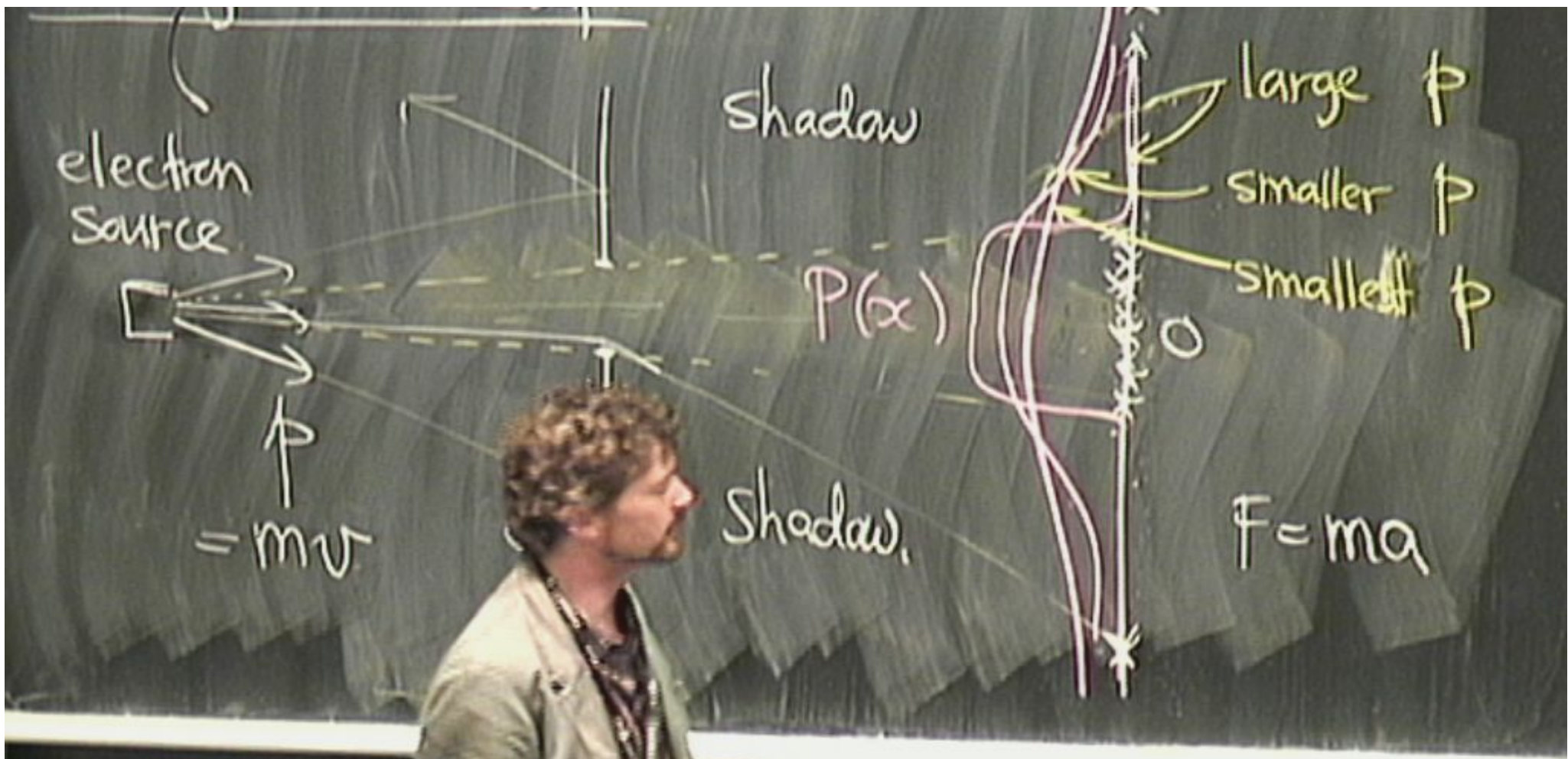
large p

smaller p

smallest p

Shadow

0



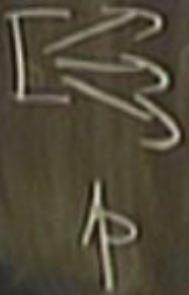
(1) Randomness

$P(x) =$ Probability

(2) Spreading of $P(x)$ as p decreases.

Double Slit Expt.

Double Slit Expt.



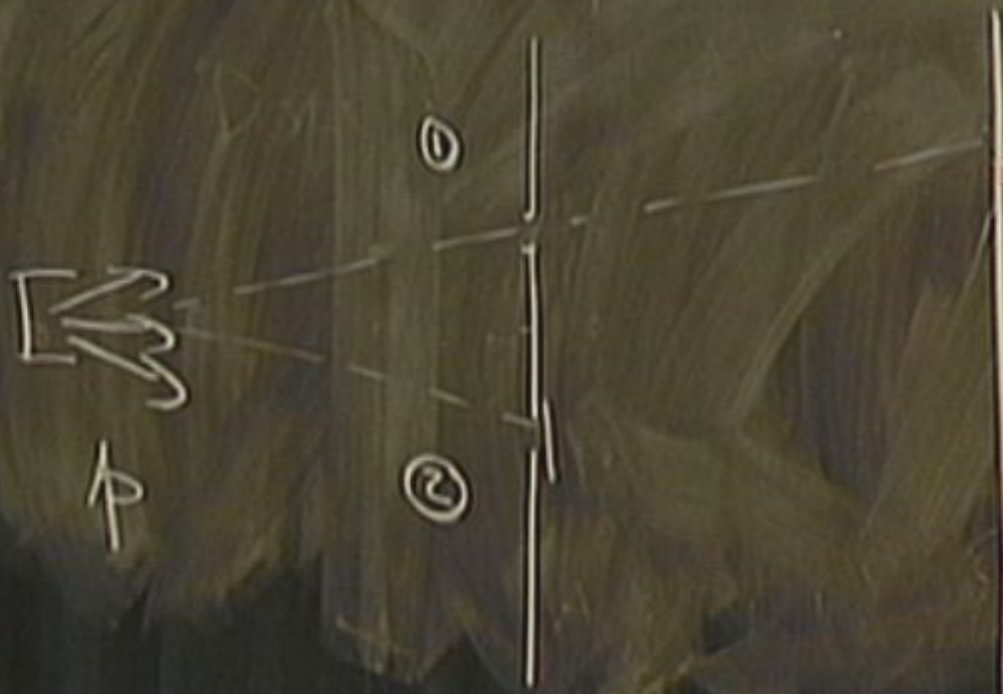
Double Slit Expt.



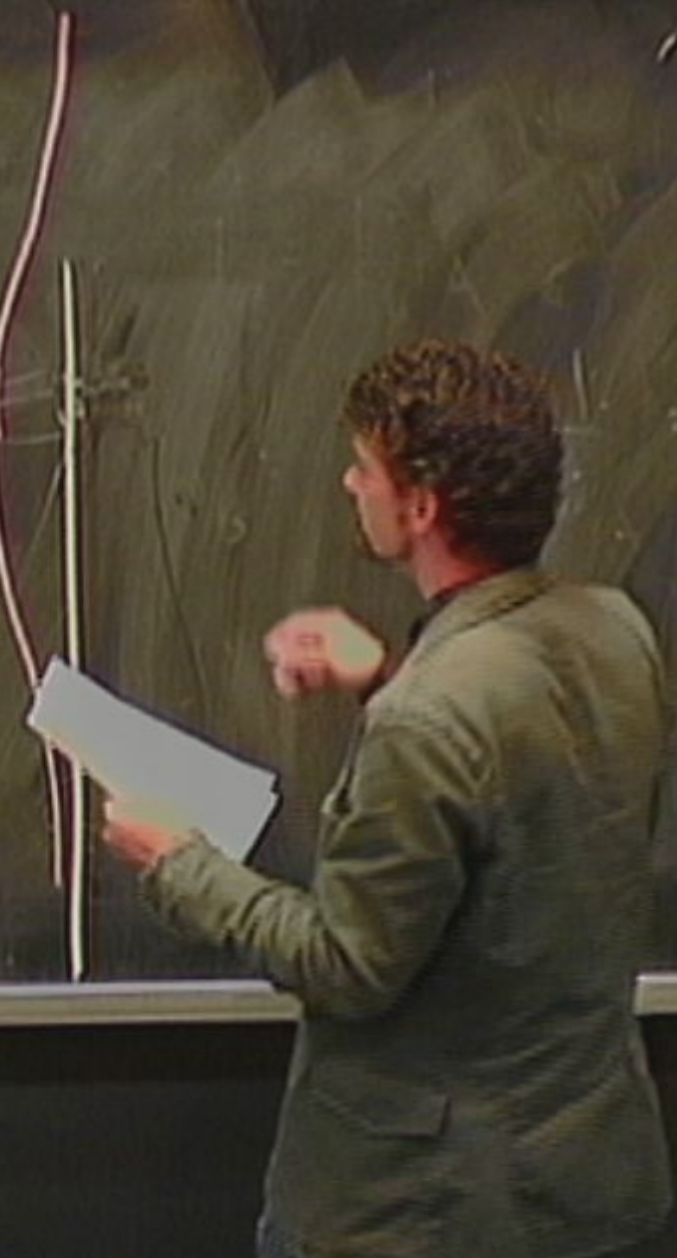
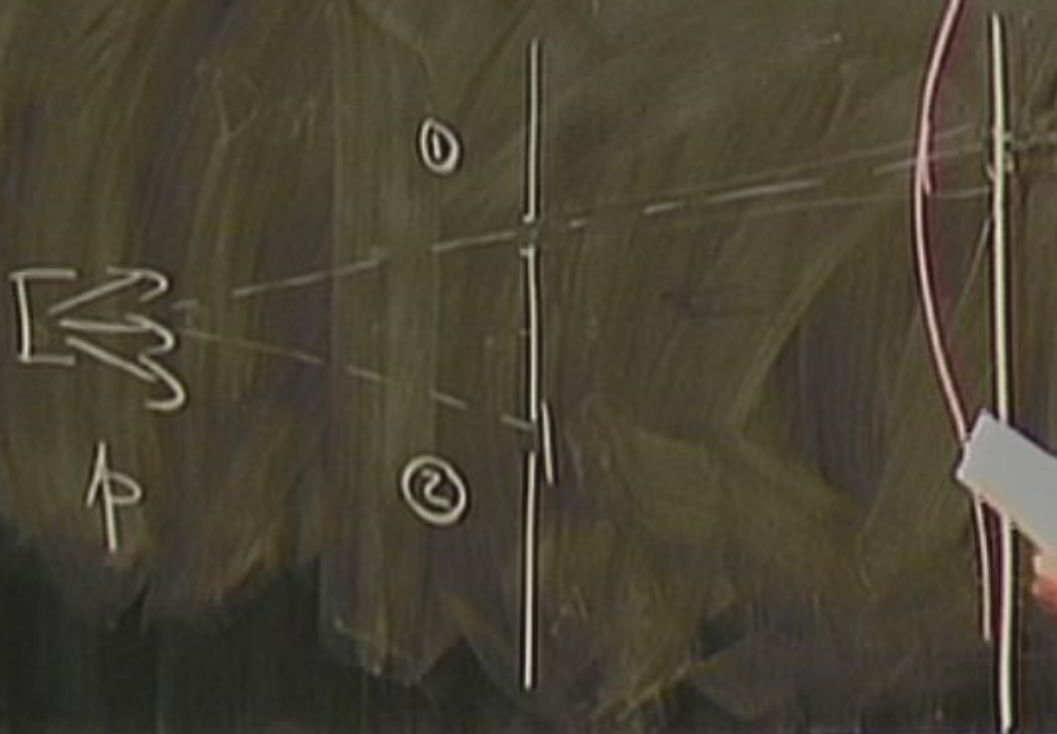
Double Slit Expt.



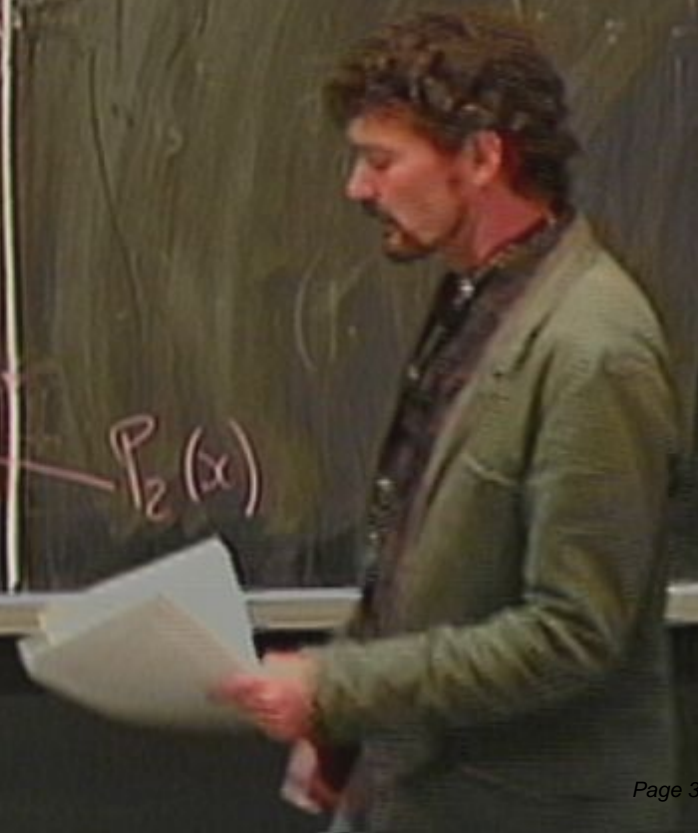
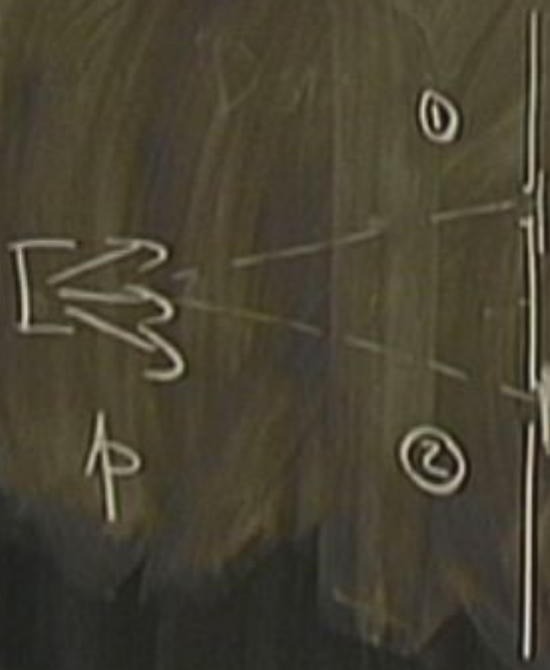
Double Slit Expt.



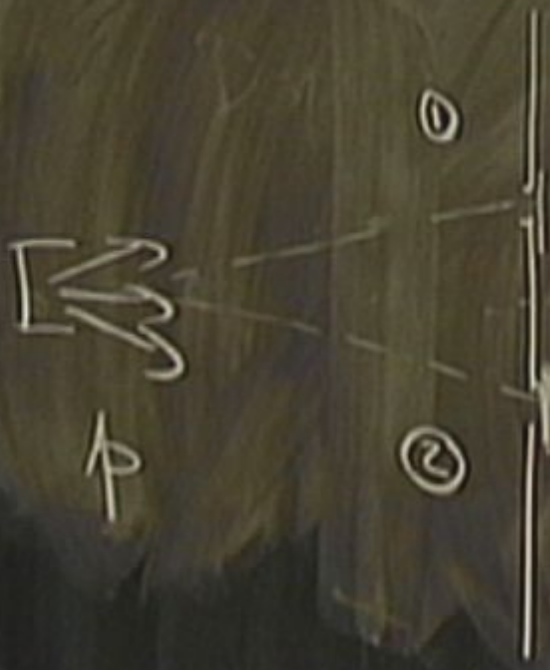
Double Slit Expt.



