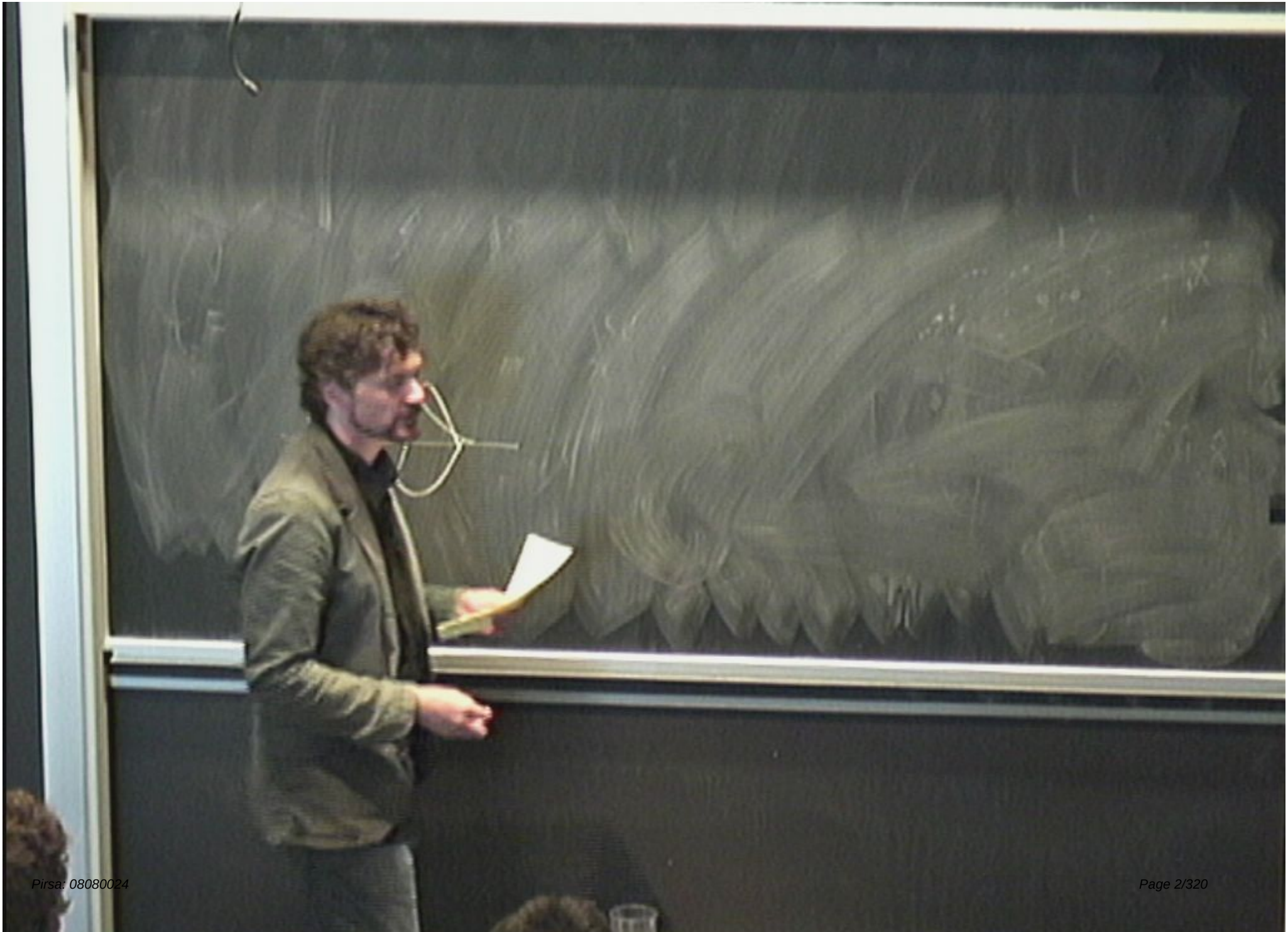
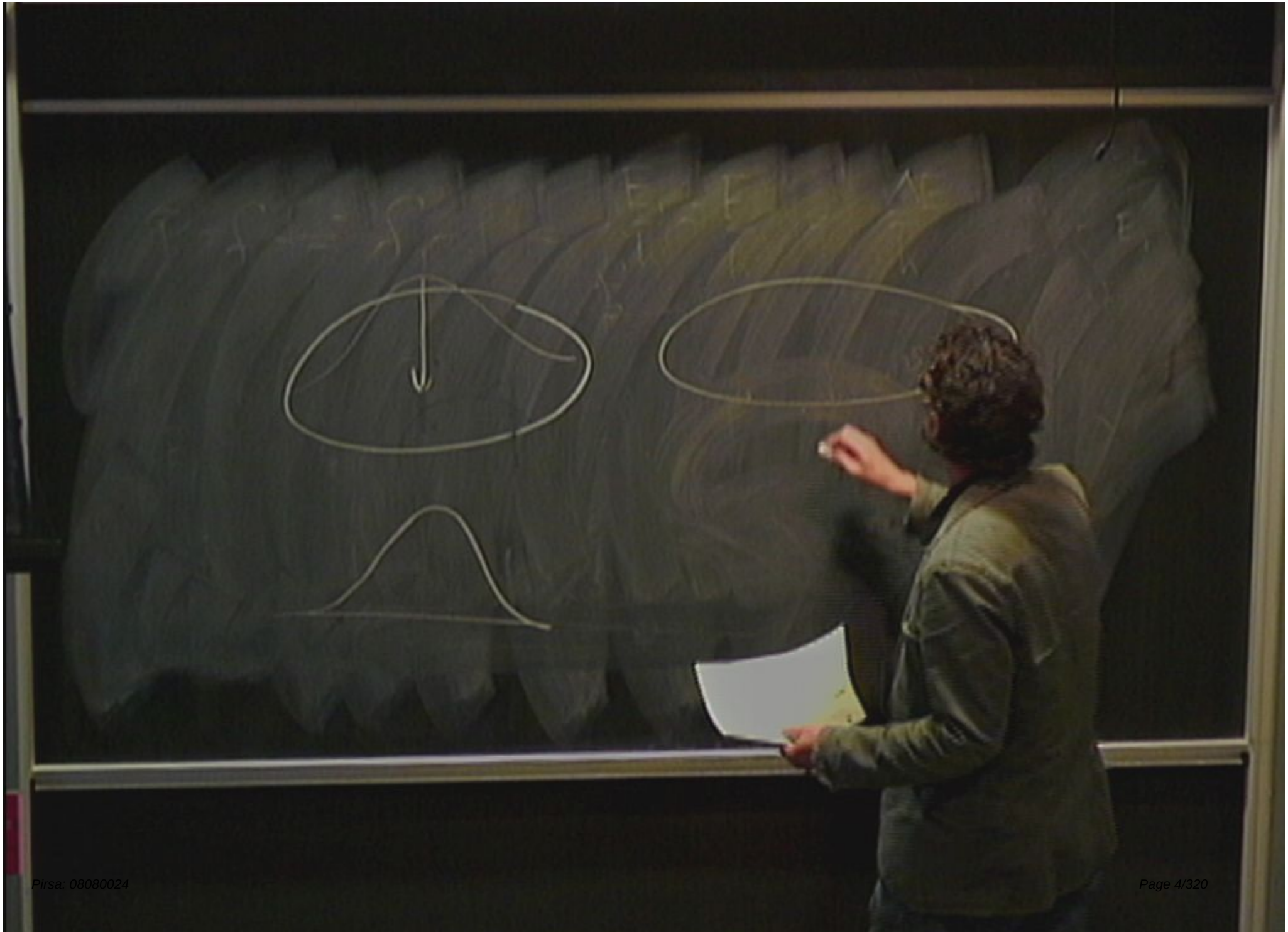
Title: Quantum 6

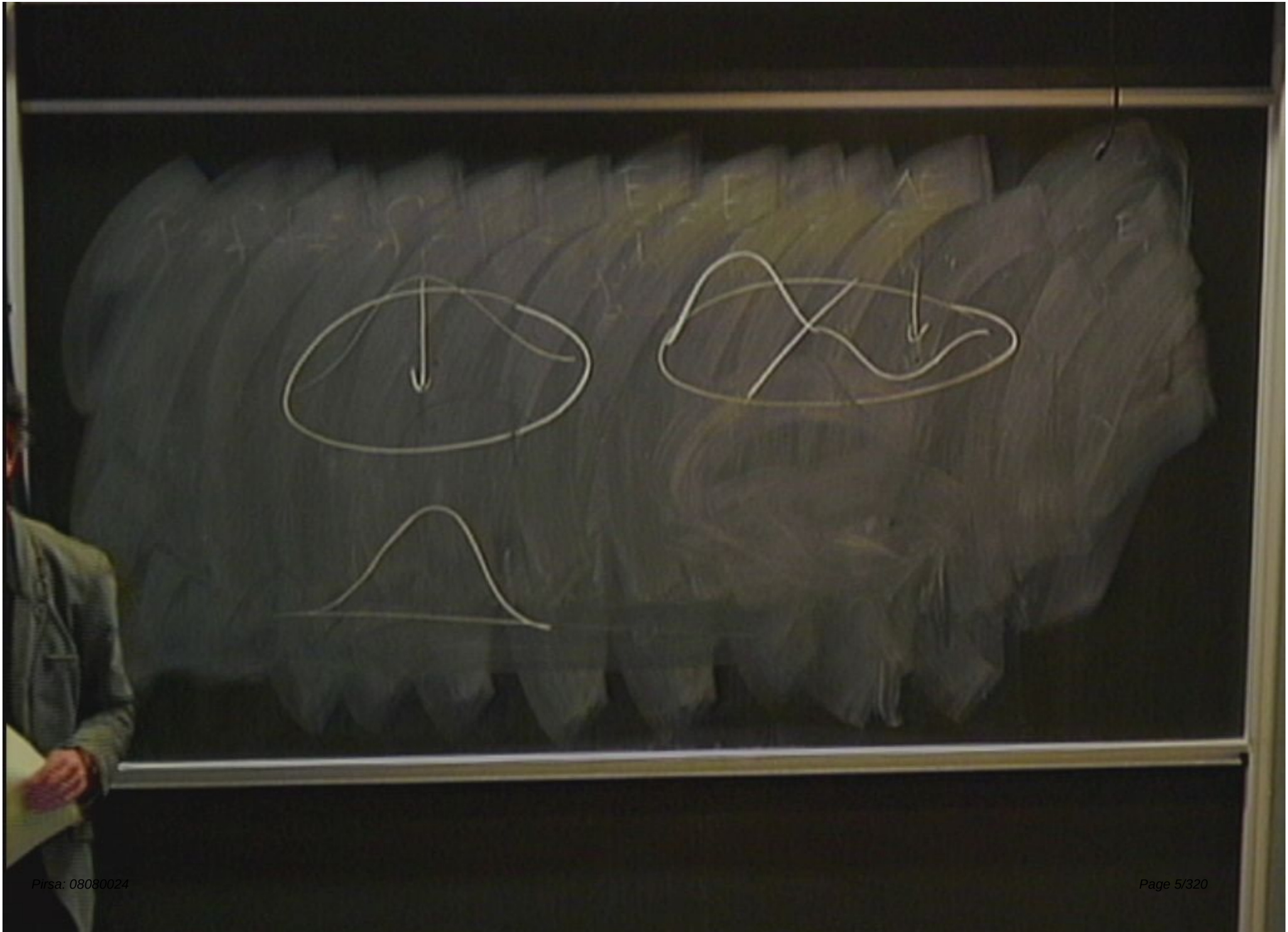
Date: Aug 16, 2008 03:30 PM

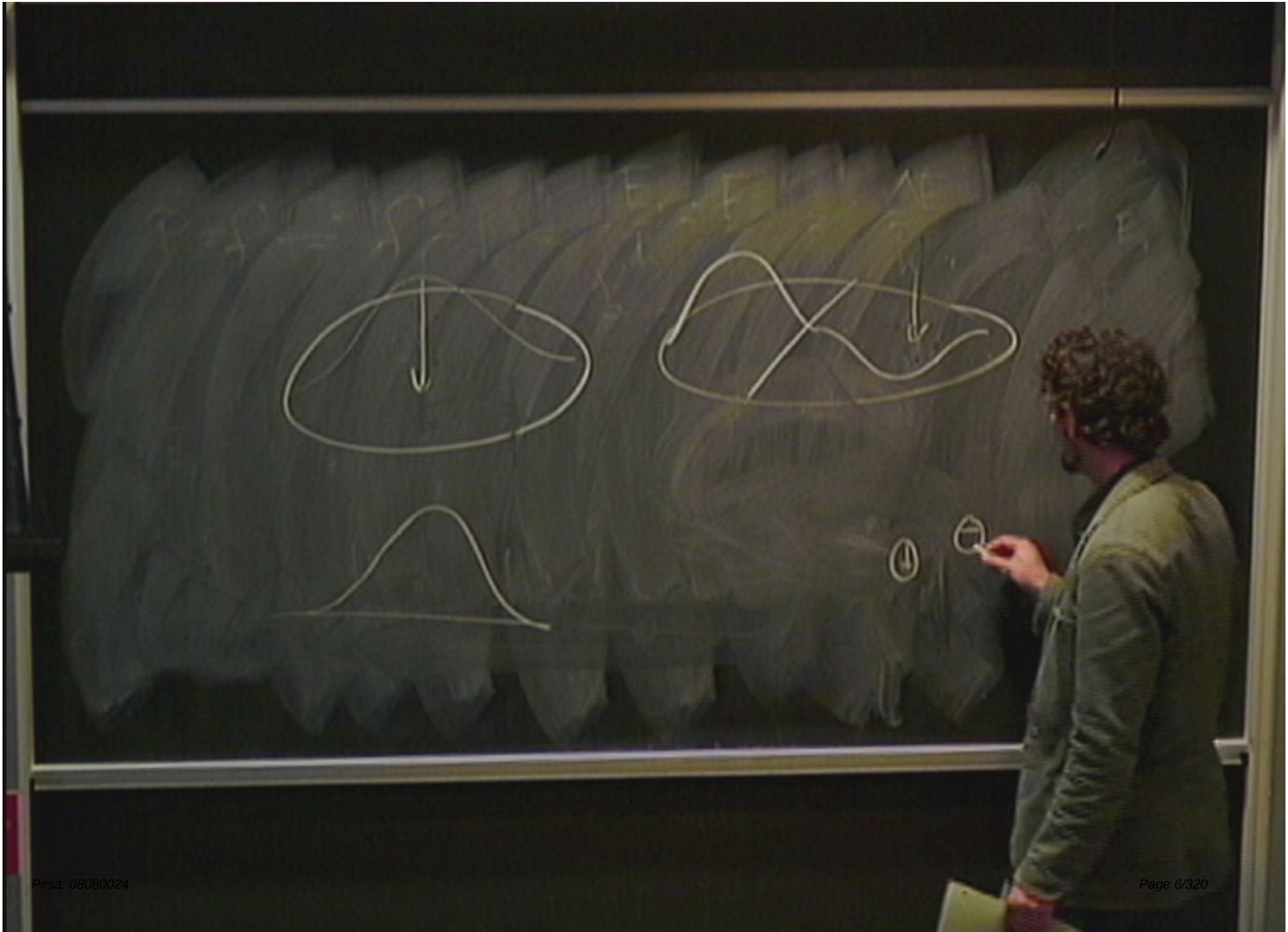
URL: http://pirsa.org/08080024

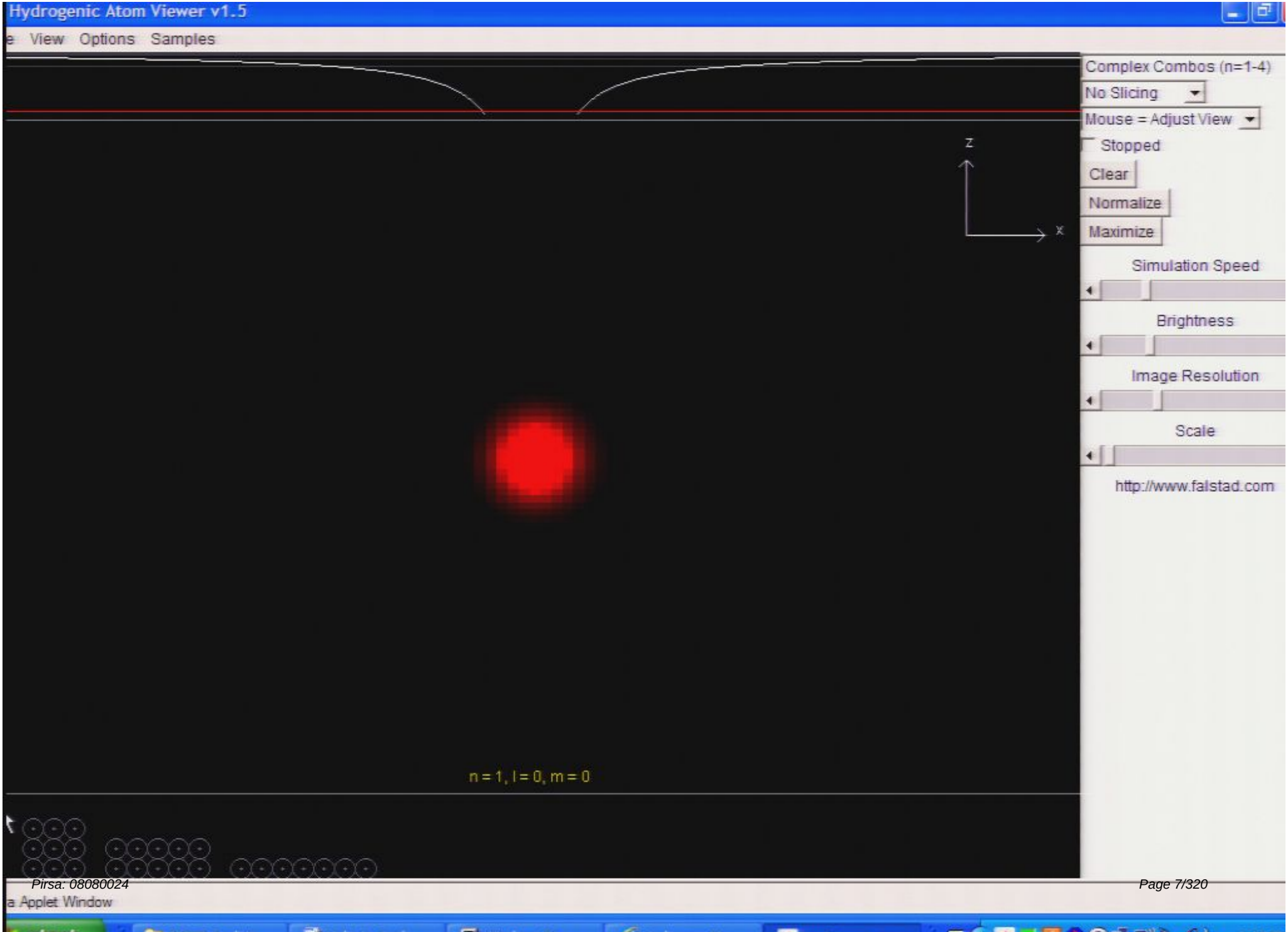
Abstract:







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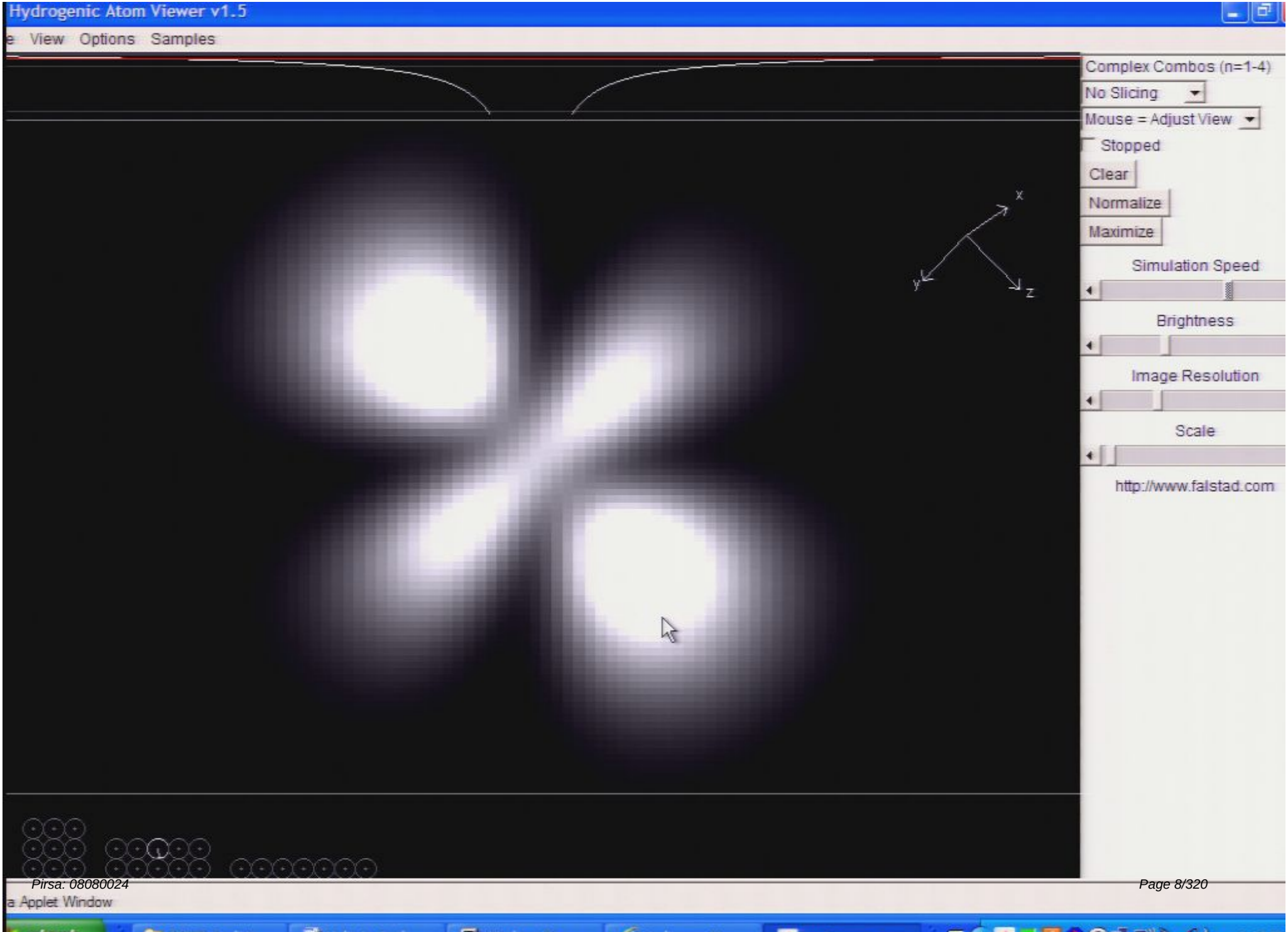
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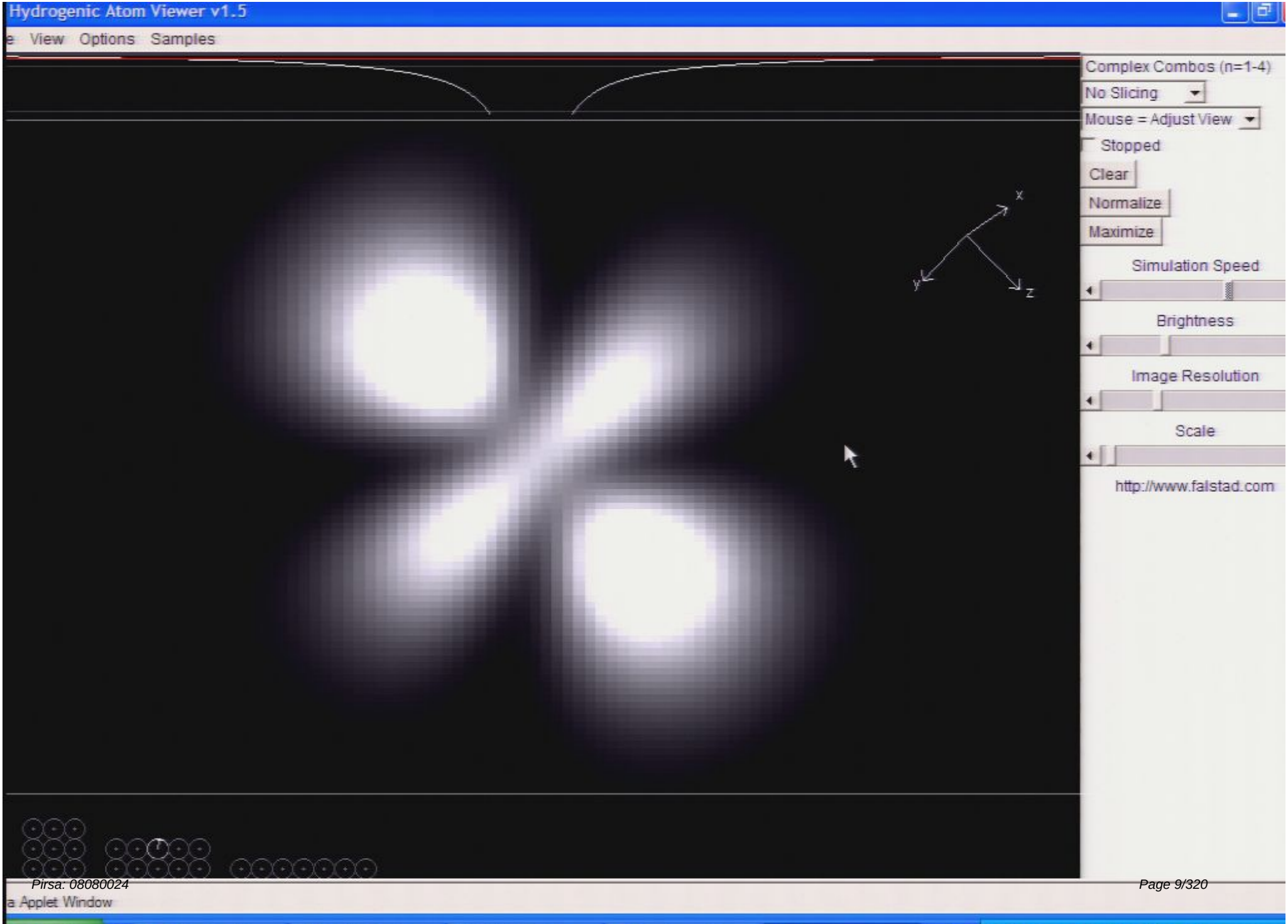