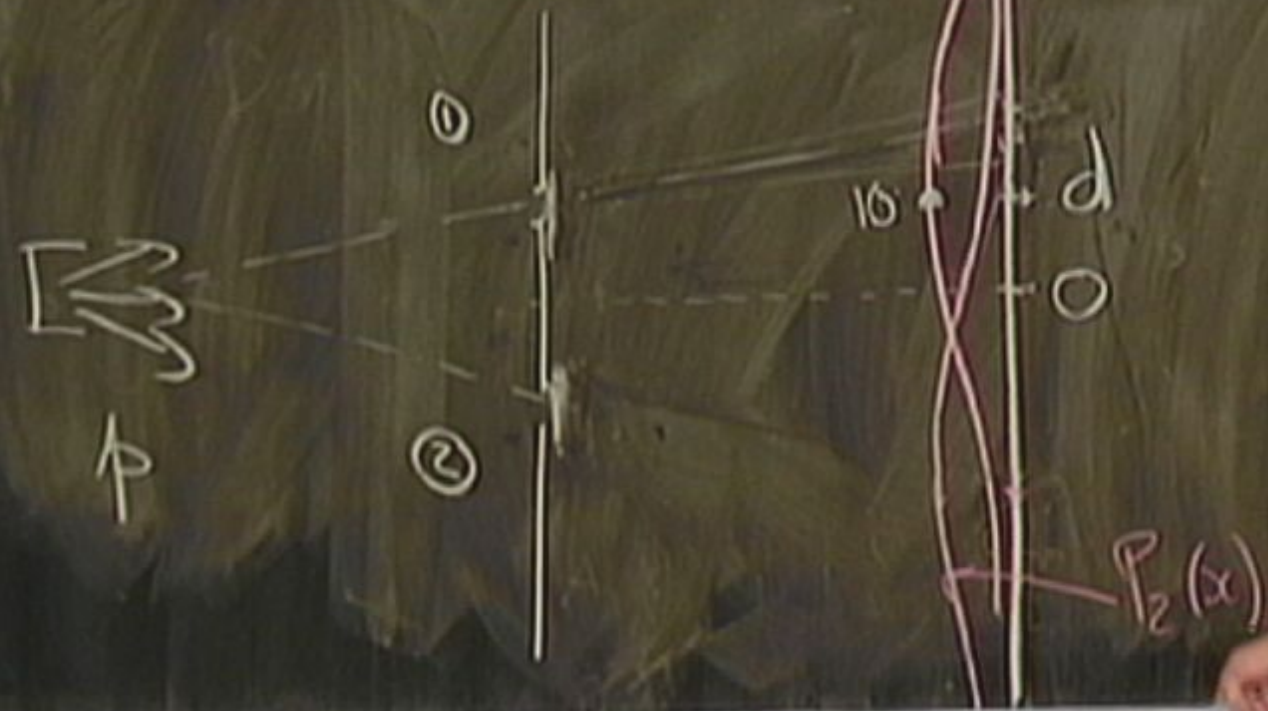
Double Slit Expt.



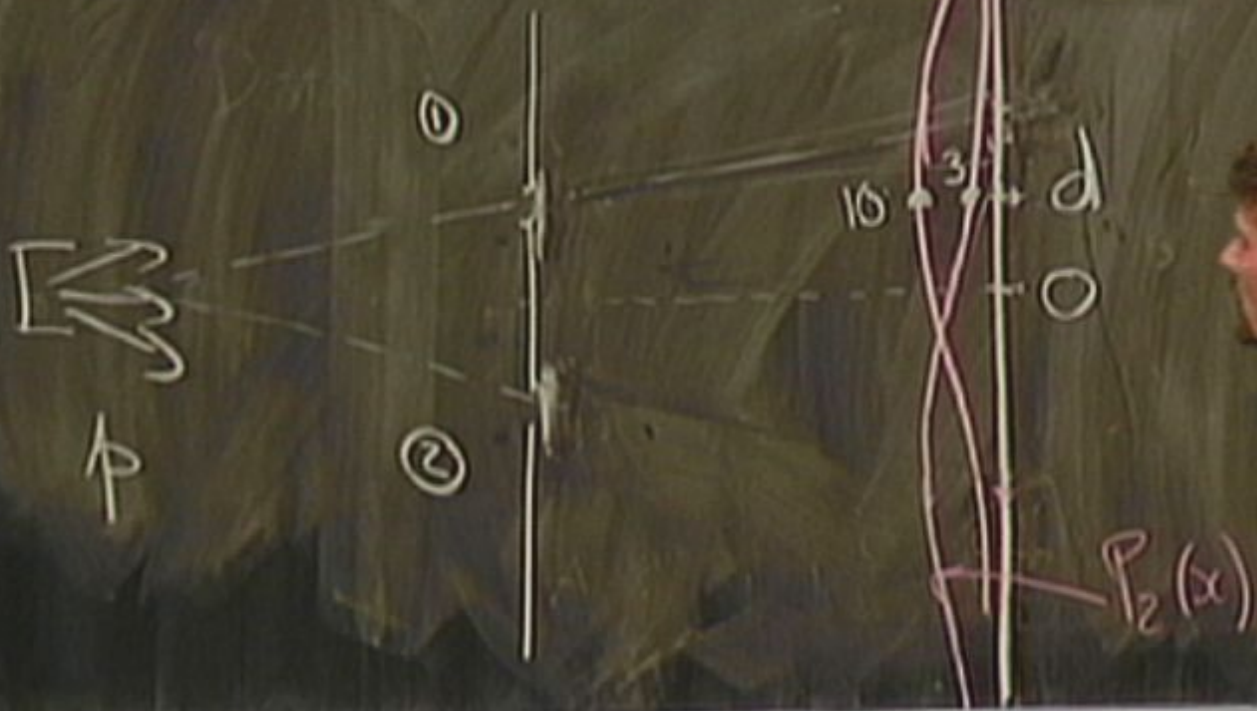
Double Slit Expt.

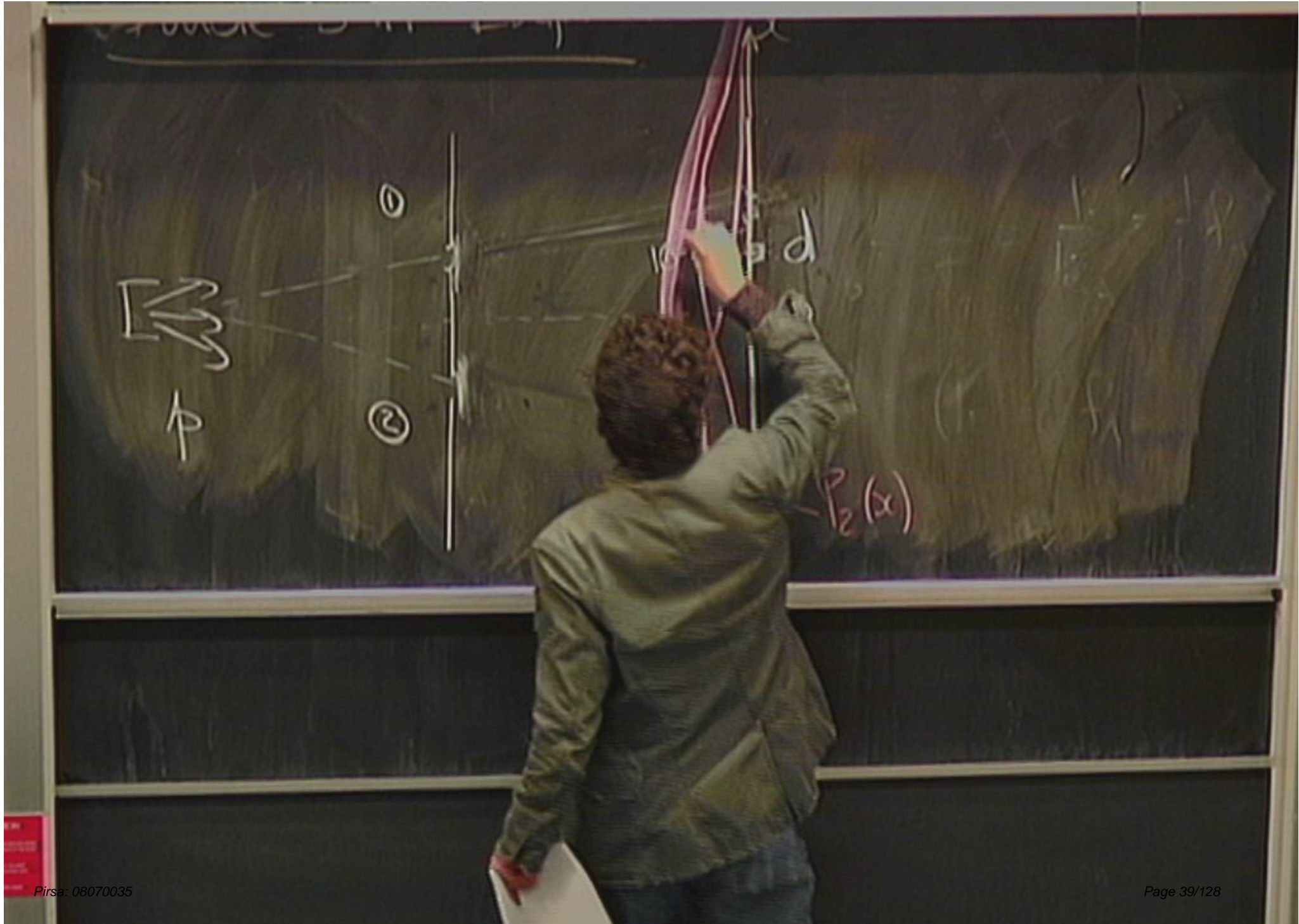


Double Slit Expt.

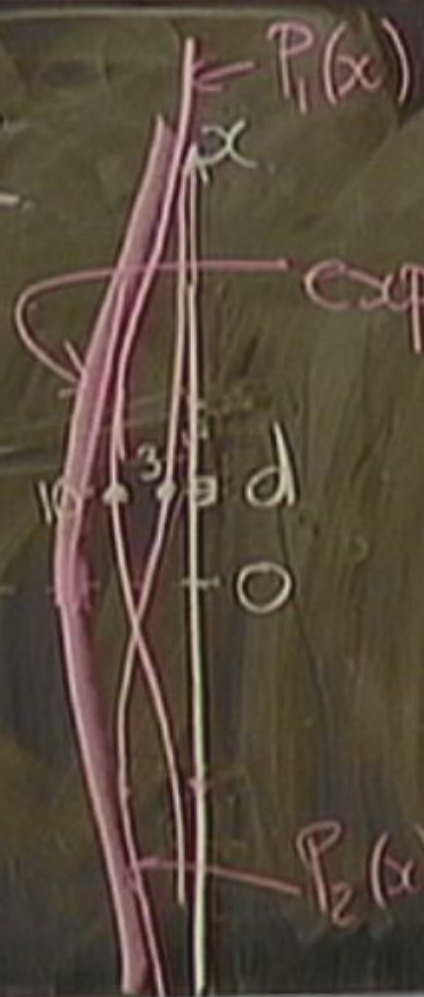
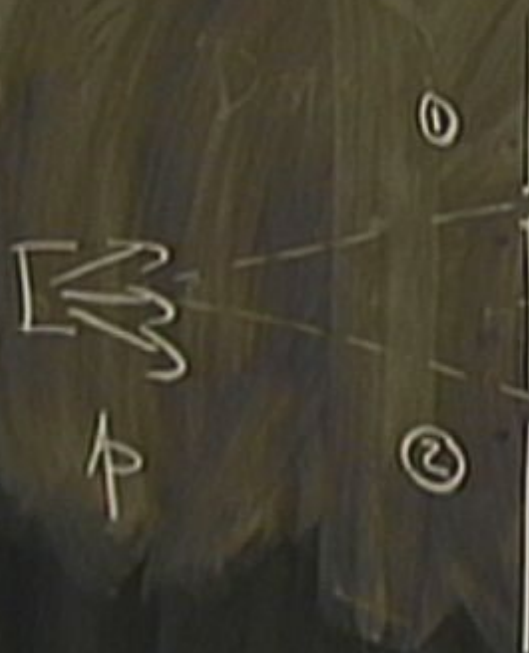


Double Slit Expt.



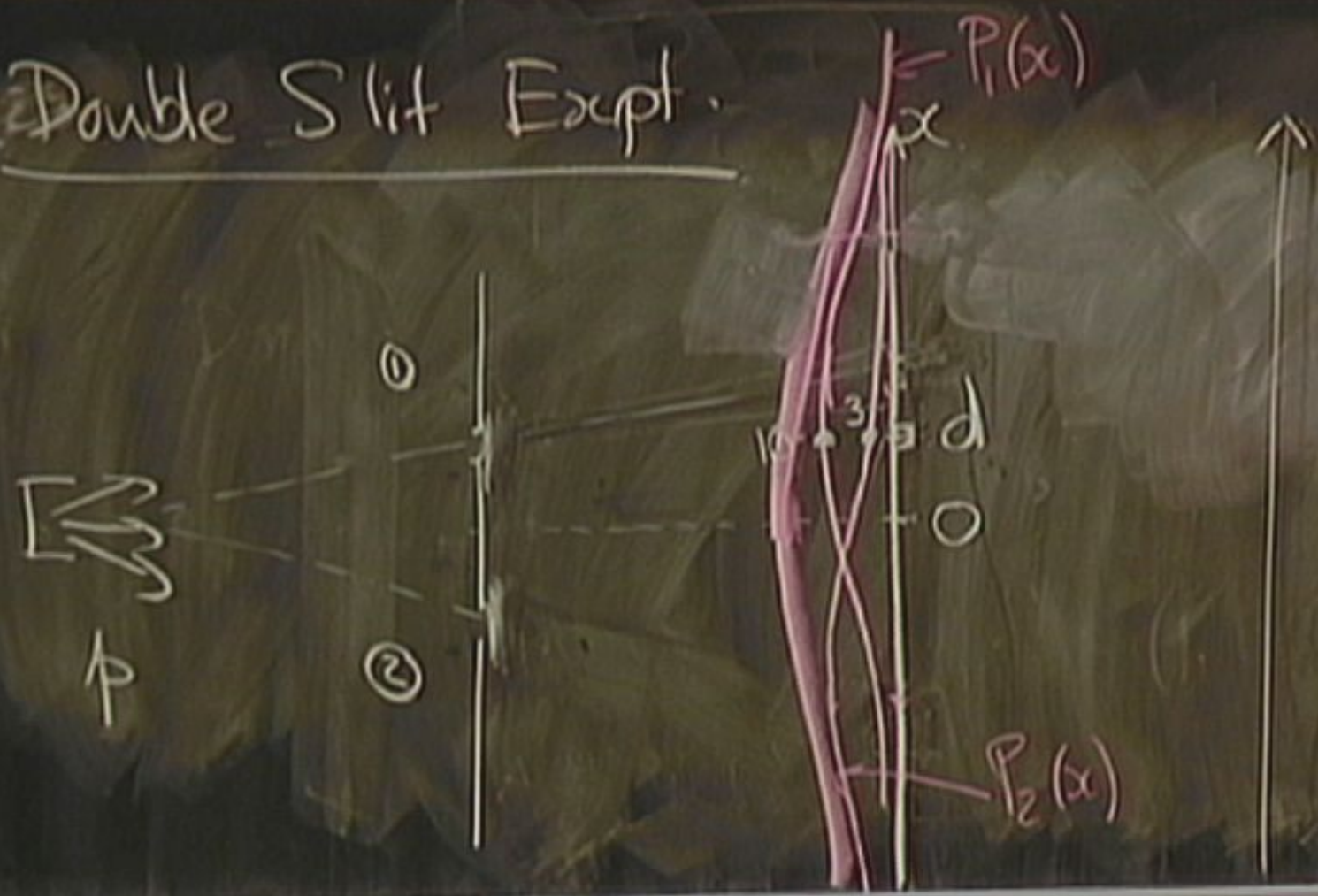


Double Slit Expt.



expect $P(x)$
 $= P_1(x) + P_2(x)$

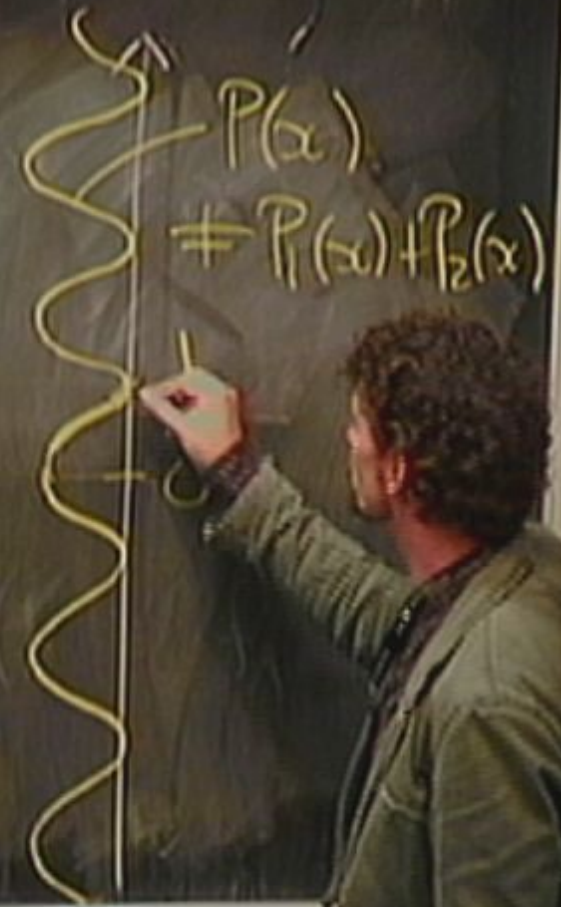
Double Slit Expt.



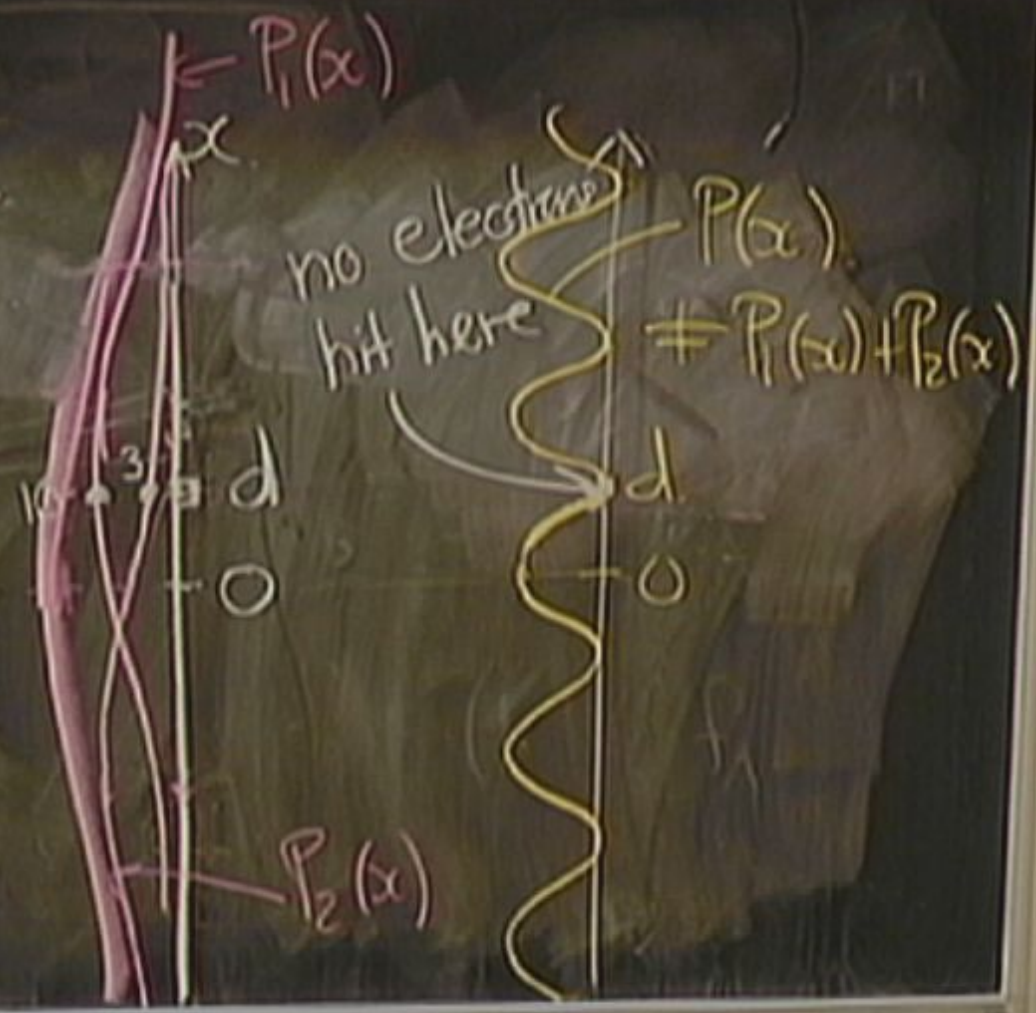
Double Slit Expt.



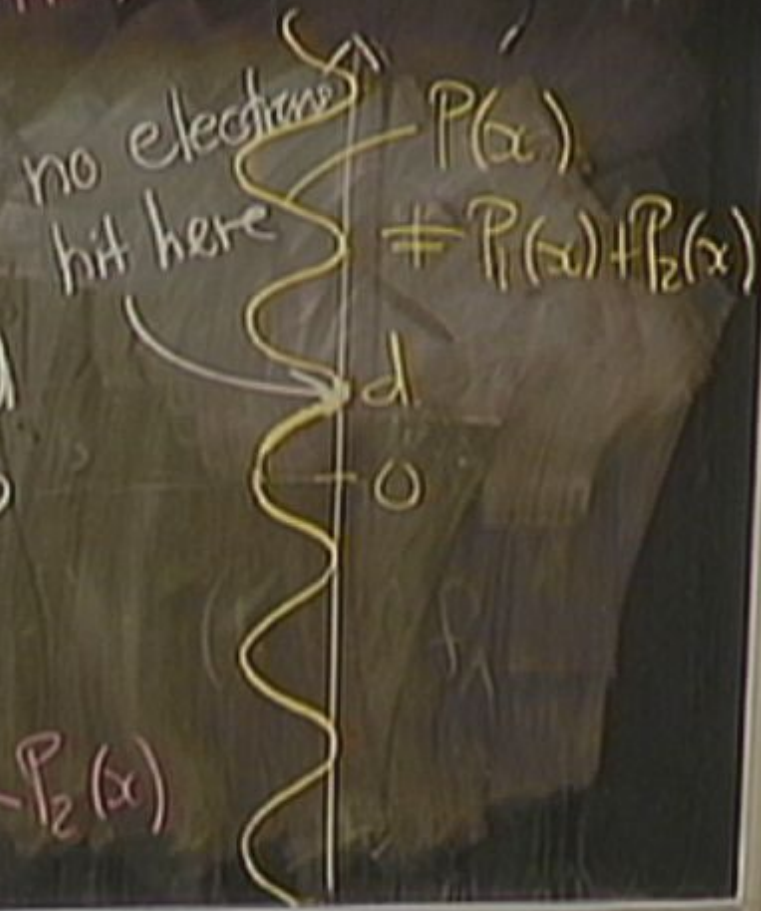
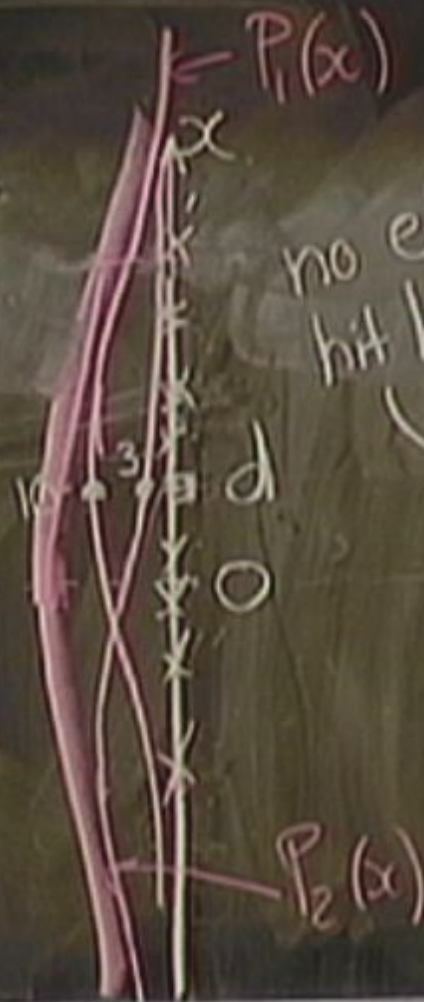
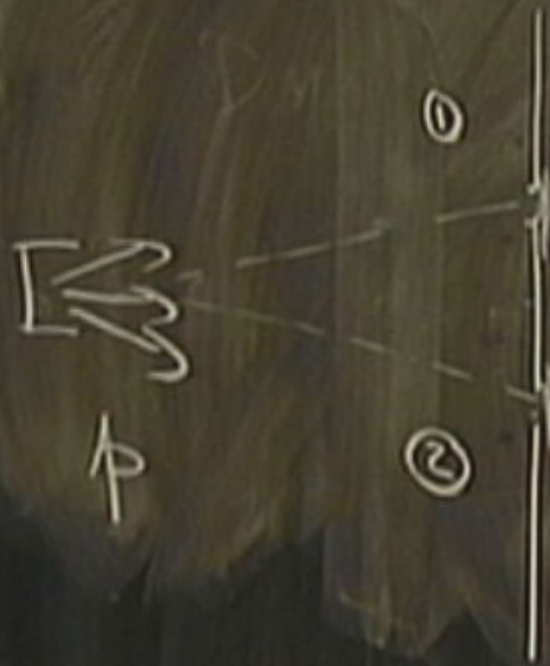
Double Slit Expt.



Double Slit Expt.



Double Slit Expt.



Now Playing

Library

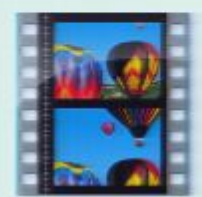
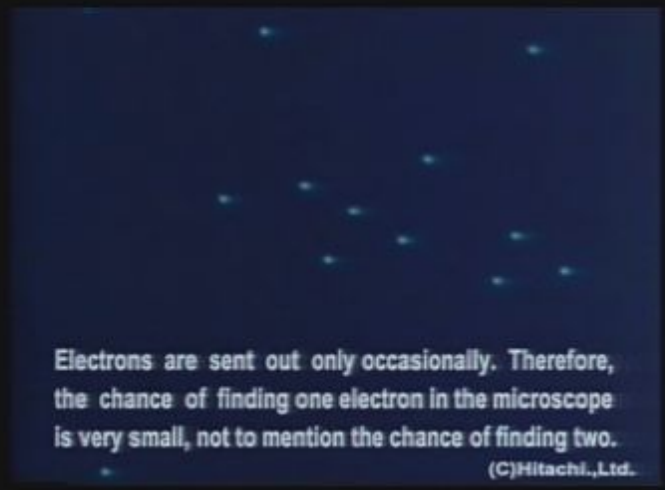
Rip

Burn

Sync



Media Guide



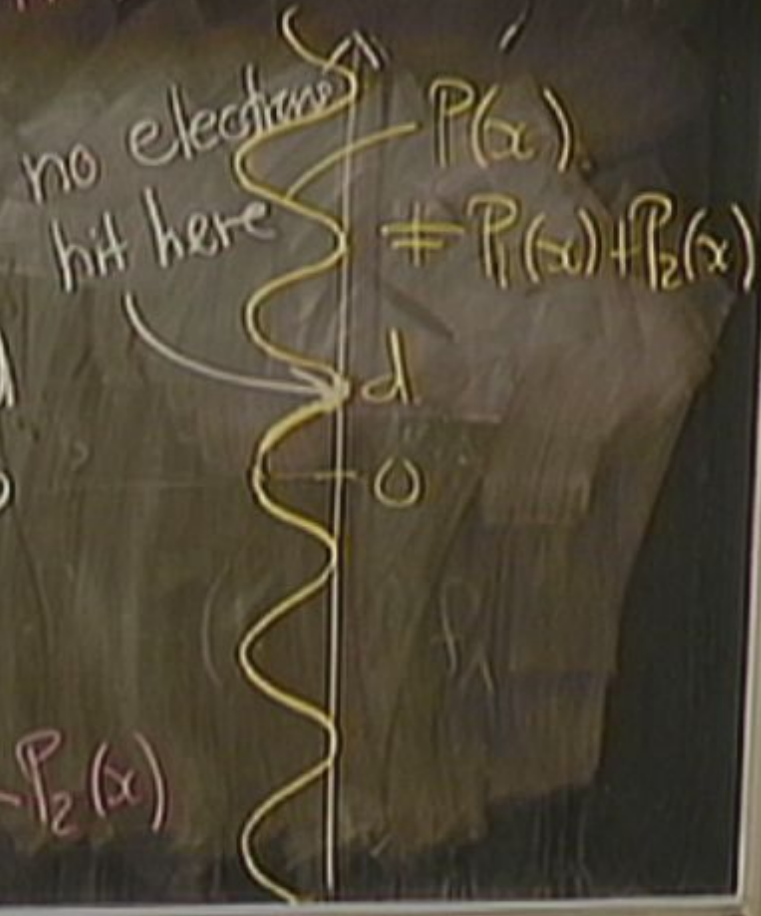
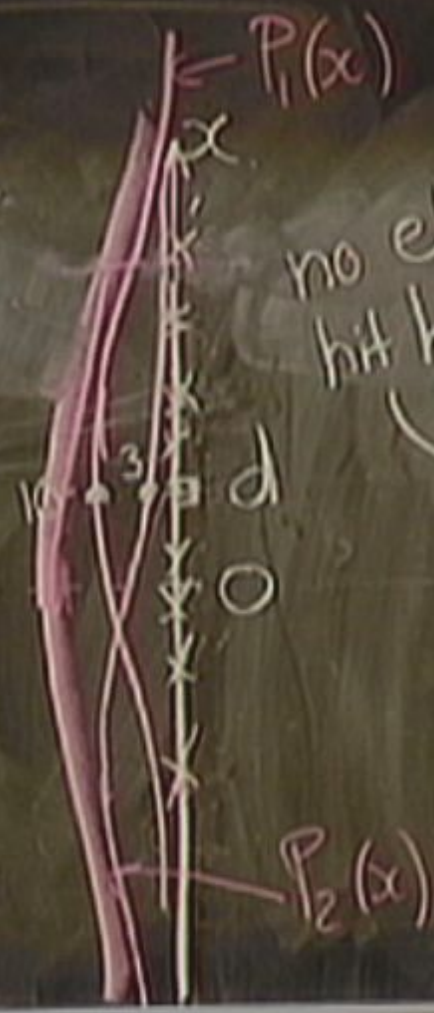
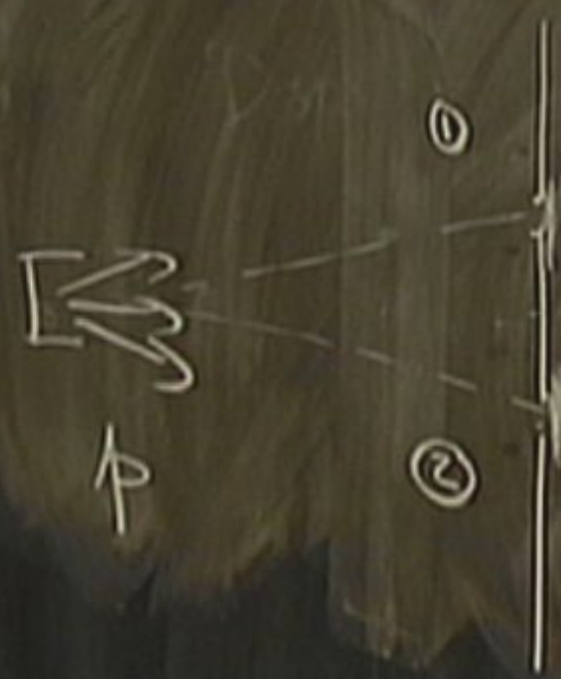
Single-Electron Build-Up of Bipris...