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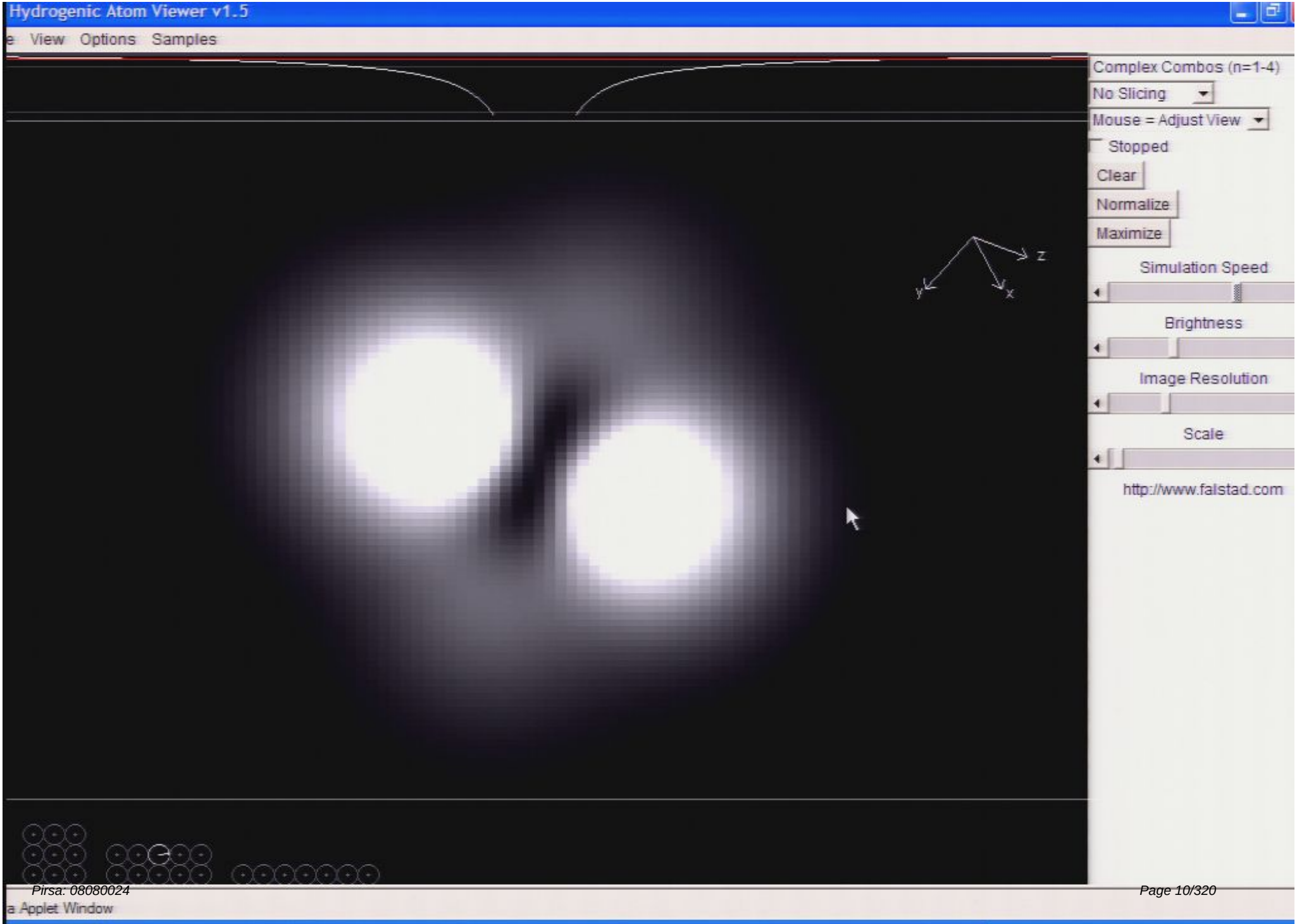
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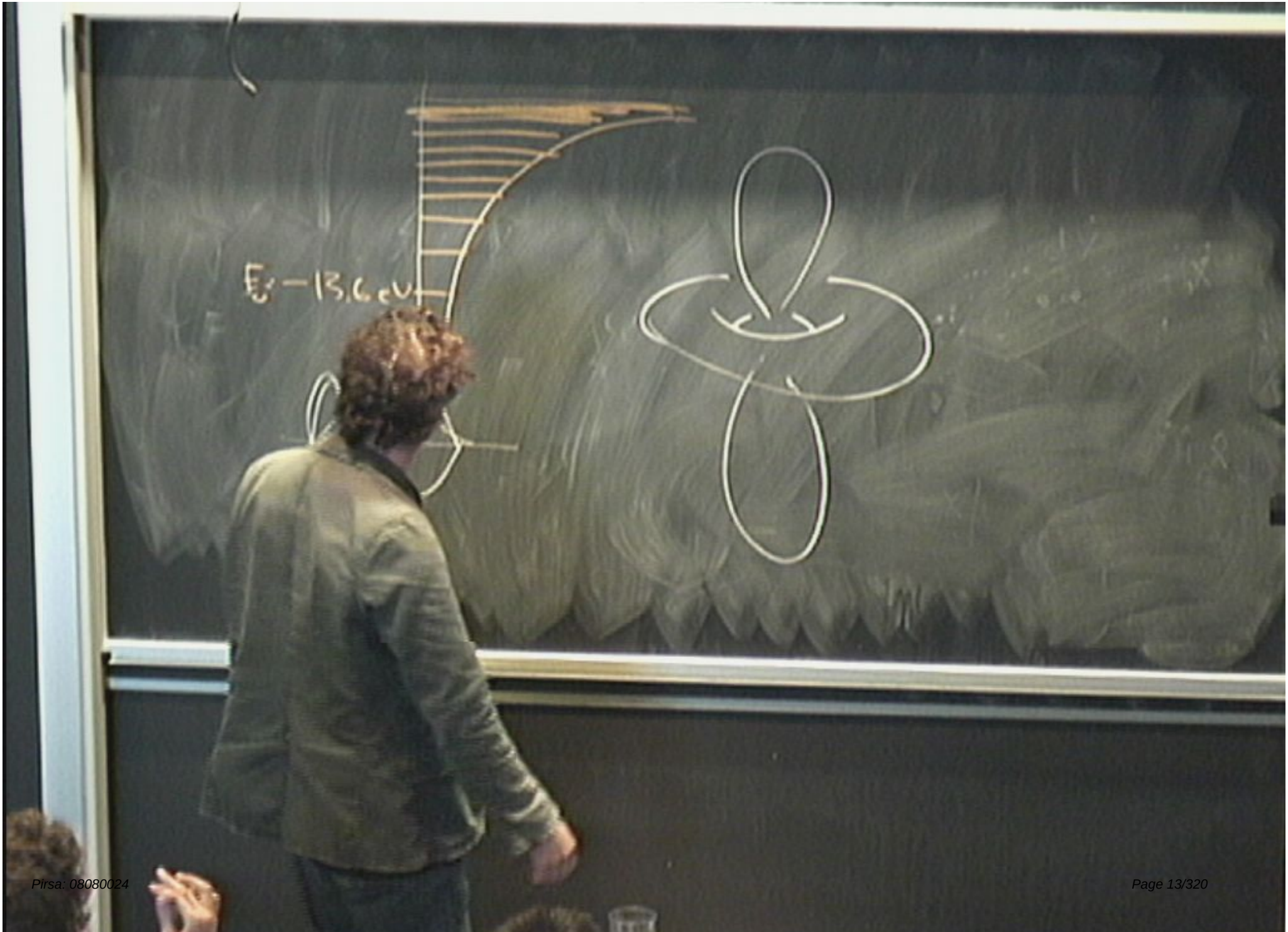