Now Playing

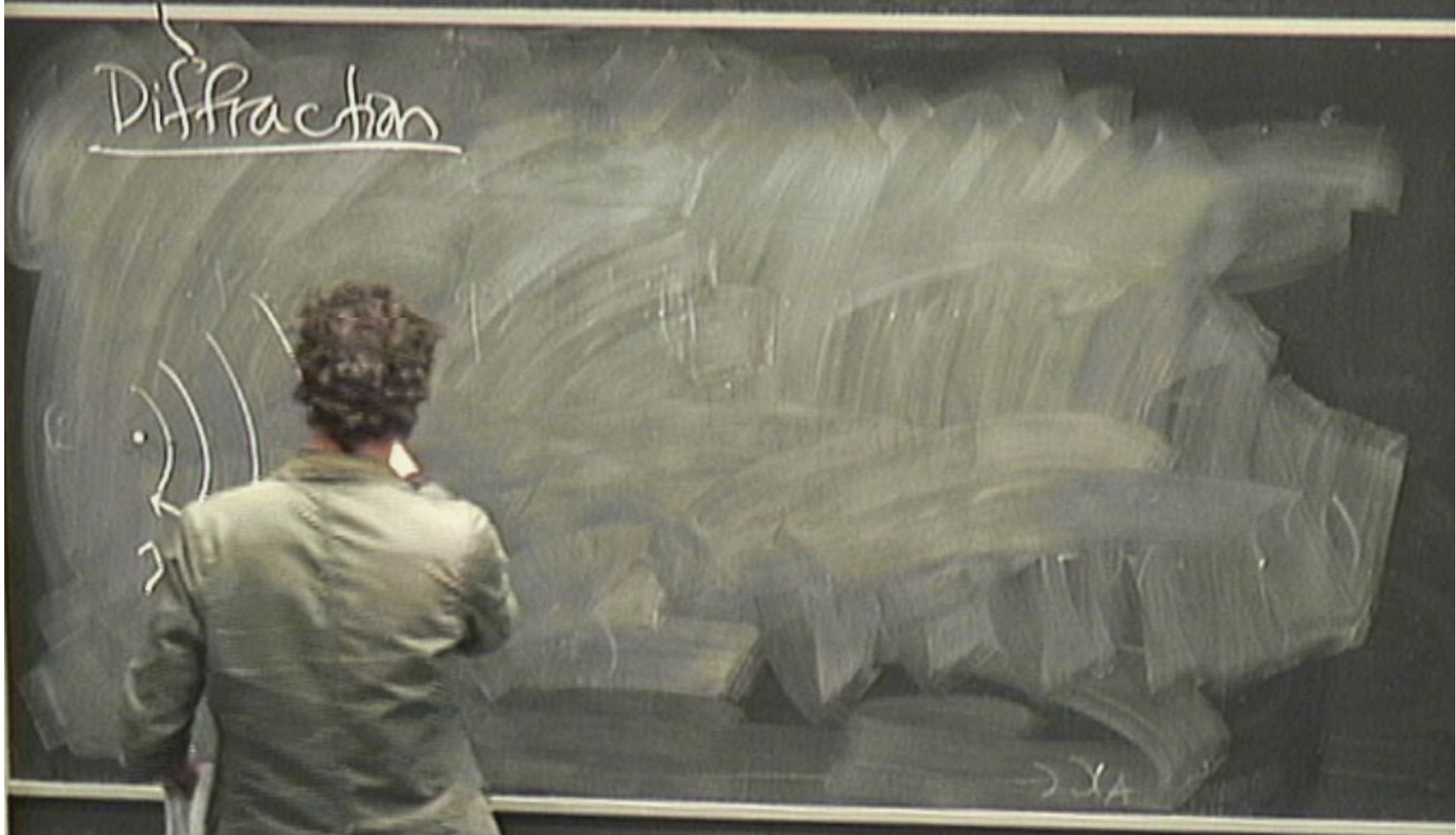
Single-Electron Build-Up of Bipri...



Double Slit Expt.



Diffraction



Diffraction



Diffraction



Diffraction



Diffraction



x

x

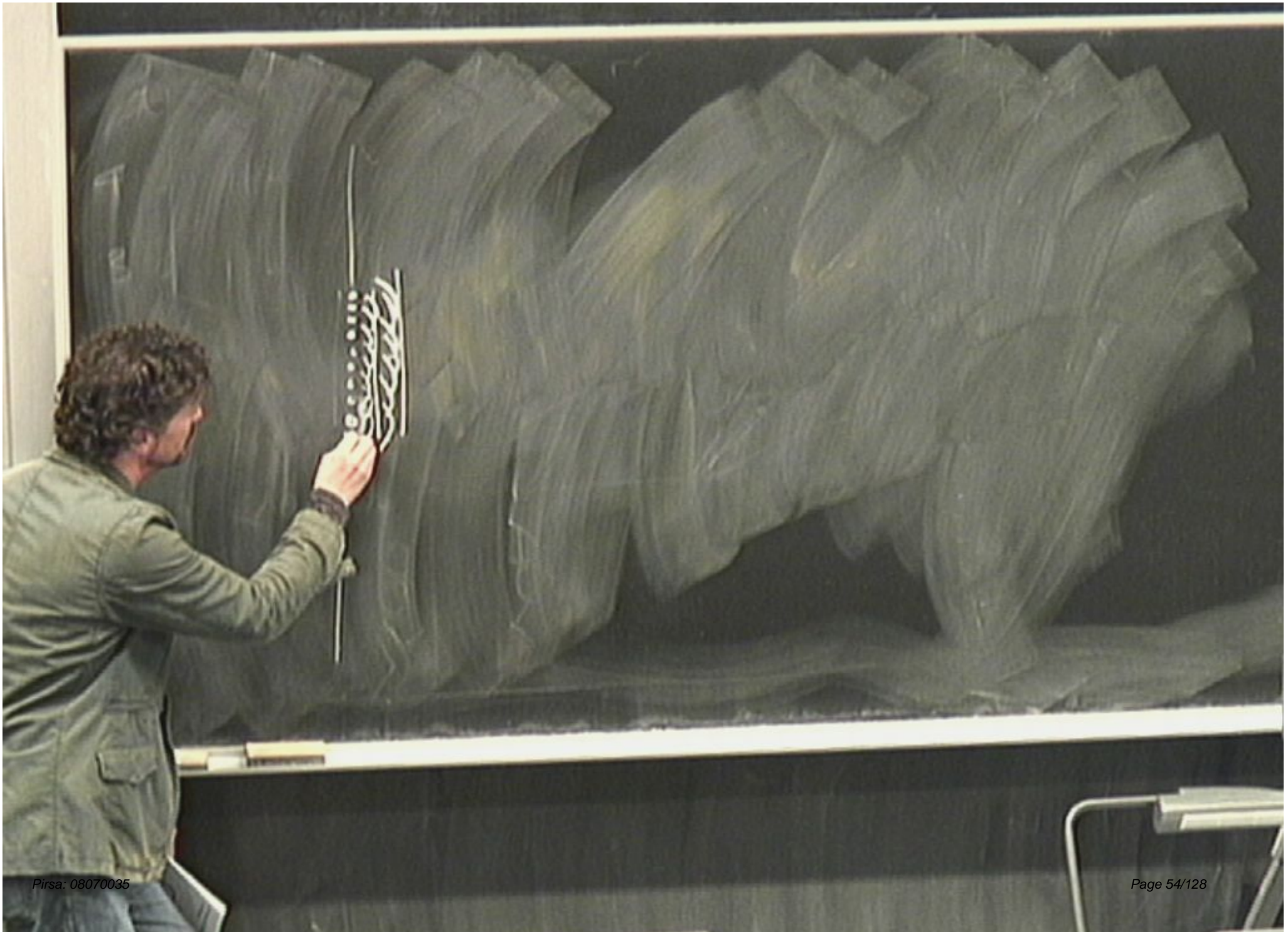
\odot

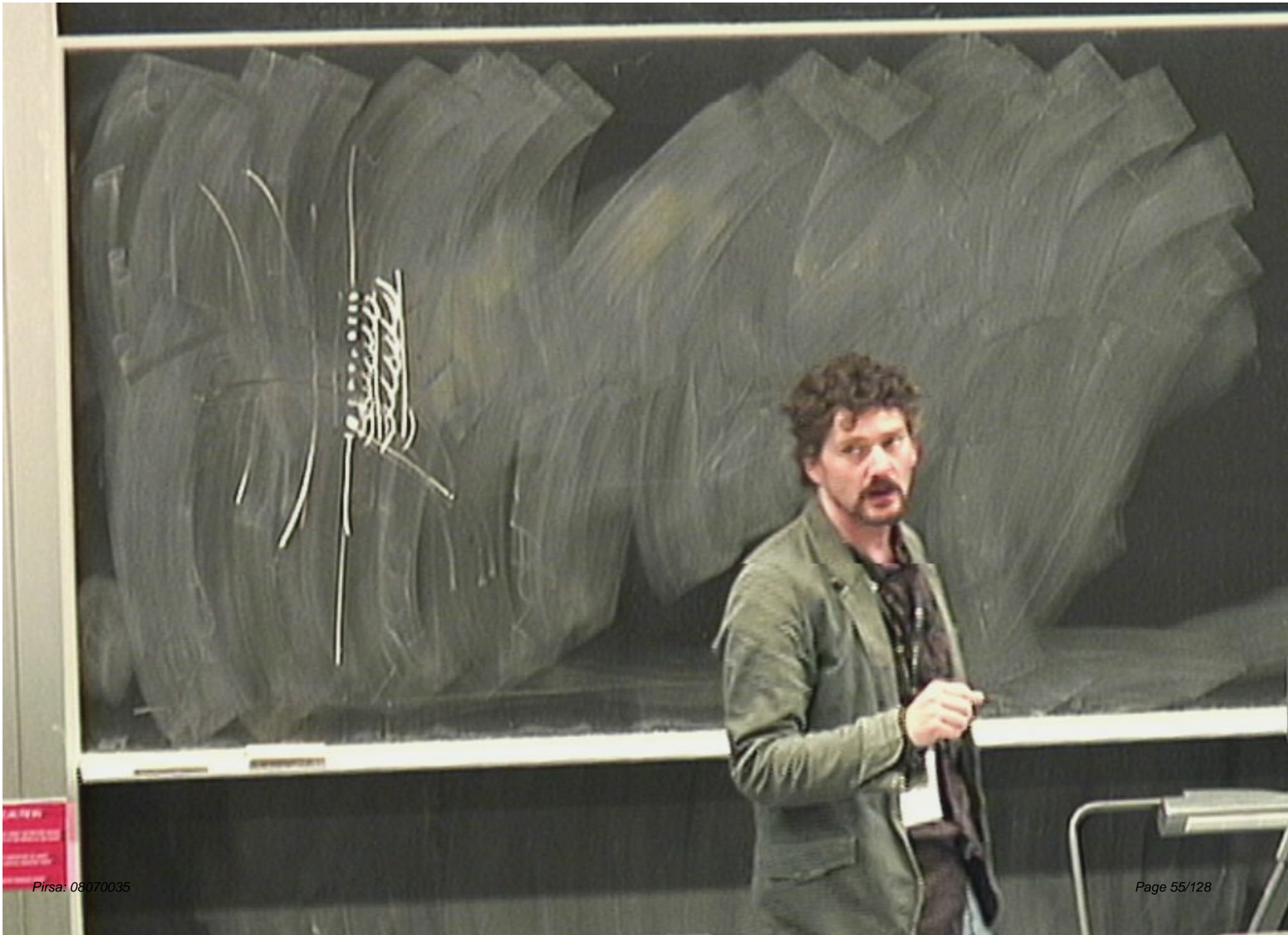
$\rightarrow x_A$

Diffraction

Huygens







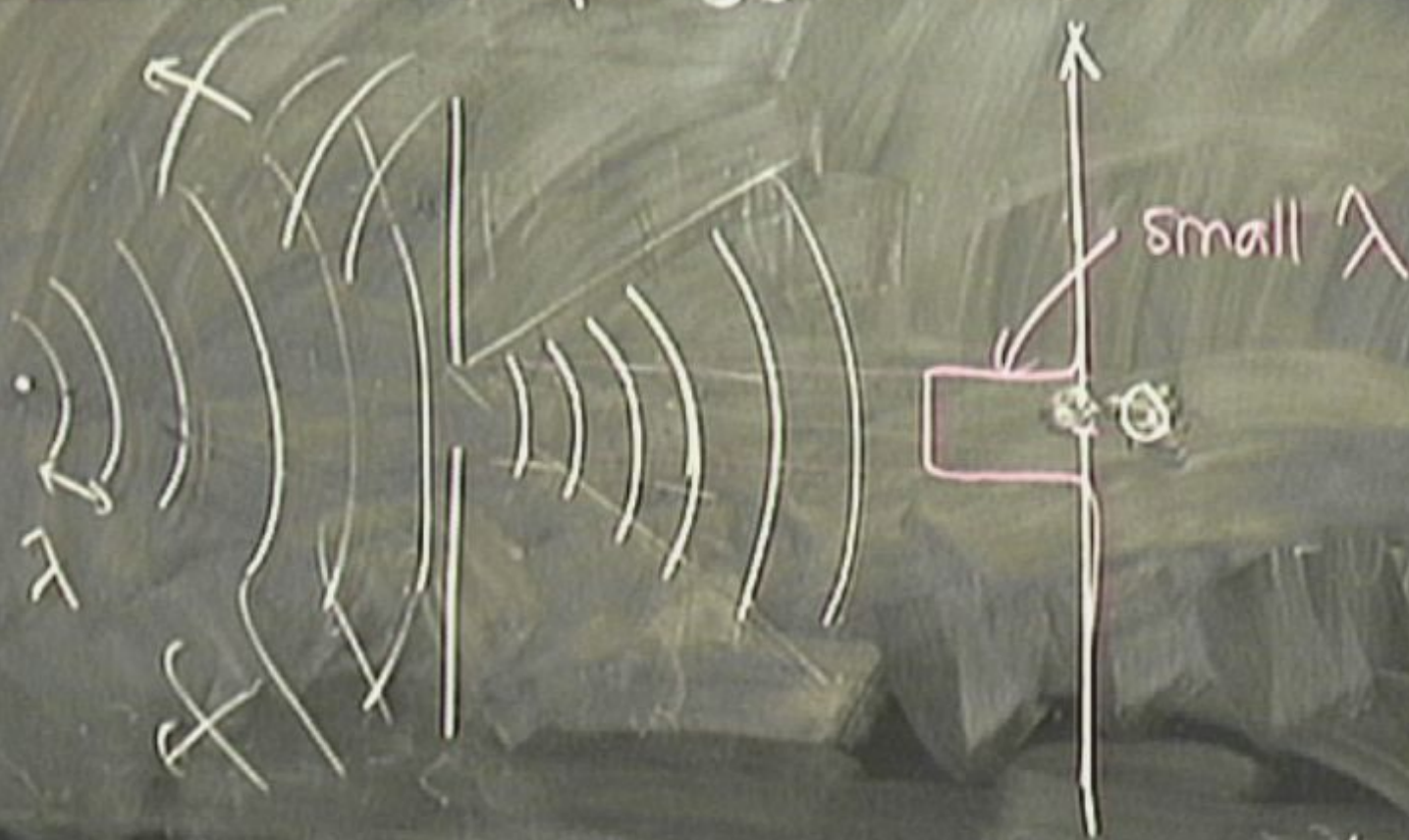
Diffraction

Huygens



Diffraction

Huygens



Diffraction

Huygens

$$I(\alpha) \propto \left(\frac{\sin \alpha}{\alpha}\right)^2$$

large λ
small λ



(1) Identify: $\psi^2(x)$ with $P(x)$

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↑ wave intensity ↑ particle probability

(1) Identify $\psi^2(x)$ with $P(x)$

↑ ↑

wave intensity particle probability

(2) large $p \leftrightarrow$

(1) Identify: $\psi^2(x)$ with $P(x)$
↑ ↑
wave intensity particle probability

(2) large $p \leftrightarrow$ small λ

Small p

(1) Identify: $\psi^2(x)$ with $P(x)$
↑ wave intensity ↑ particle probability

(2) large $p \leftrightarrow$ small λ
Small $p \leftrightarrow$ large λ

Guess: $\lambda \propto \frac{1}{p}$

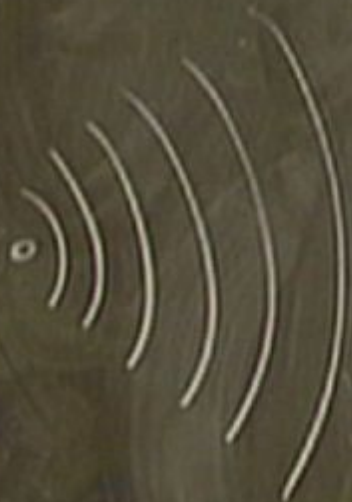
(1) Identify: $\psi^2(x)$ with $P(x)$
↑ wave intensity ↑ particle probability

(2) large $p \leftrightarrow$ small λ
Small $p \leftrightarrow$ large λ

ess: $\lambda \propto \frac{1}{p} ?$

Interference

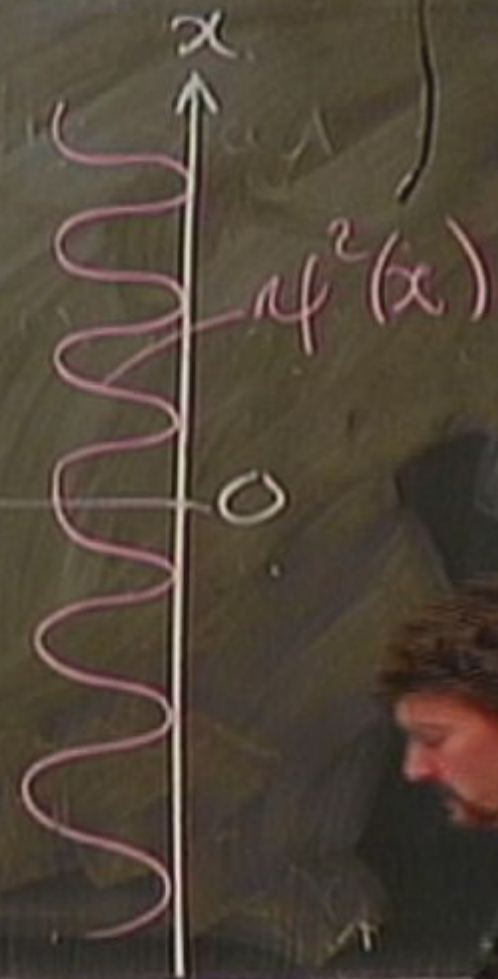
Interference



Interference



Interference



Interference

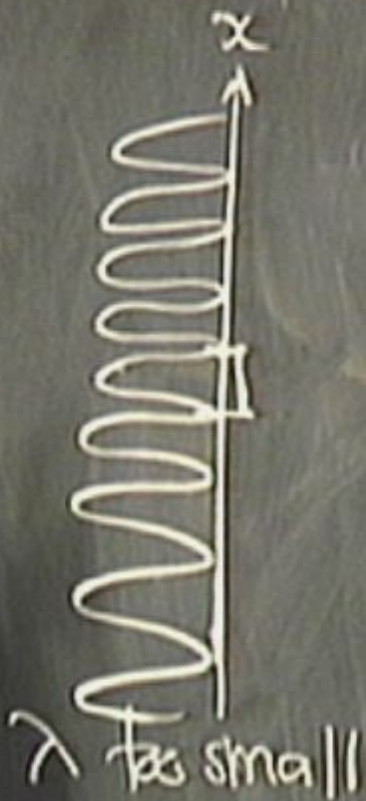


x
↑
 λ too small

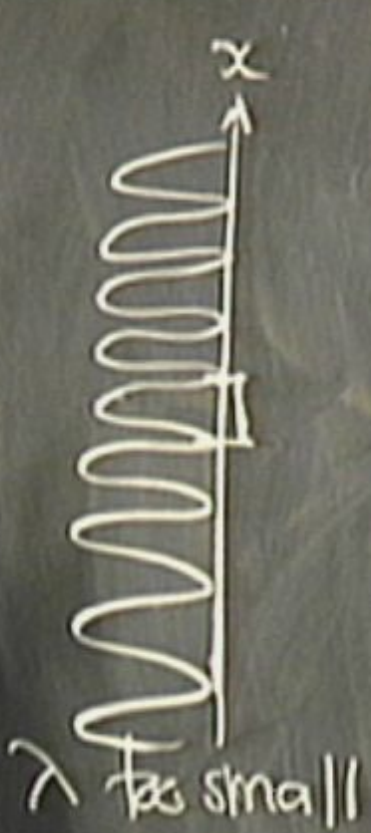


λ small

λ too large



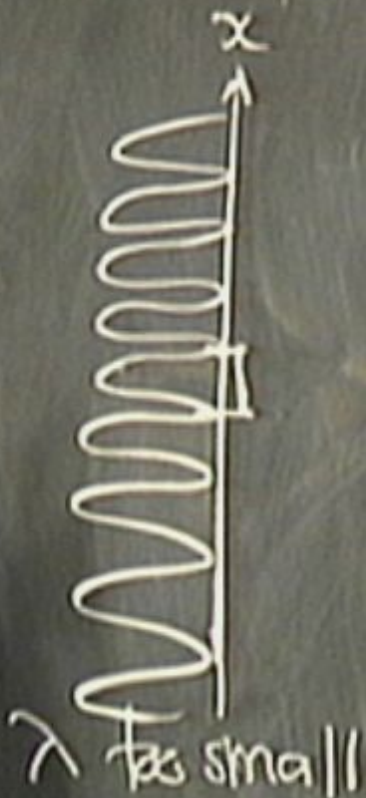
$$\psi^2(x)$$



$$\psi^2(x) = P(x)$$

$$\lambda = \frac{h}{p}$$

$$\lambda = \frac{h}{p}$$



$$\psi^2(x) = P(x)$$

$$\lambda = \frac{h}{p}$$

$$\lambda = \frac{h}{p}$$



λ too small



λ too large



λ just right.

$$\psi^2(x) = P(x)$$

$$\lambda = \frac{h}{p}$$

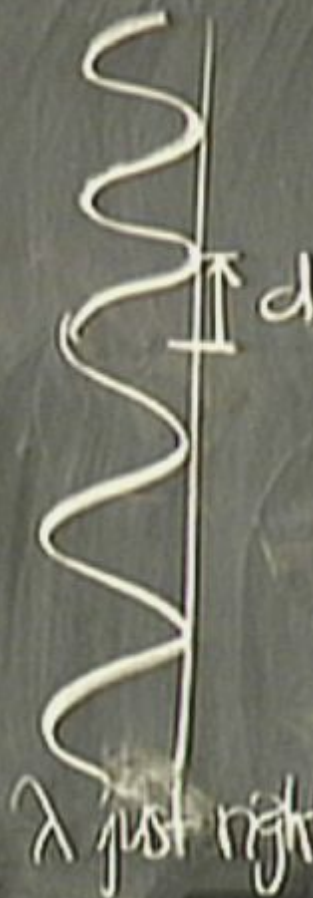
$h = \text{Planck}$
 $= 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$



λ too small



λ too large



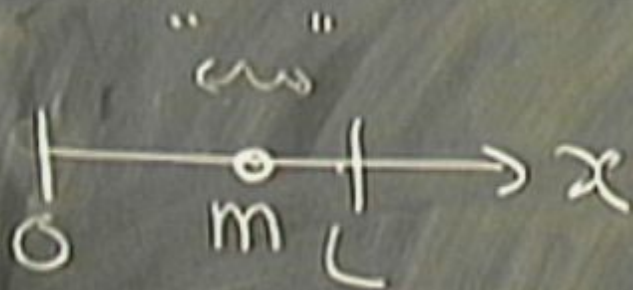
λ just right.

$$\psi^2(x) = P(x)$$

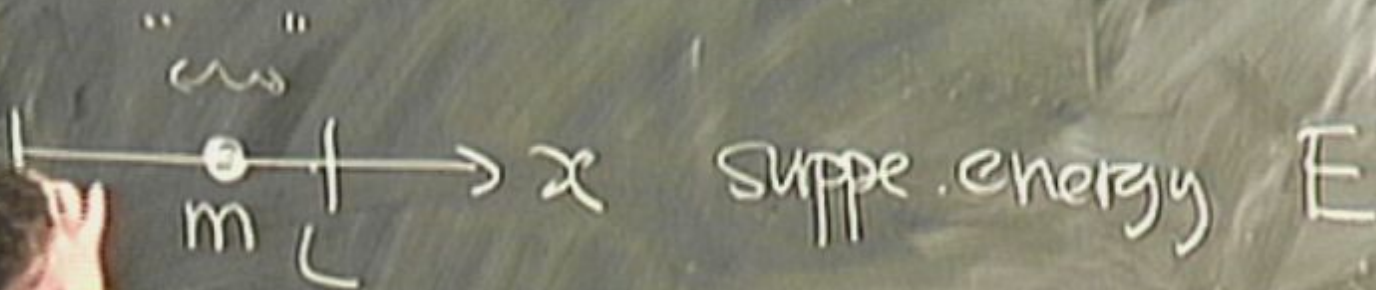
$$\lambda = \frac{h}{p}$$

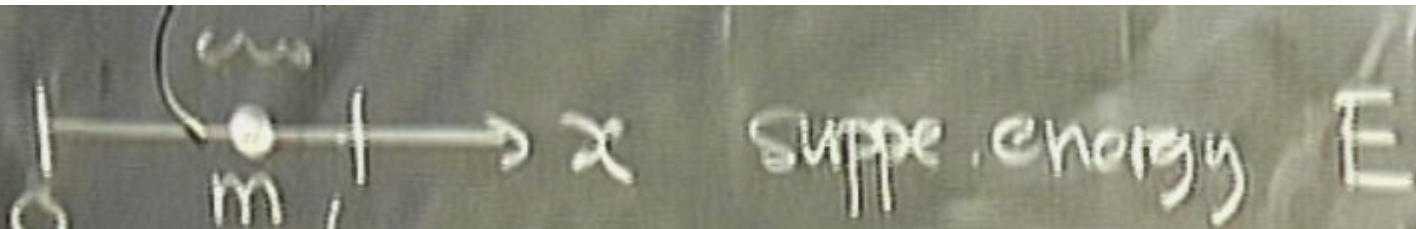
de Broglie

Particle in a Box.



Particle in a Box.





use $\lambda = \frac{h}{p}$



$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m}$$

$$p = m v$$

$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m} \Rightarrow p = \sqrt{2mE}$$

$$p = m v$$

$$E = \frac{1}{2}mv^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \begin{matrix} \text{(right)} \\ \text{(left)} \end{matrix}$$

$$p = mv$$

$$E = \frac{1}{2}mv^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \begin{matrix} \text{(right)} \\ \text{(left)} \end{matrix}$$

$$p = mv$$

and $\lambda =$

$$E = \frac{1}{2}mv^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \begin{matrix} \text{(right)} \\ \text{(left)} \end{matrix}$$

$$p = mv$$

$$\text{and } \lambda = \frac{h}{\sqrt{2mE}}$$

$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \begin{matrix} \text{(right)} \\ \text{(left)} \end{matrix}$$

$$p = mv$$

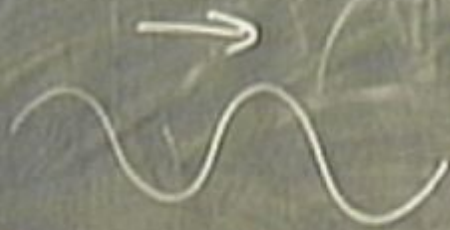
$$\text{and } \lambda = \frac{h}{\sqrt{2mE}}$$

$$p = +\sqrt{2mE}$$

$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \begin{matrix} \text{(right)} \\ \text{(left)} \end{matrix}$$

and $\lambda = \frac{h}{\sqrt{2mE}}$

$$p = +\sqrt{2mE}$$



$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \left(\begin{array}{l} \text{right} \\ \text{left} \end{array} \right)$$

~~$p = mv$~~

and $\lambda = \frac{h}{\sqrt{2mE}}$

$$p = +\sqrt{2mE}$$



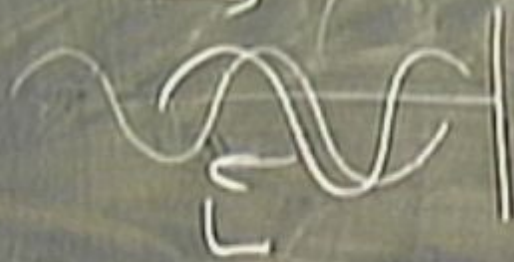
$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \left(\begin{array}{l} \text{right} \\ \text{left} \end{array} \right)$$

~~$$p = mv$$~~

$\downarrow R$

$$\text{and } \lambda = \frac{h}{\sqrt{2mE}}$$

$$p = +\sqrt{2mE}$$



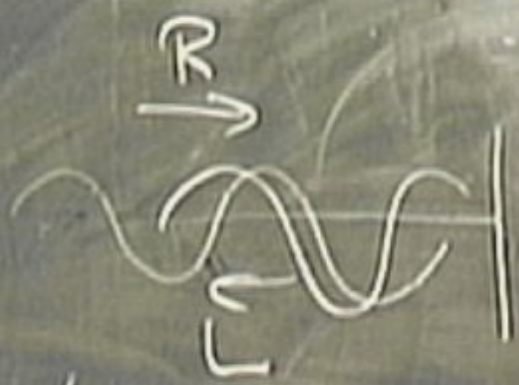
$$p = -\sqrt{2mE}$$

$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \begin{matrix} \text{(right)} \\ \text{(left)} \end{matrix}$$

~~$$p = mv$$~~

and $\lambda = \frac{h}{\sqrt{2mE}}$

$$p = +\sqrt{2mE}$$



$$p = -\sqrt{2mE}$$



$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m} \Rightarrow p = \pm \sqrt{2mE} \quad \left(\begin{array}{l} \text{right} \\ \text{left} \end{array} \right)$$

$$\text{and } \lambda = \frac{h}{\sqrt{2mE}}$$

$$p = +\sqrt{2mE}$$

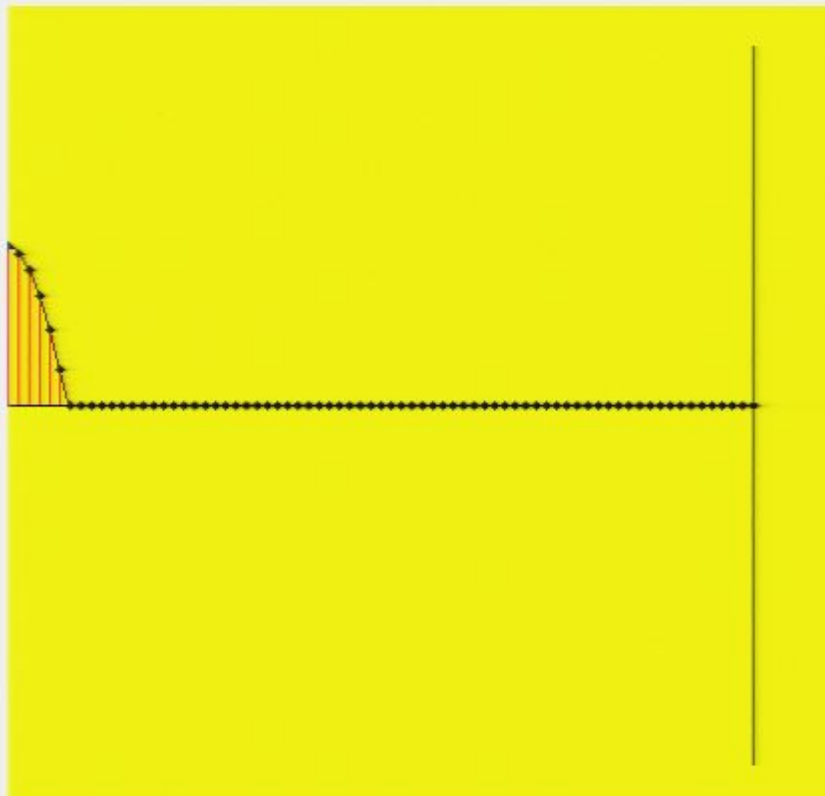


$$p = -\sqrt{2mE}$$



forced to have
superposition of R and L

Standing Wave (Explanation by Superposition with the Reflected Wave)