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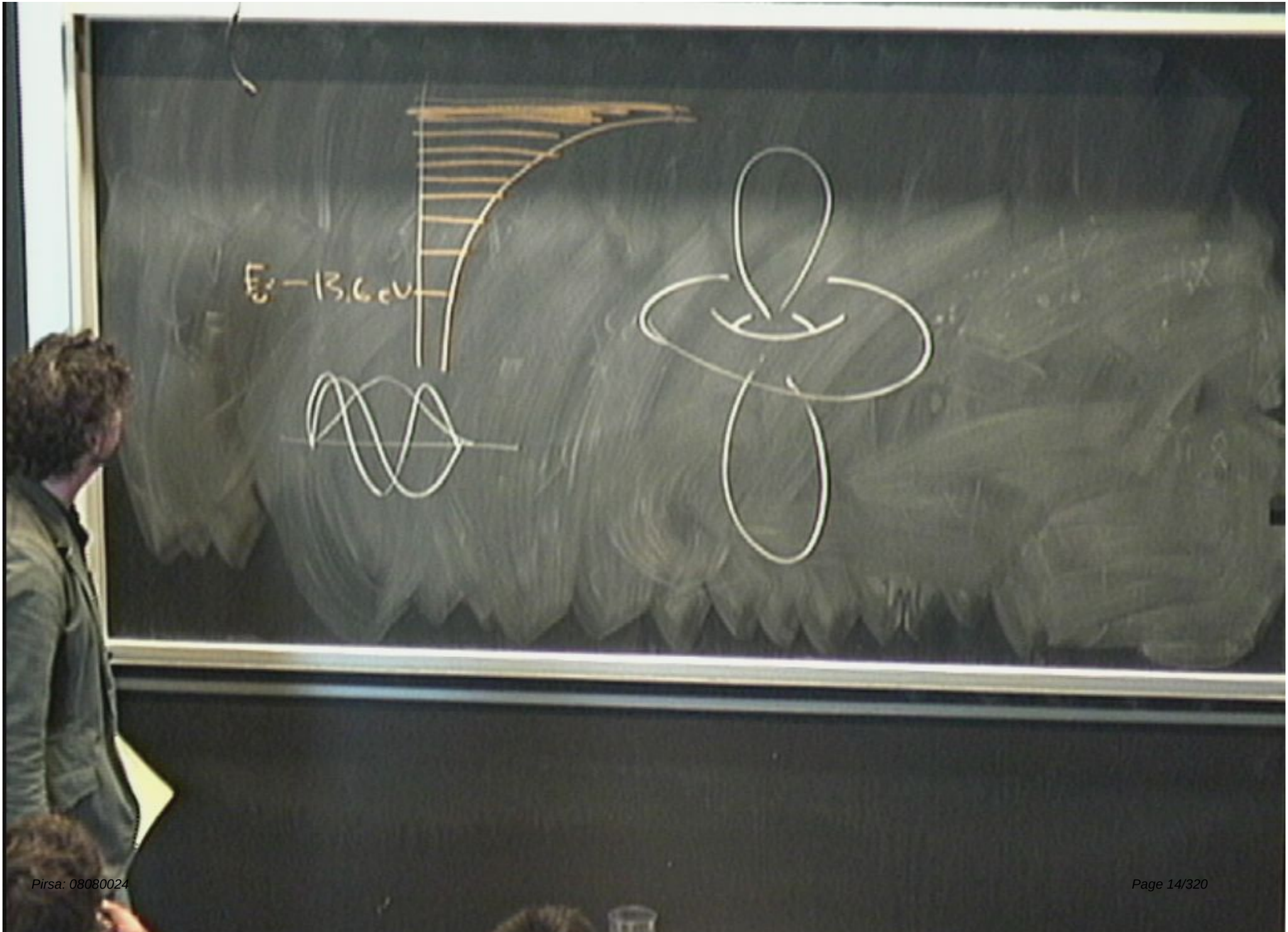
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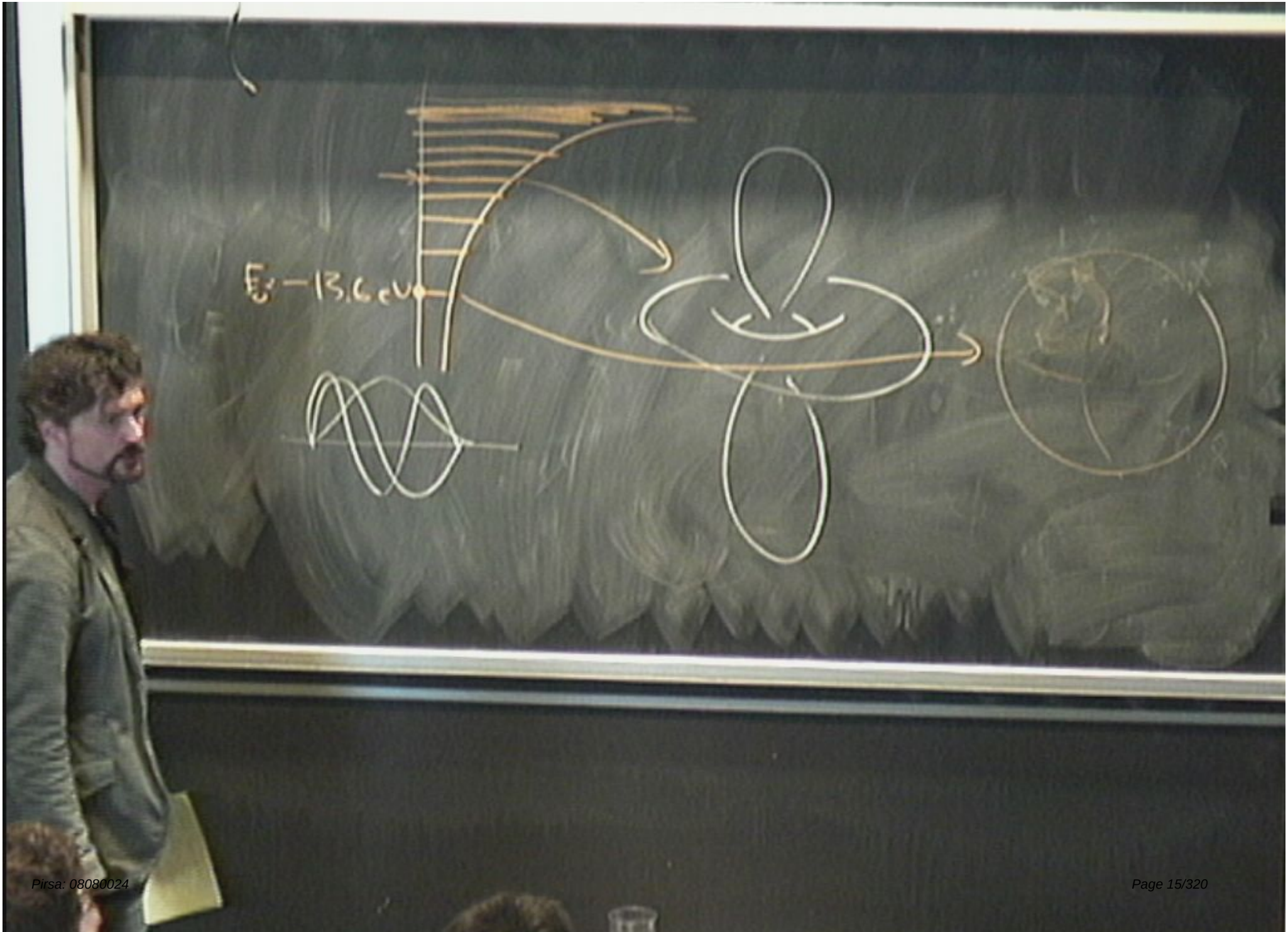
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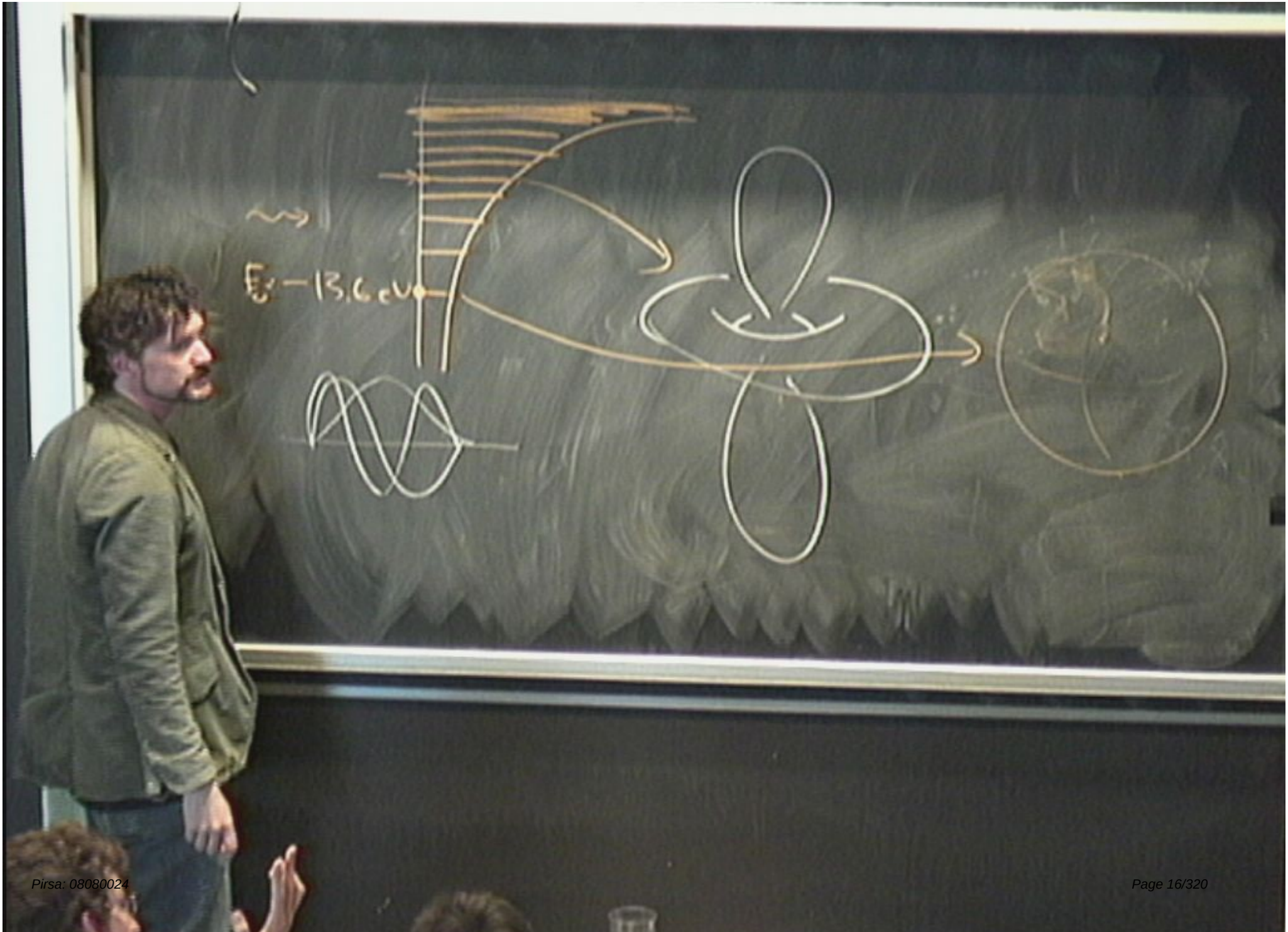