Reflection

- from a fixed end
- from a free end

Reset

Pause

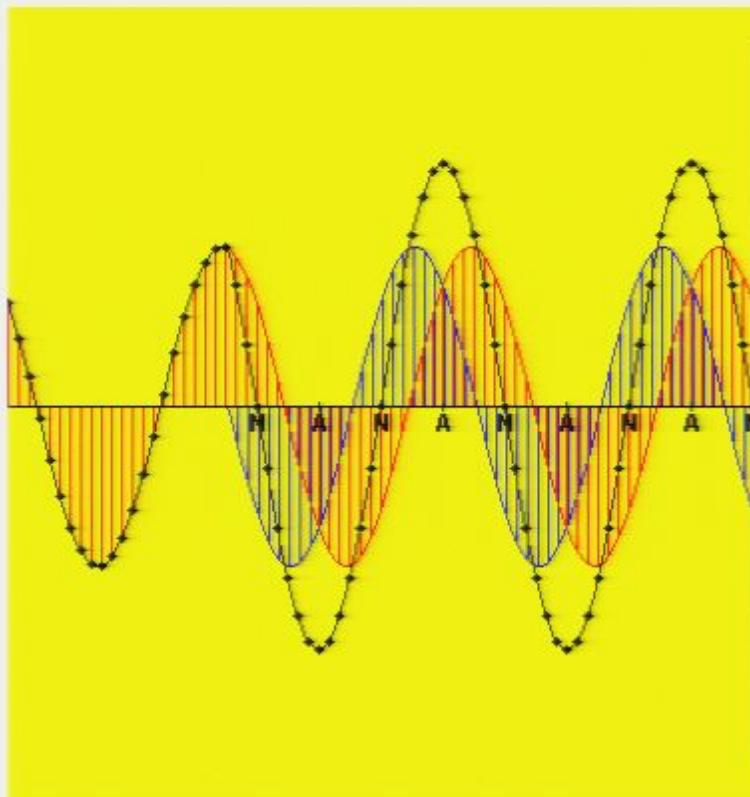
Slow motion

- Animation
- Single steps T/8

- Incidenting wave
- Reflected wave
- Resultant standing wave

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Standing Wave (Explanation by Superposition with the Reflected Wave)