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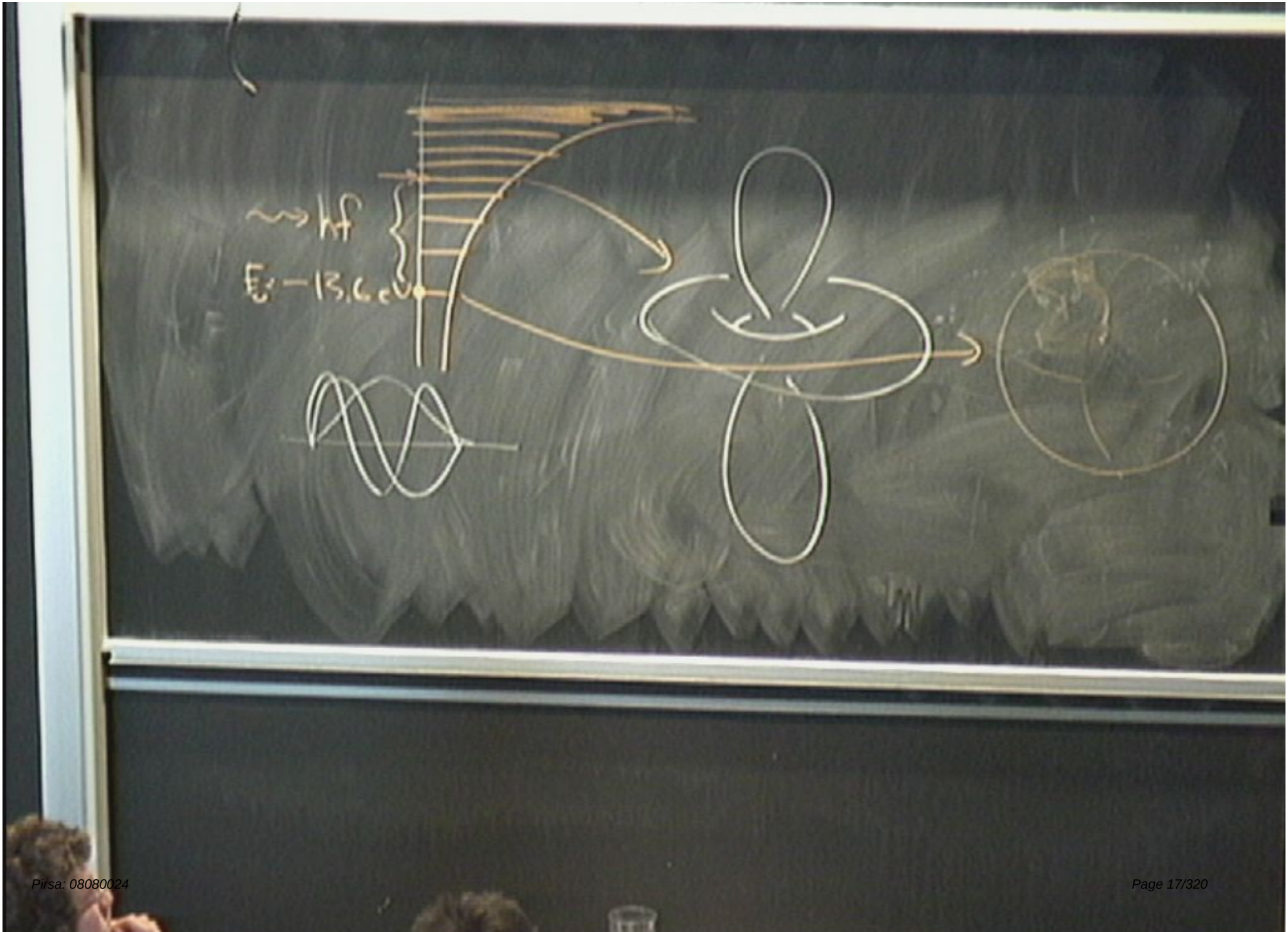
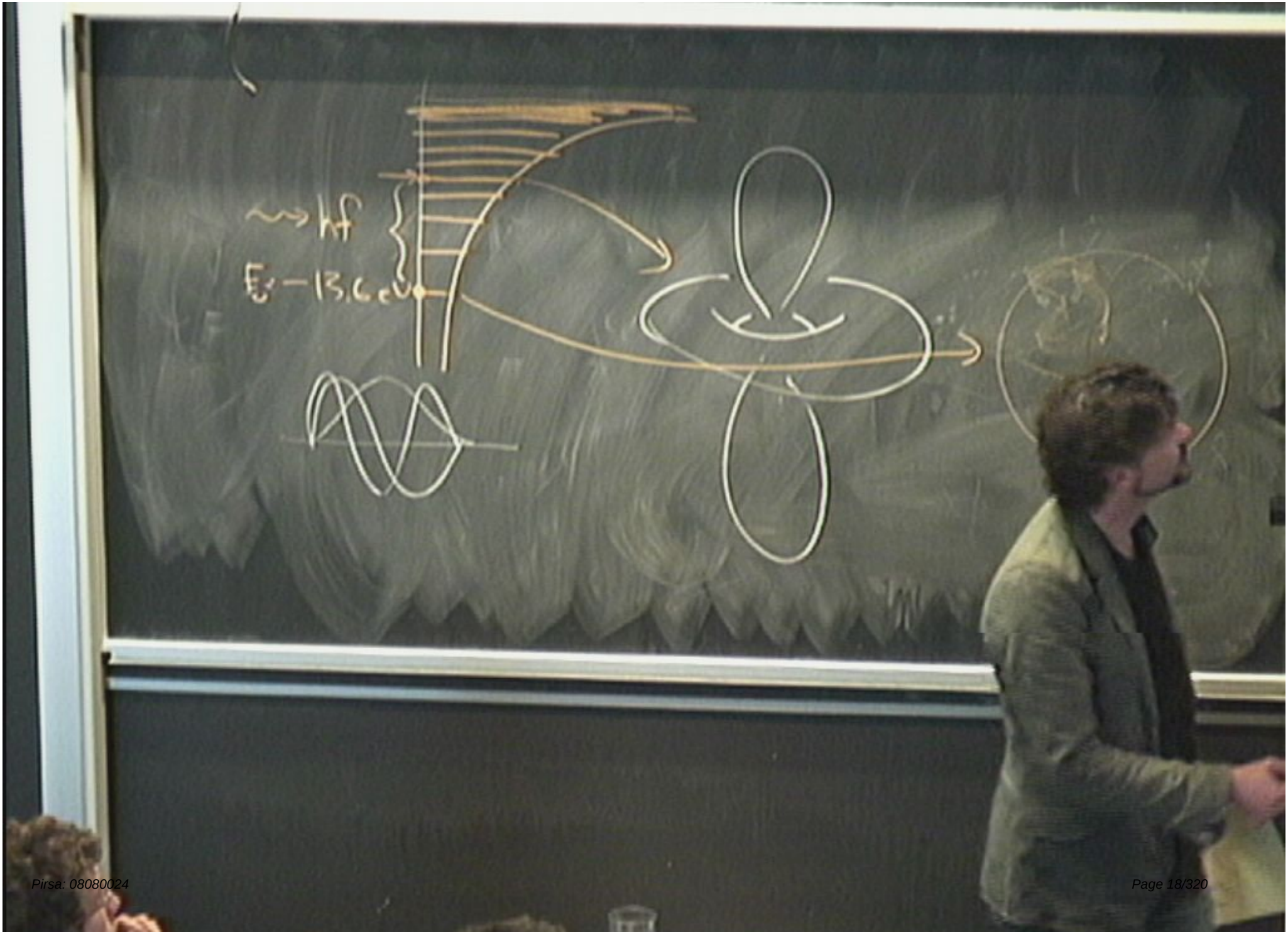

hf
E₀ = −13,6 eV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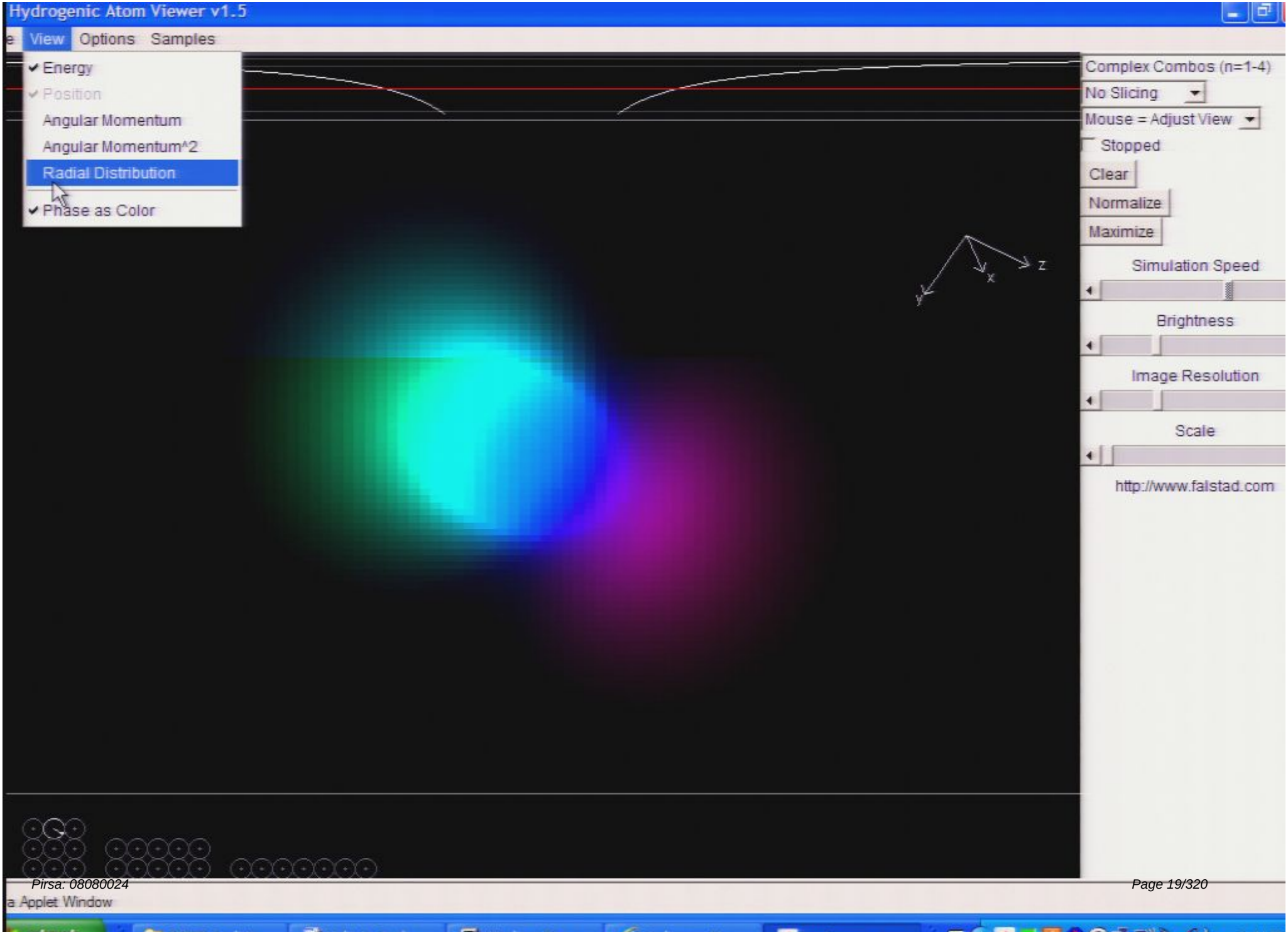
E₀ − 13.6 eV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Angular Momentum^2
Radial Distribution
Phase as Color
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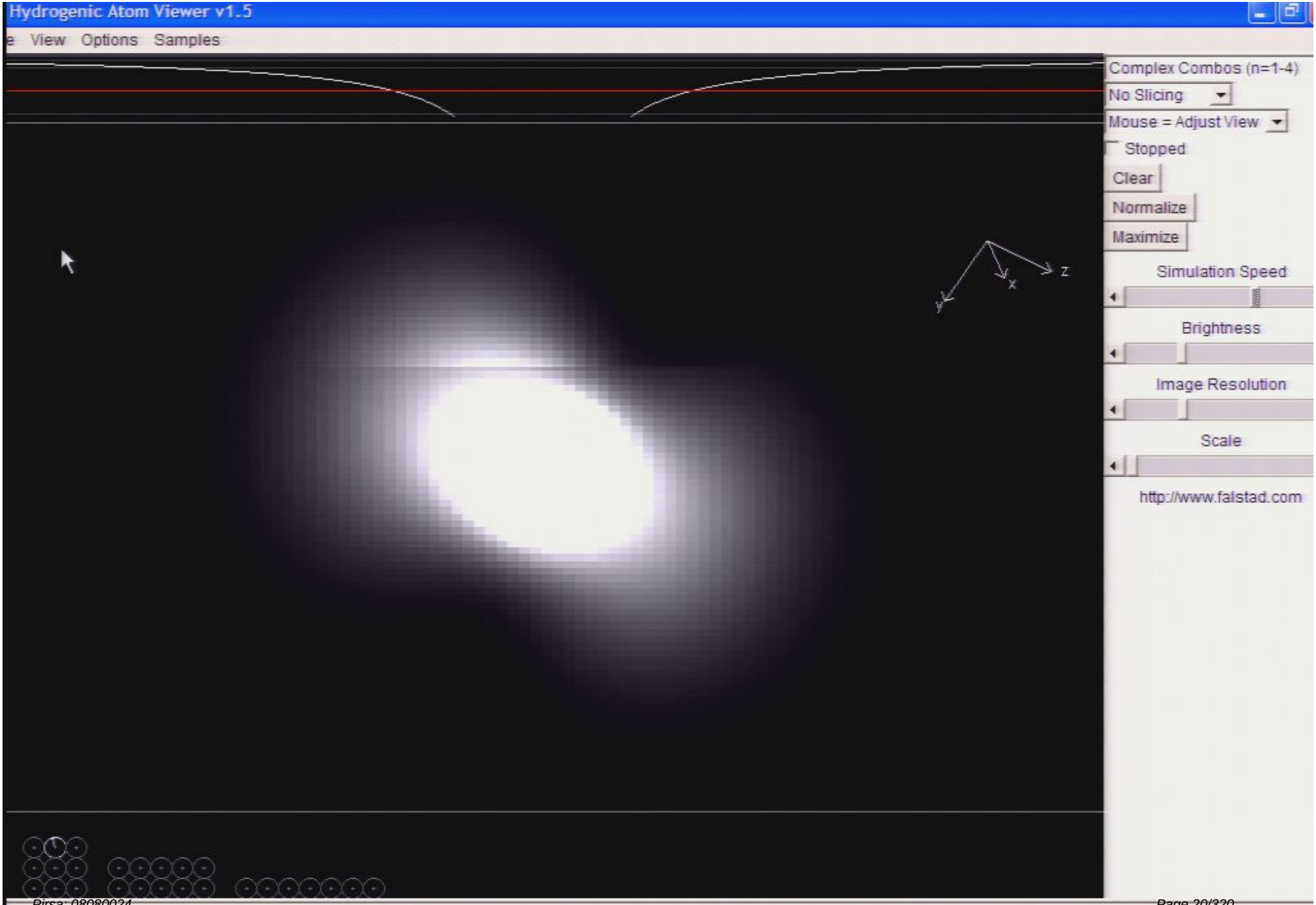