Reflection

- from a fixed end
- from a free end

Reset

Pause

Slow motion

Animation

Single steps

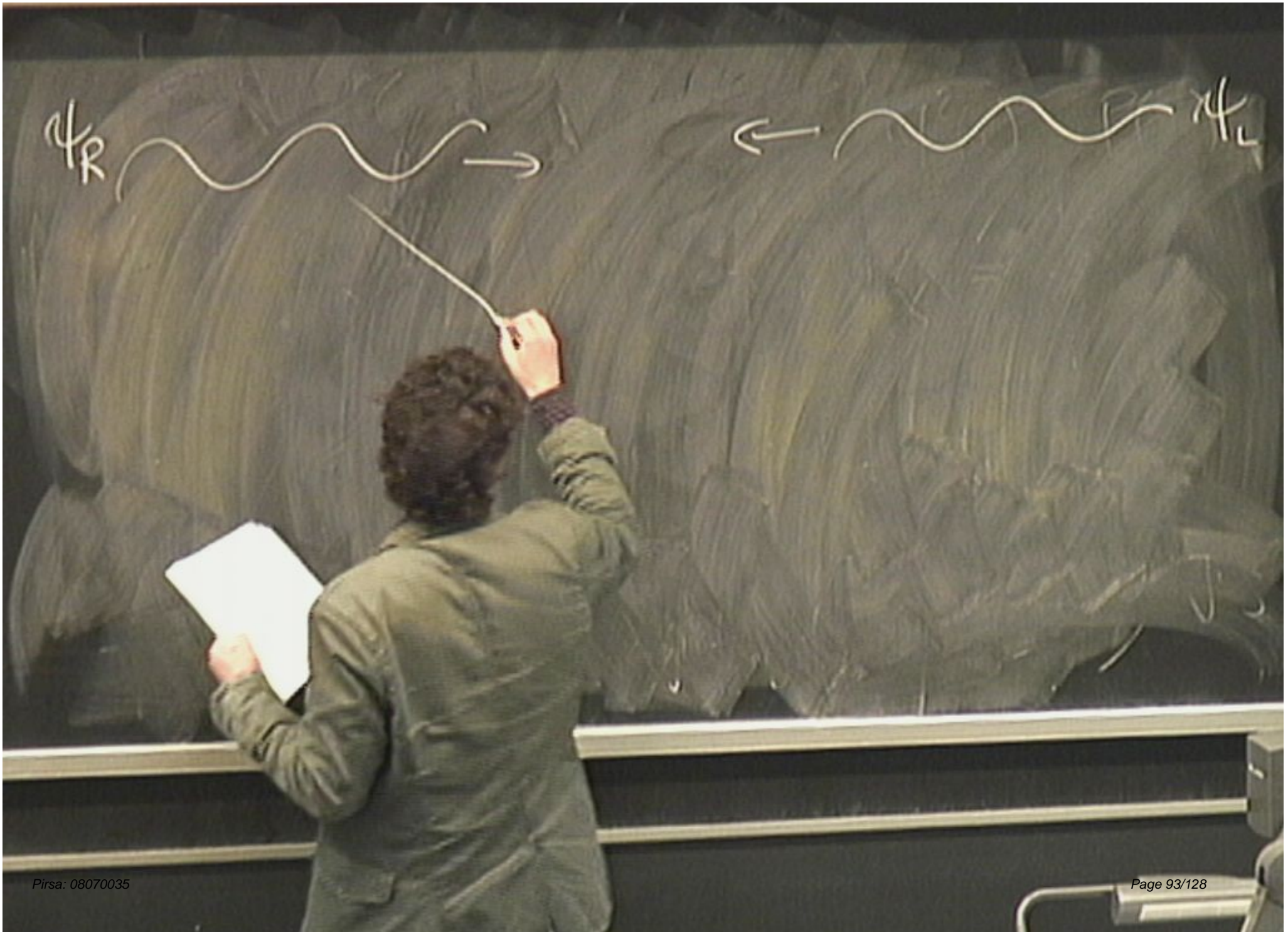
T/8

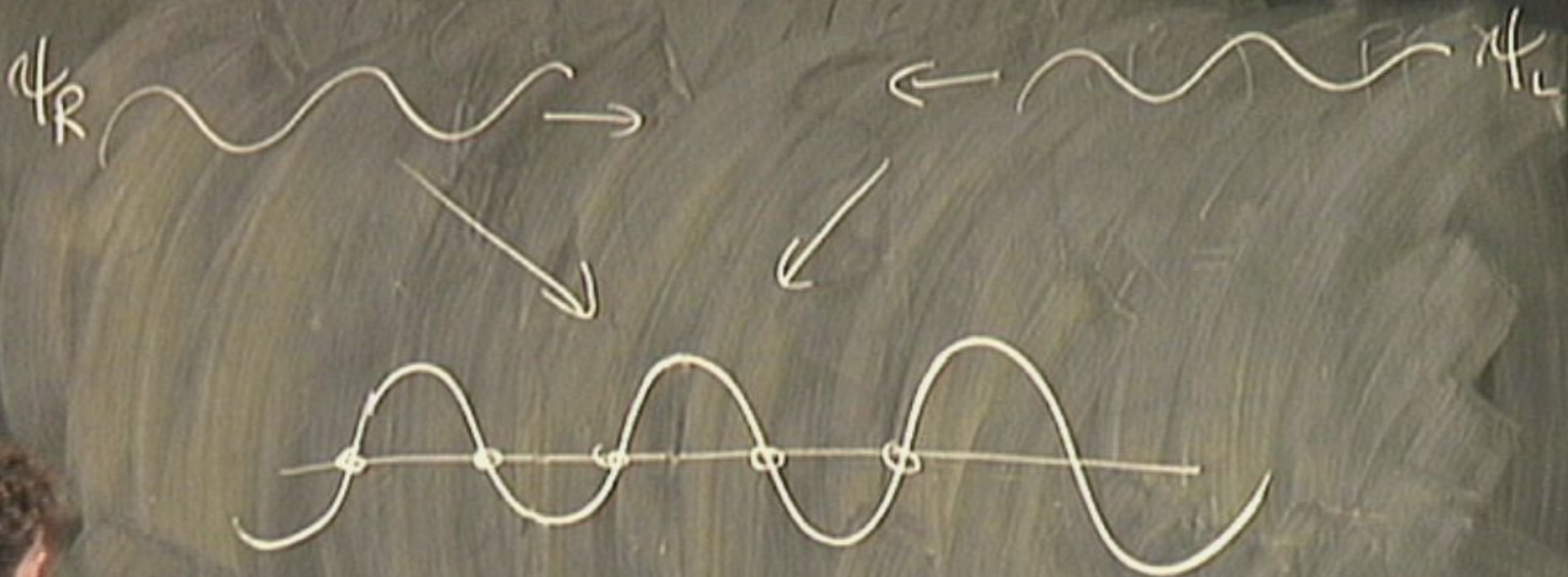
Incidenting wave

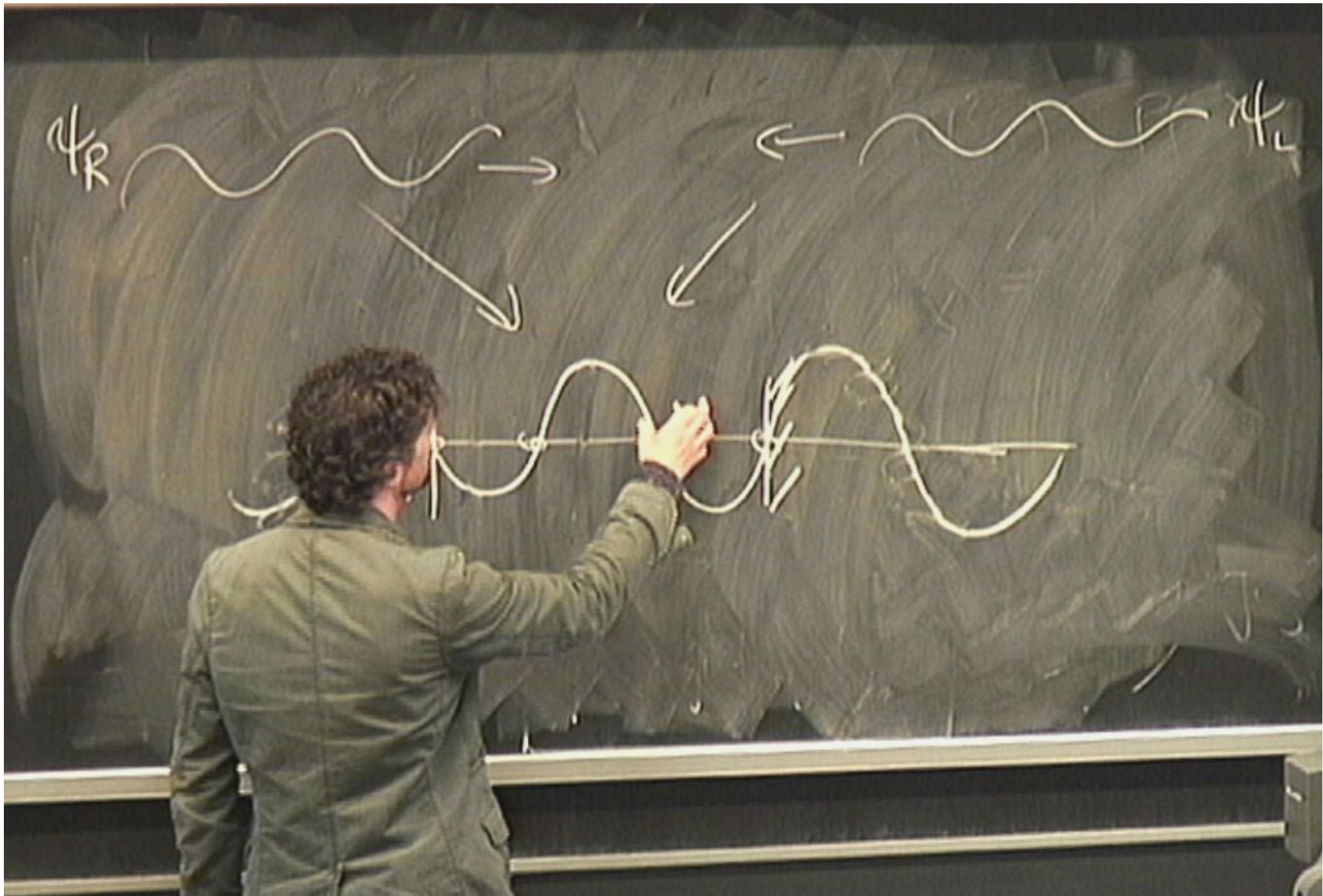
Reflected wave

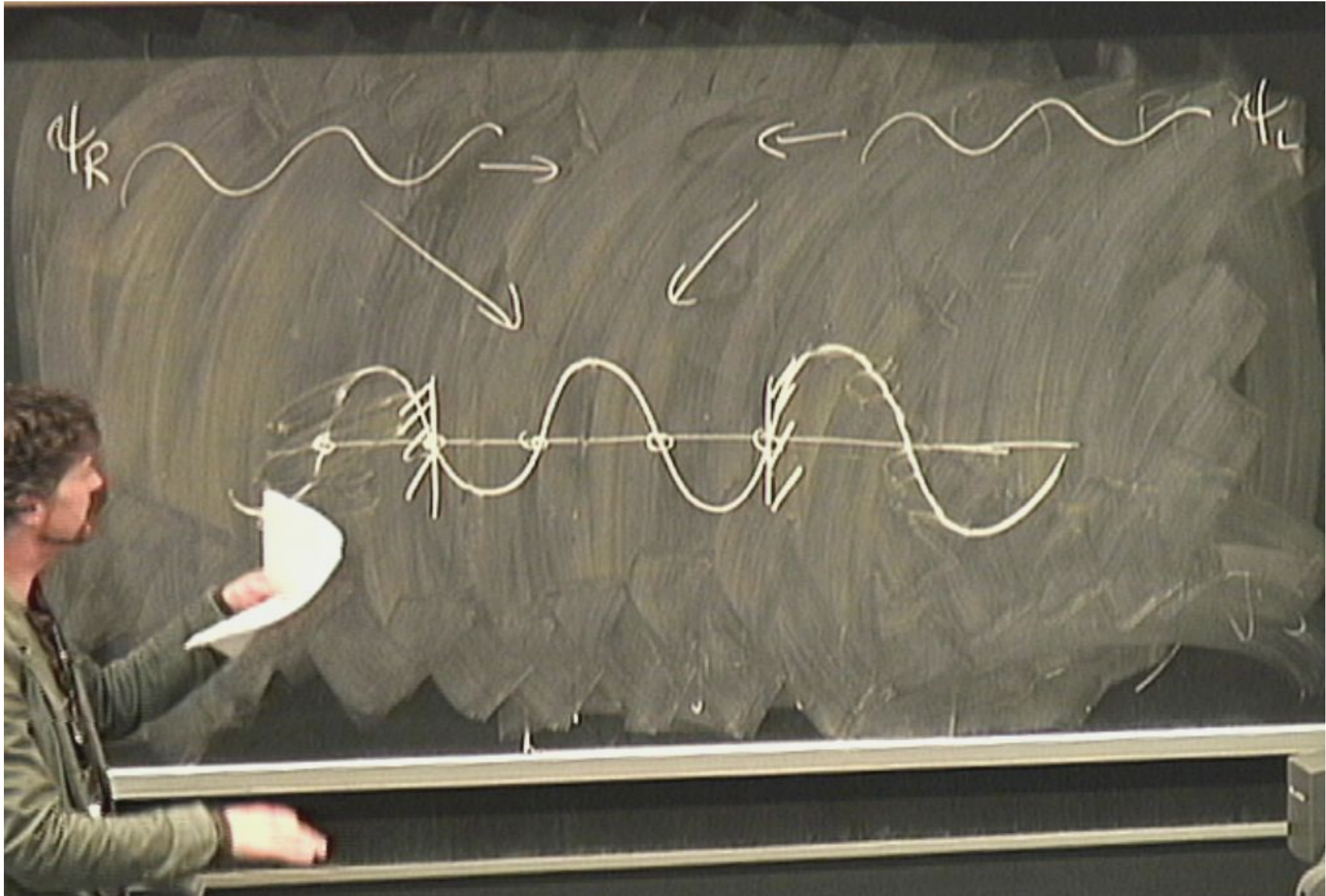
Resultant standing wave

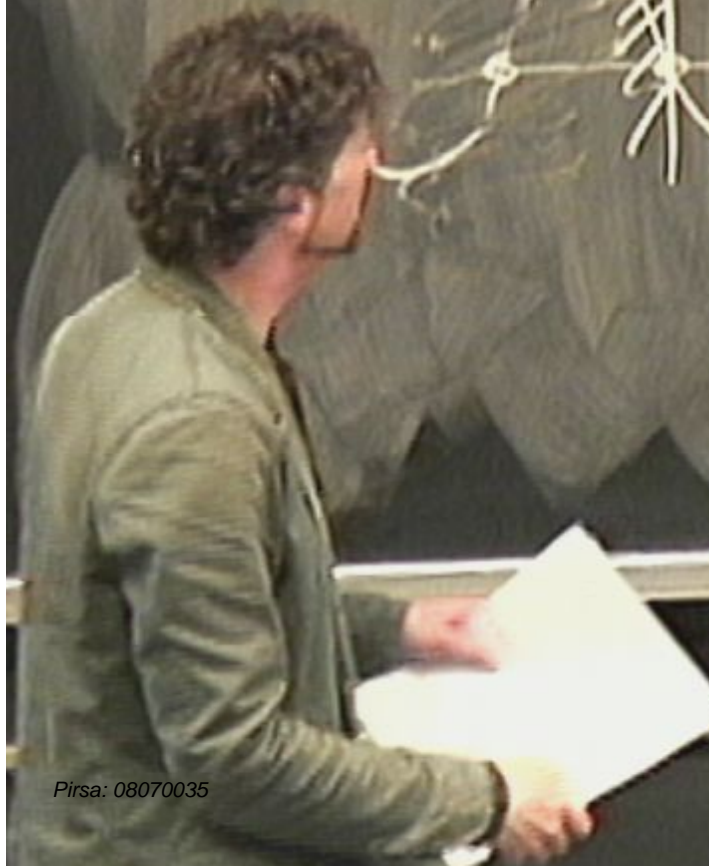
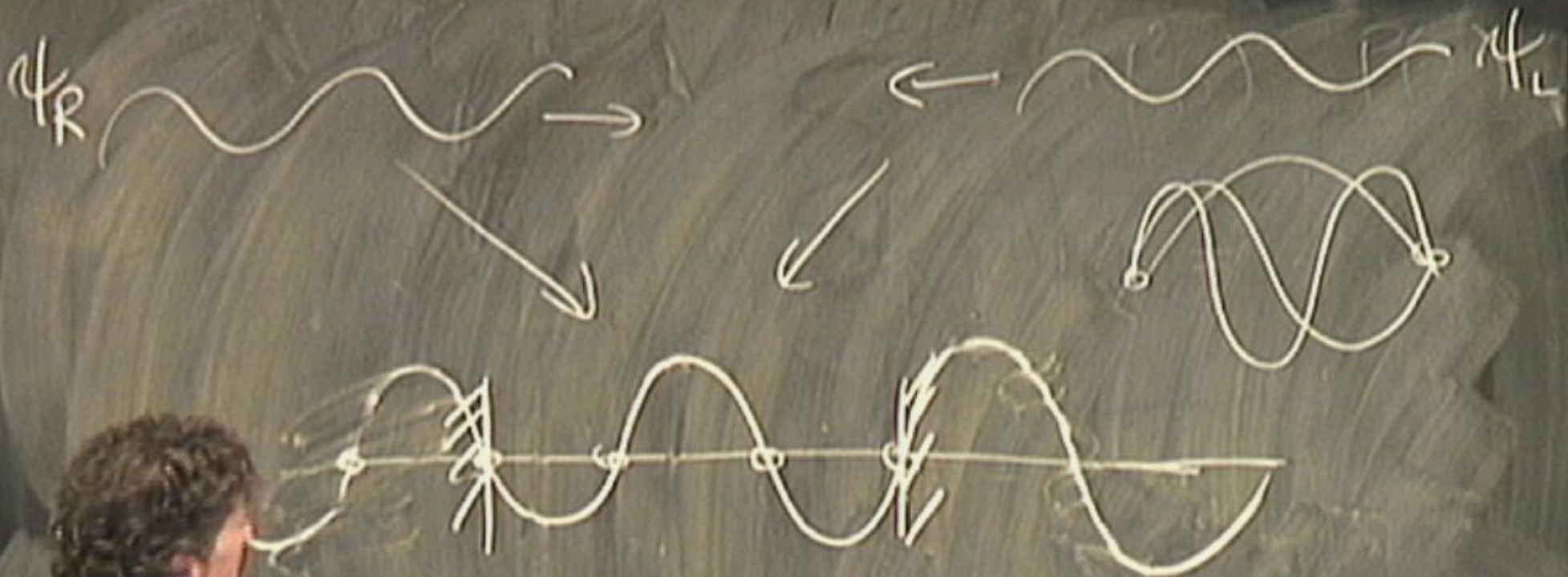
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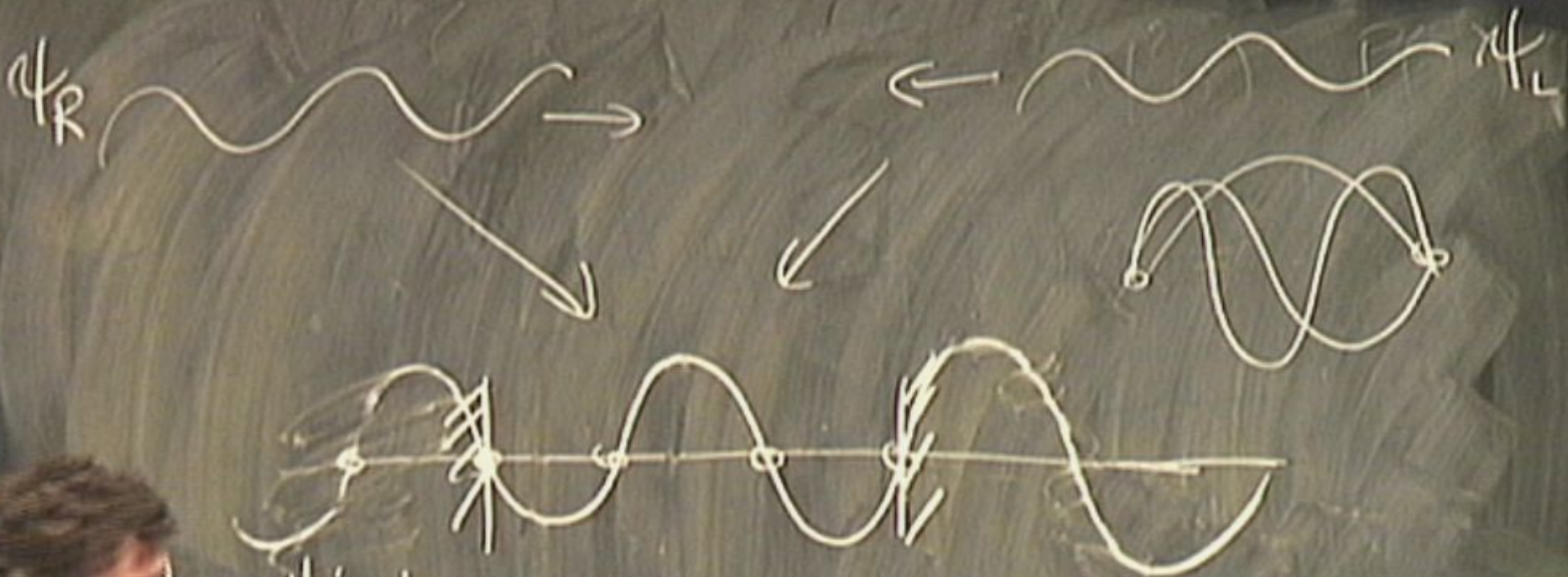




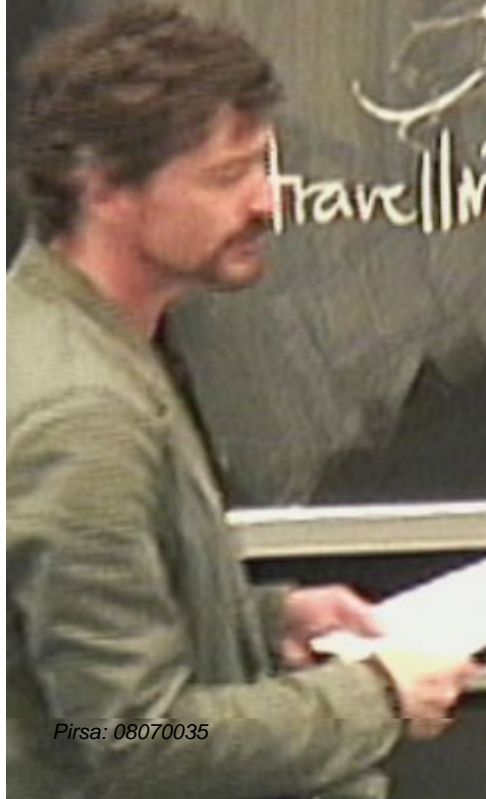






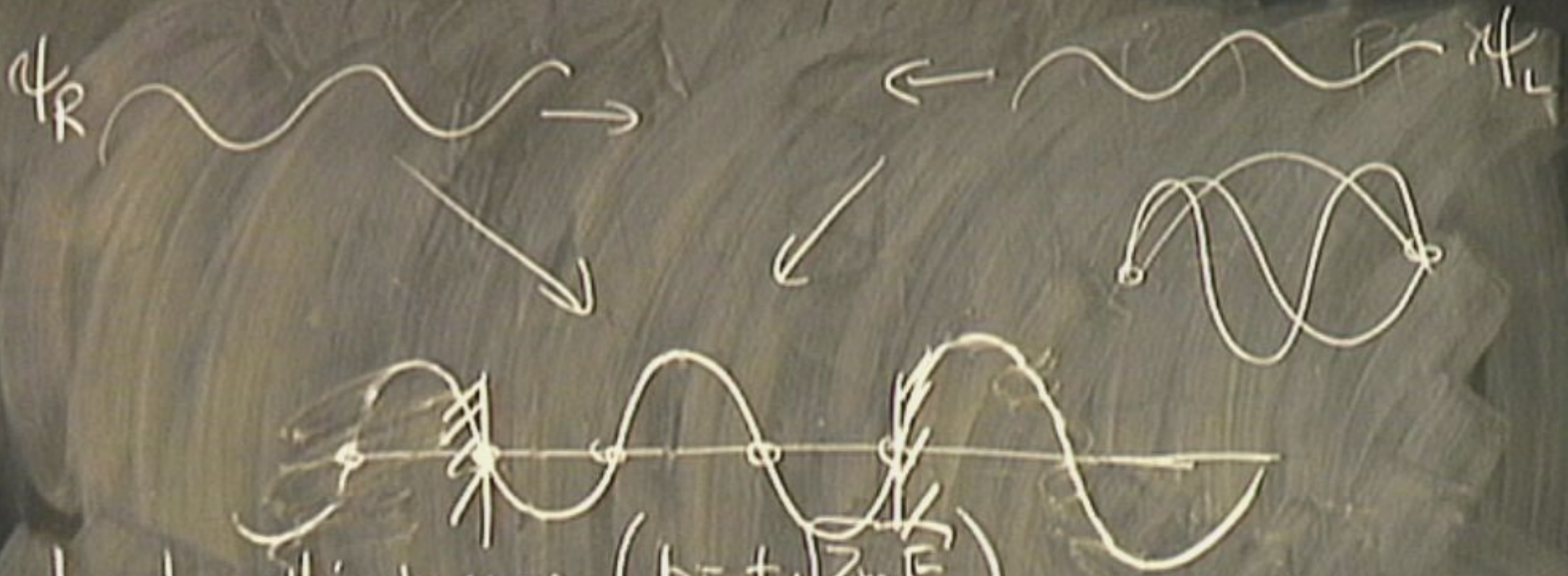


travelling waves





two travelling waves ($p = \pm u$) z in E



two travelling waves ($p = \pm \omega / c$)
 self reinforcing on multiple reflections.

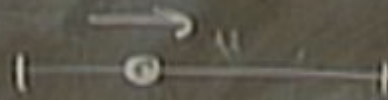


two traveling waves ($p = \pm \omega Z_m E$)
 self reflecting on multiple reflections.



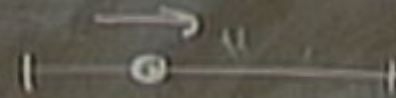
two travelling waves ($p = \pm \omega / c$)
 self reinforcing on multiple reflections.

classical:

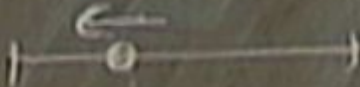


α

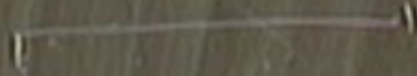
classical:



OR

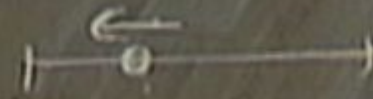


quantum

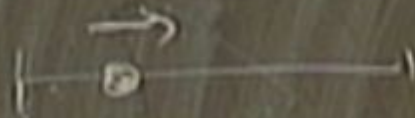


α

classical:

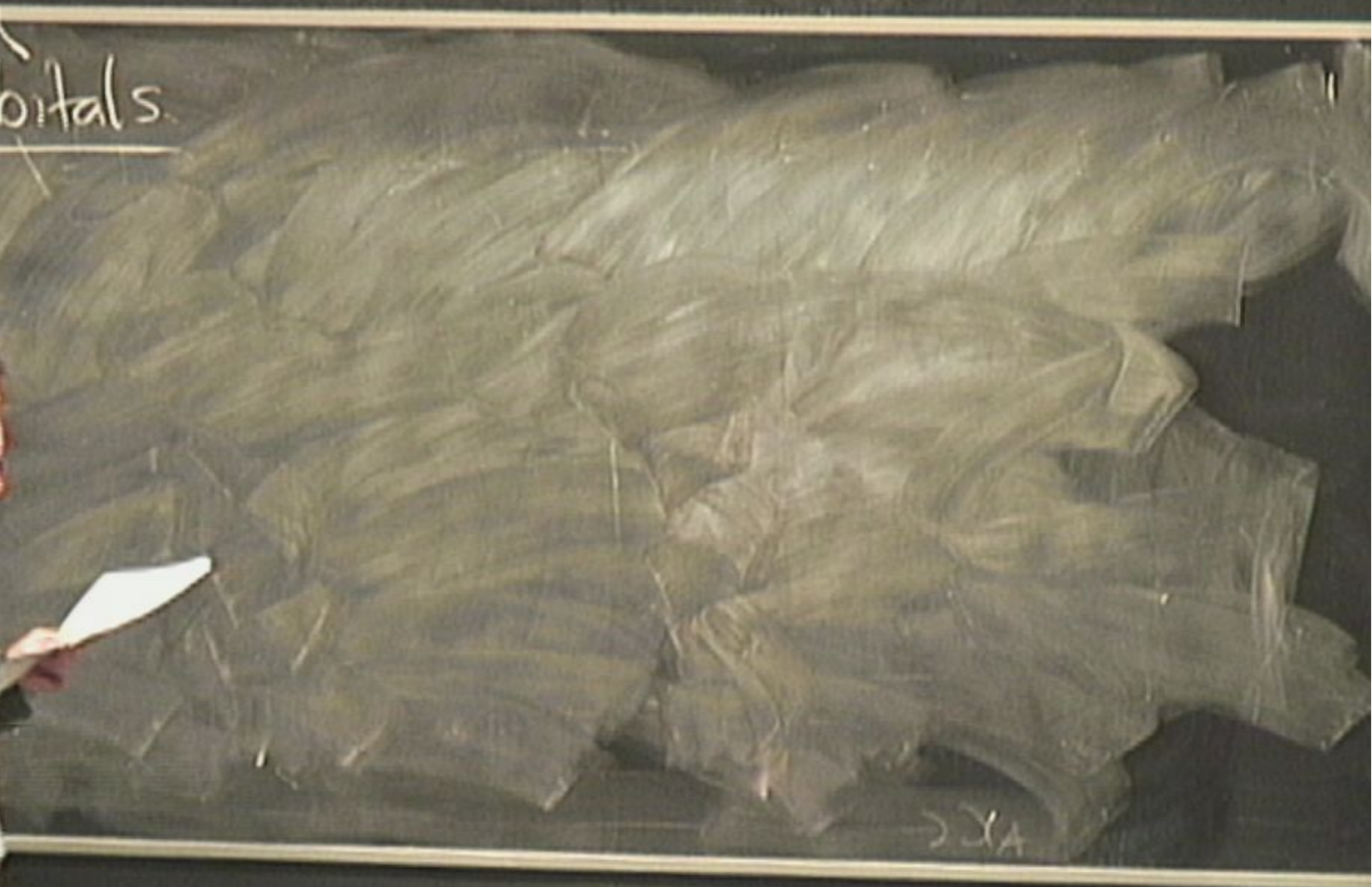


quantum



α

Orbitals



Orbitals



ARC

Orbitals



Orbitals



Orbitals

$n=0$



Orbitals

ψ_0



$\lambda = 2l$

Orbitals

ψ_0



$$\lambda = 2L$$

$$P_0 = \psi_0^2$$

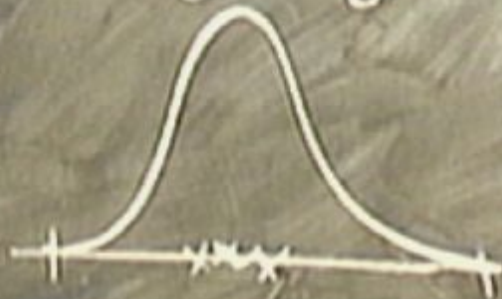


Orbitals

ψ_0

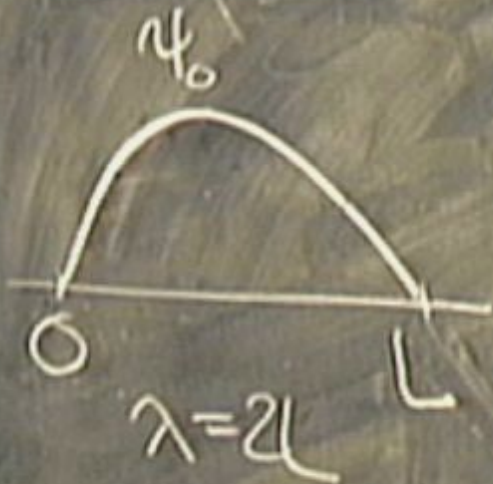


$P_0 = \psi_0^2$



$\psi_0 = 0$

Orbitals



$$P_0 = \psi_0^2$$



$$P_0 = \frac{\psi_0^2}{2m} =$$

Orbitals

ψ_0



$\lambda =$

$$P_0 = \psi_0^2$$



$$p = h/\lambda$$

$$E_0 = \frac{p^2}{2m} = \frac{h^2}{2m\lambda^2}$$

Orbitals

ψ_0



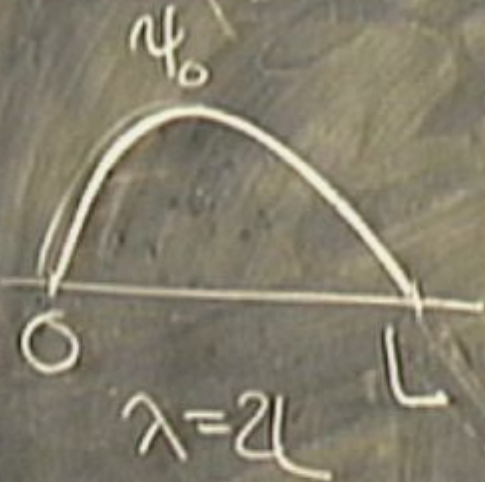
$$P_0 = \psi_0^2$$



$$p = h/\lambda$$

$$E_0 = \frac{p^2}{2m} = \frac{h^2}{2m\lambda^2} = \frac{h^2}{8mL^2}$$

Orbitals



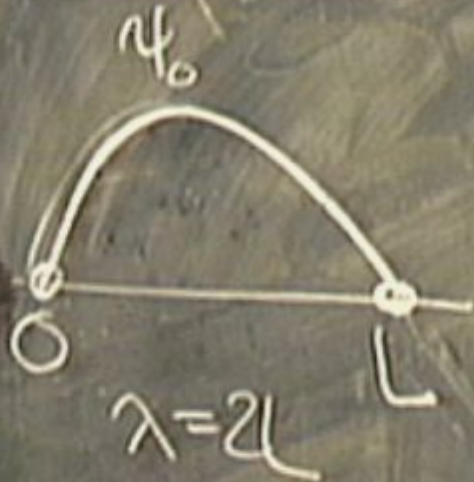
$$P_0 = \psi_0^2$$



$$p = h/\lambda$$

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Orbitals



$$P_0 = \psi_0^2$$

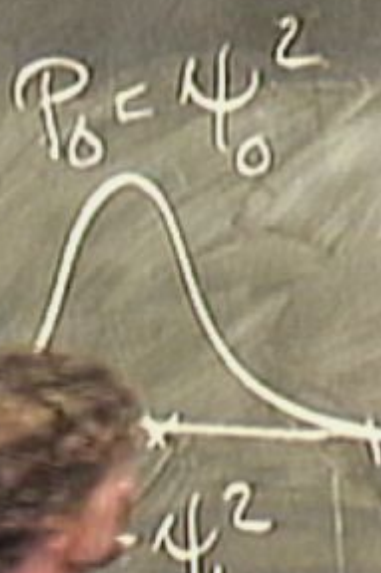
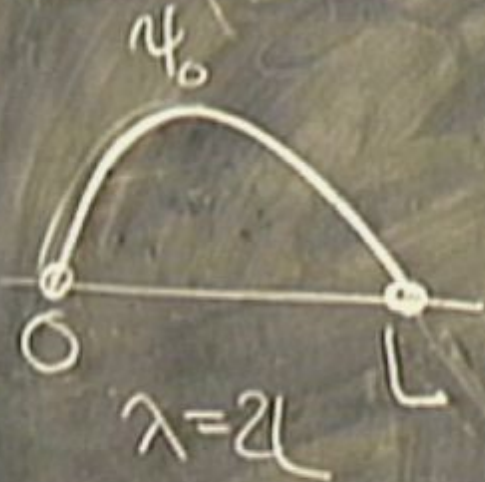


$$p = h/\lambda$$

$$E_0 = \frac{p^2}{2m} = \frac{h^2}{2m\lambda^2} = \frac{h^2}{8mL^2}$$



Orbitals



$p = h/\lambda$

$$E_0 = \frac{p^2}{2m} = \frac{h^2}{2m\lambda^2} = \frac{h^2}{8mL^2}$$

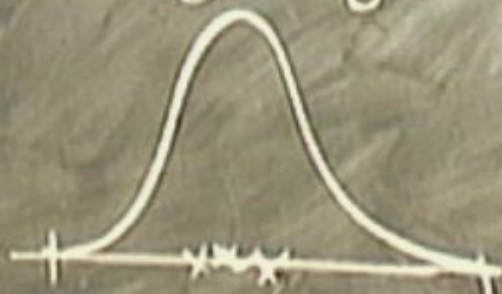
Orbitals

ψ_0

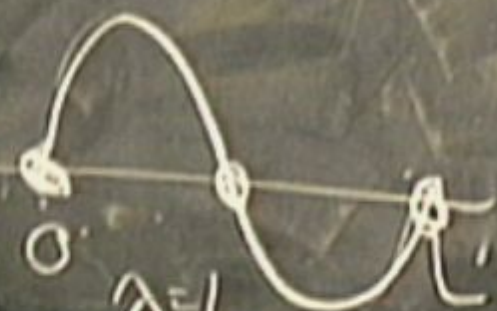
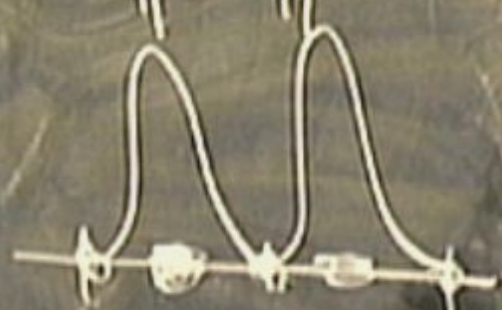


$\lambda = 2L$

$P_0 = \psi_0^2$



$P = \psi^2$



$\lambda = L$

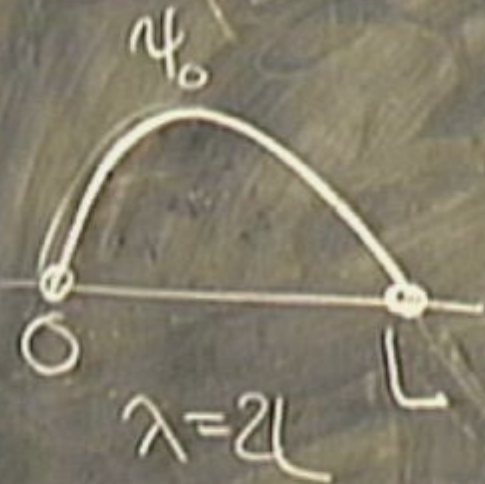
$$p = h/\lambda$$

$$\frac{h}{\lambda} = \frac{h}{2L} \Rightarrow \frac{h^2}{4m\lambda^2} = \frac{h^2}{4m(2L)^2} = \frac{h^2}{16mL^2}$$

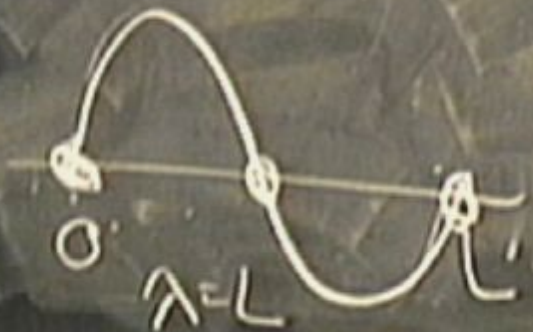
$$\frac{h}{\lambda} = \frac{h}{L} \Rightarrow \frac{h^2}{4m\lambda^2} = \frac{h^2}{4mL^2}$$

$\frac{h^2}{4mL^2}$

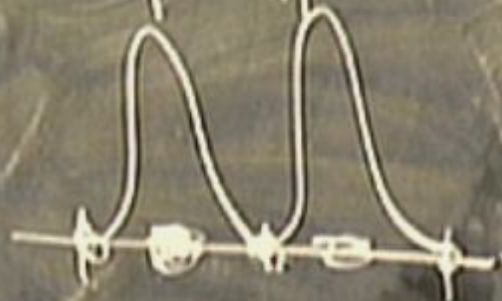
Orbitals



$$P_0 = \psi_0^2$$



$$P_1 = \psi_1^2$$

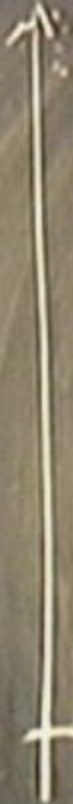


$$E_0 = \frac{1}{2m} \int_0^L \psi_0^2 dx = \frac{1}{2m} \int_0^L \frac{h^2}{4L^2} dx = \frac{h^2}{8mL^2}$$

$p = h/\lambda$

$$E_1 = \frac{1}{2m} \int_0^L \psi_1^2 dx = \frac{1}{2m} \int_0^L \frac{h^2}{L^2} dx = \frac{h^2}{2mL^2} = 4E_0$$

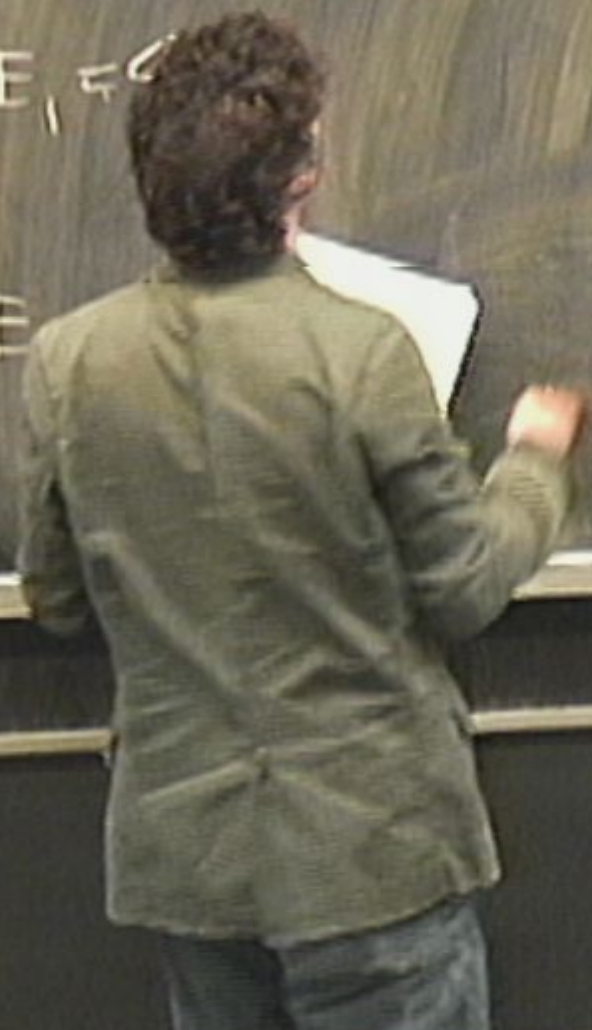
energy



$E_2 = 4E_0$
energy



(1)



energy $E_2 = 9E_0$



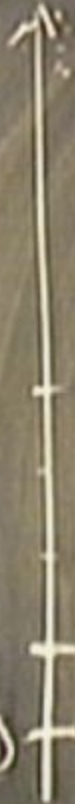
$E_1 = 4E_0$

E_0

O

(1) any ba

energy



$$E_1 = 4E_0$$

$$E_0$$

0

(1) any bound particle

energy $E_2 = 9E_0$



$$p = \frac{h}{\lambda}$$

- (i) any bound particle
- ⇒ bound wave
- ⇒ discrete harmonics ("orbitals")
- ⇒

energy $E_2 = 9E_0$



$$p = \frac{h}{\lambda}$$

(1) any bound particle
 \Rightarrow bound wave

\Rightarrow discrete λ

\Rightarrow discrete p

\Rightarrow discrete E (quantized)

energy $E_n = 9E_0$

$$p = \frac{h}{\lambda}$$



$E = 4E_0$

(1) any bound particle
 \Rightarrow bound wave

\Rightarrow discrete λ

\Rightarrow discrete p

\Rightarrow discrete E (quantized)

(2) $E_0 > 0$ (zero point energy)