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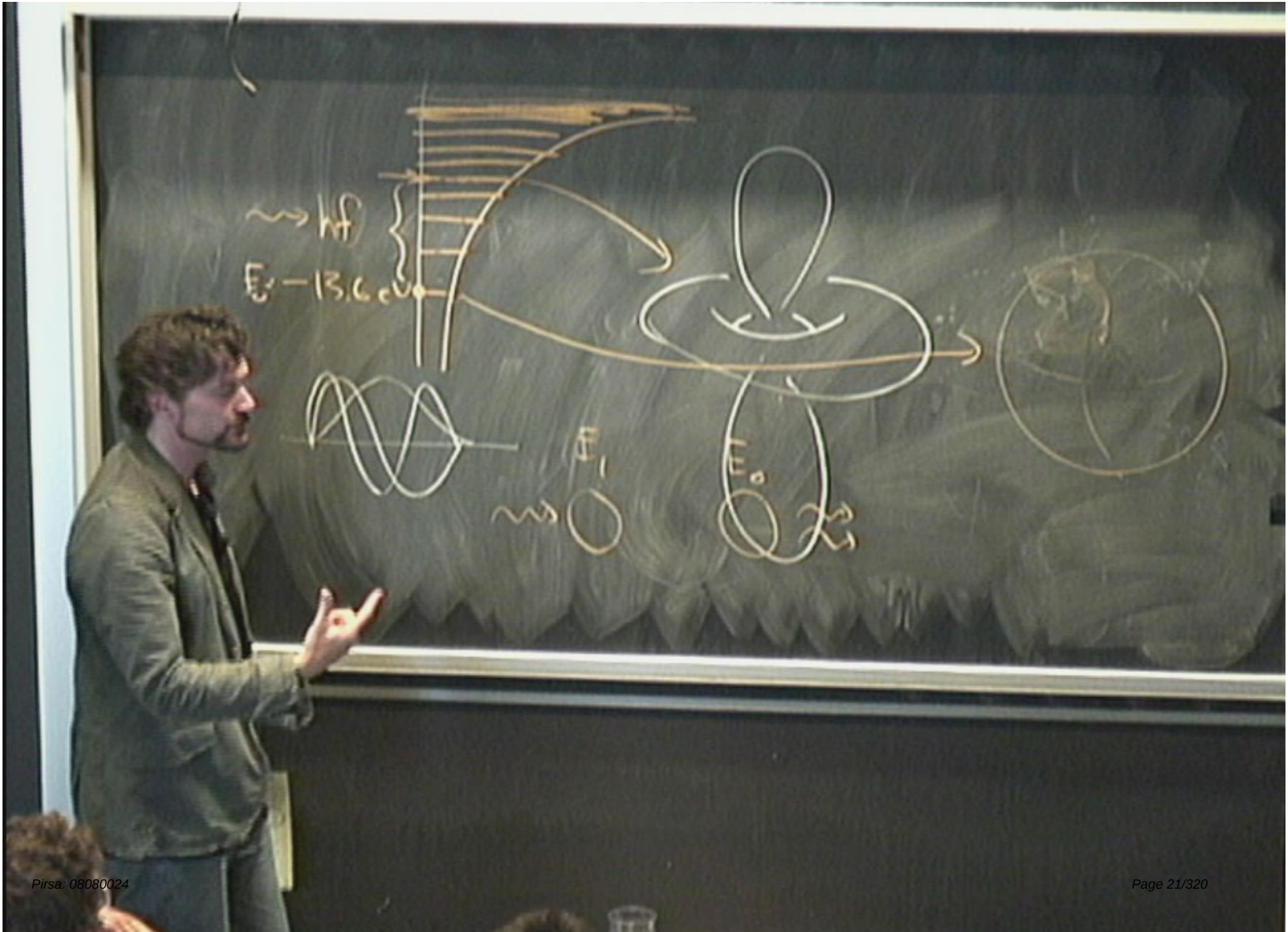
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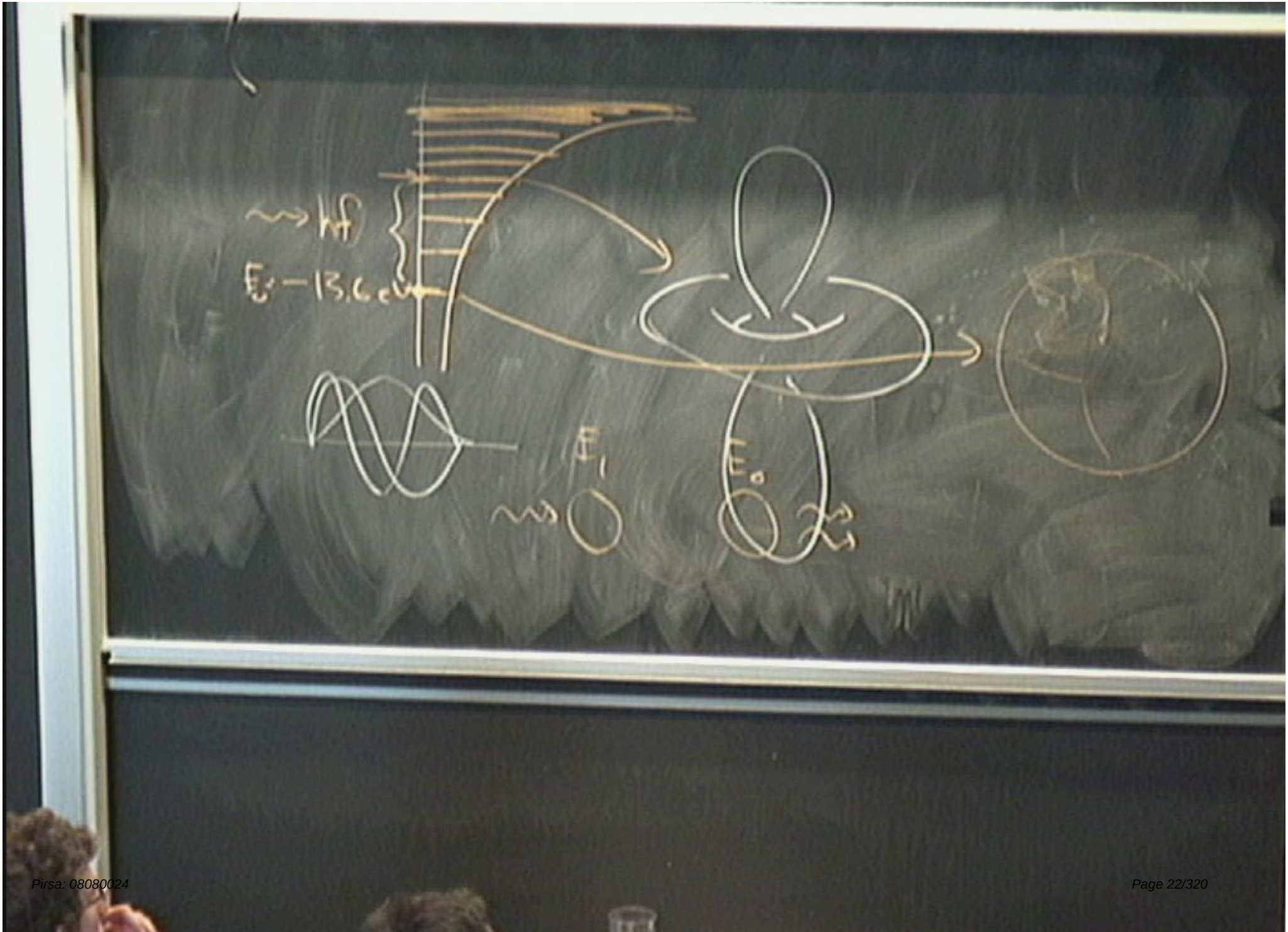
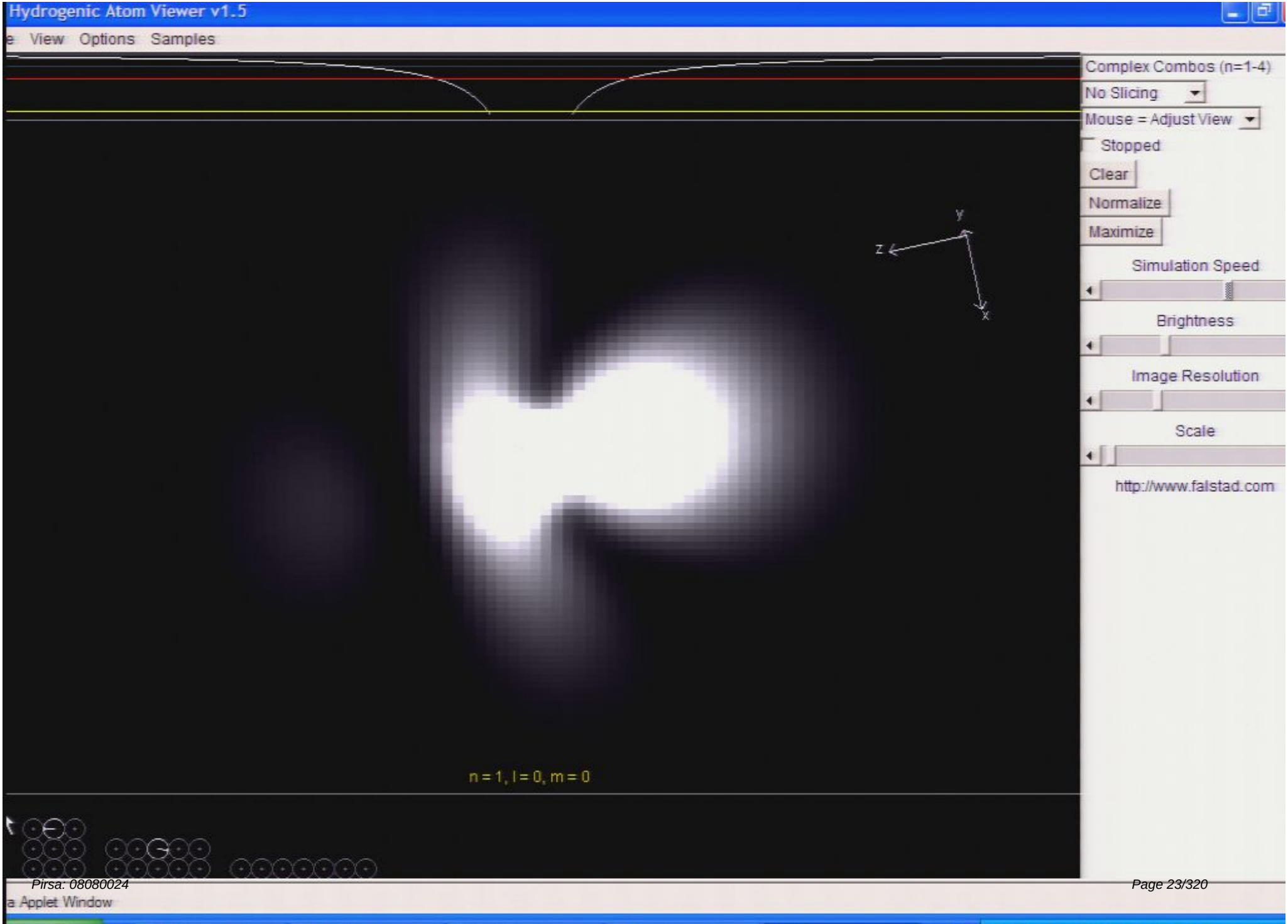
E = -13.6 eV
E1


hf
E₀ = −13.6 eV
E₁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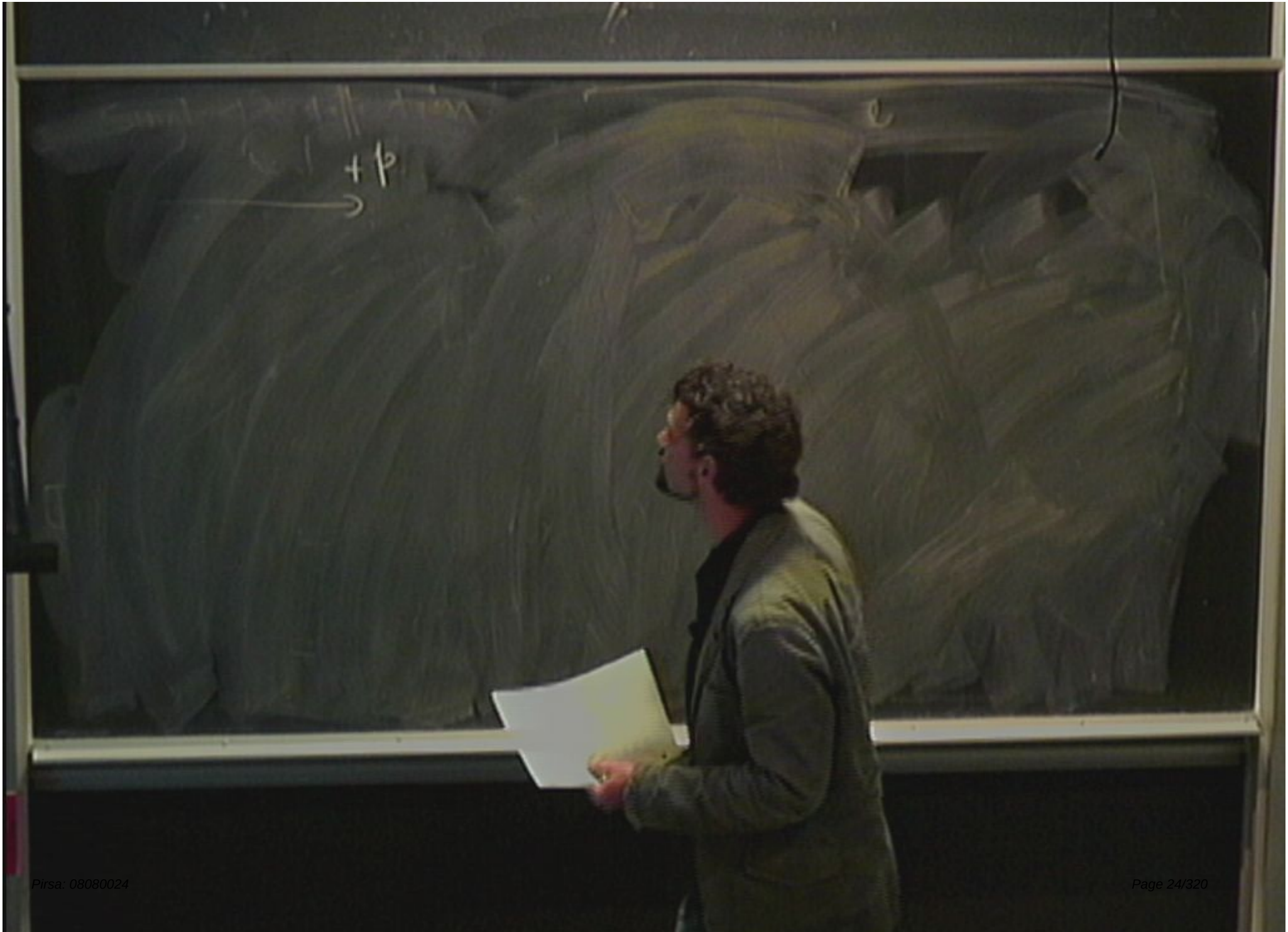
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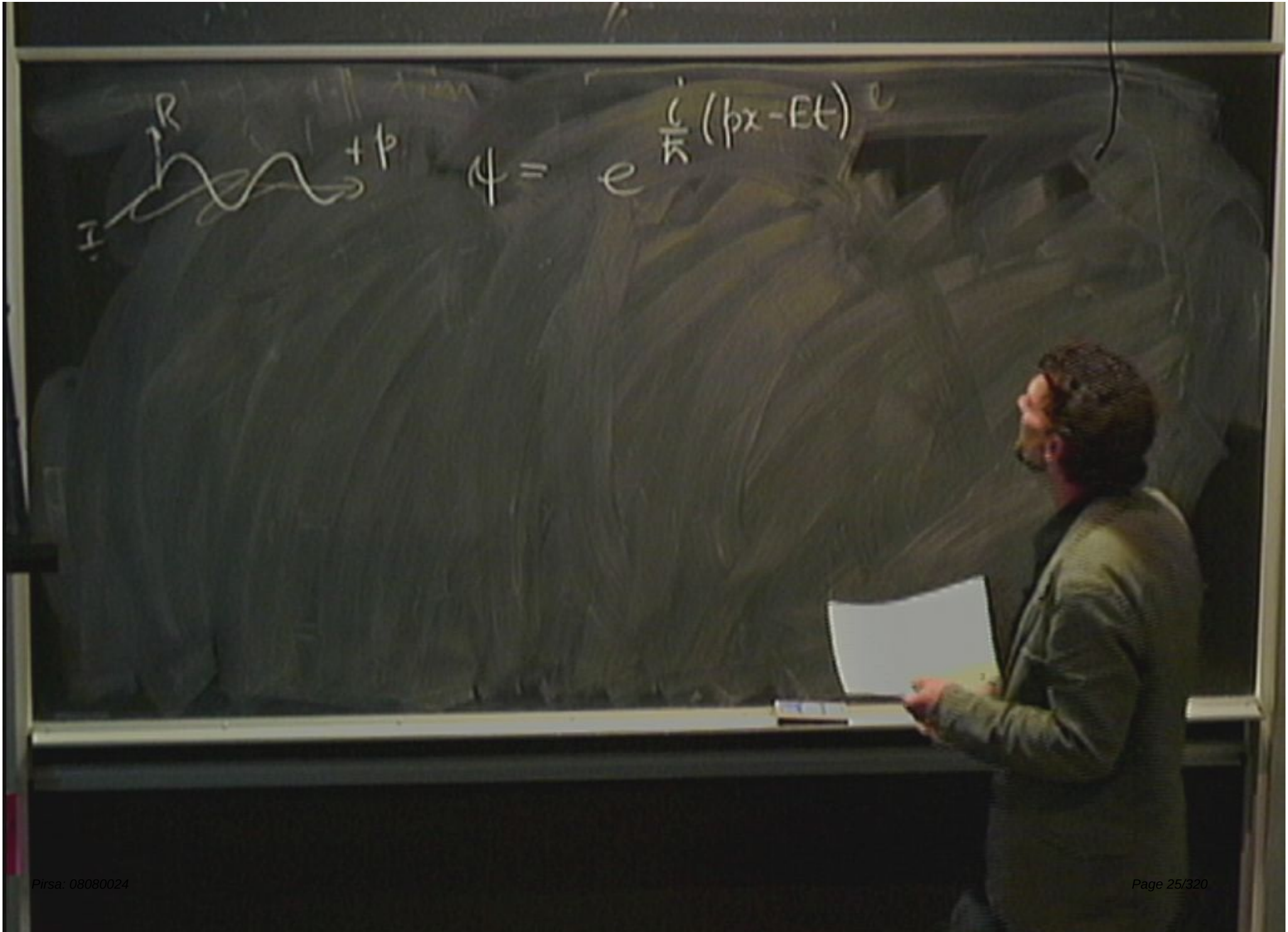
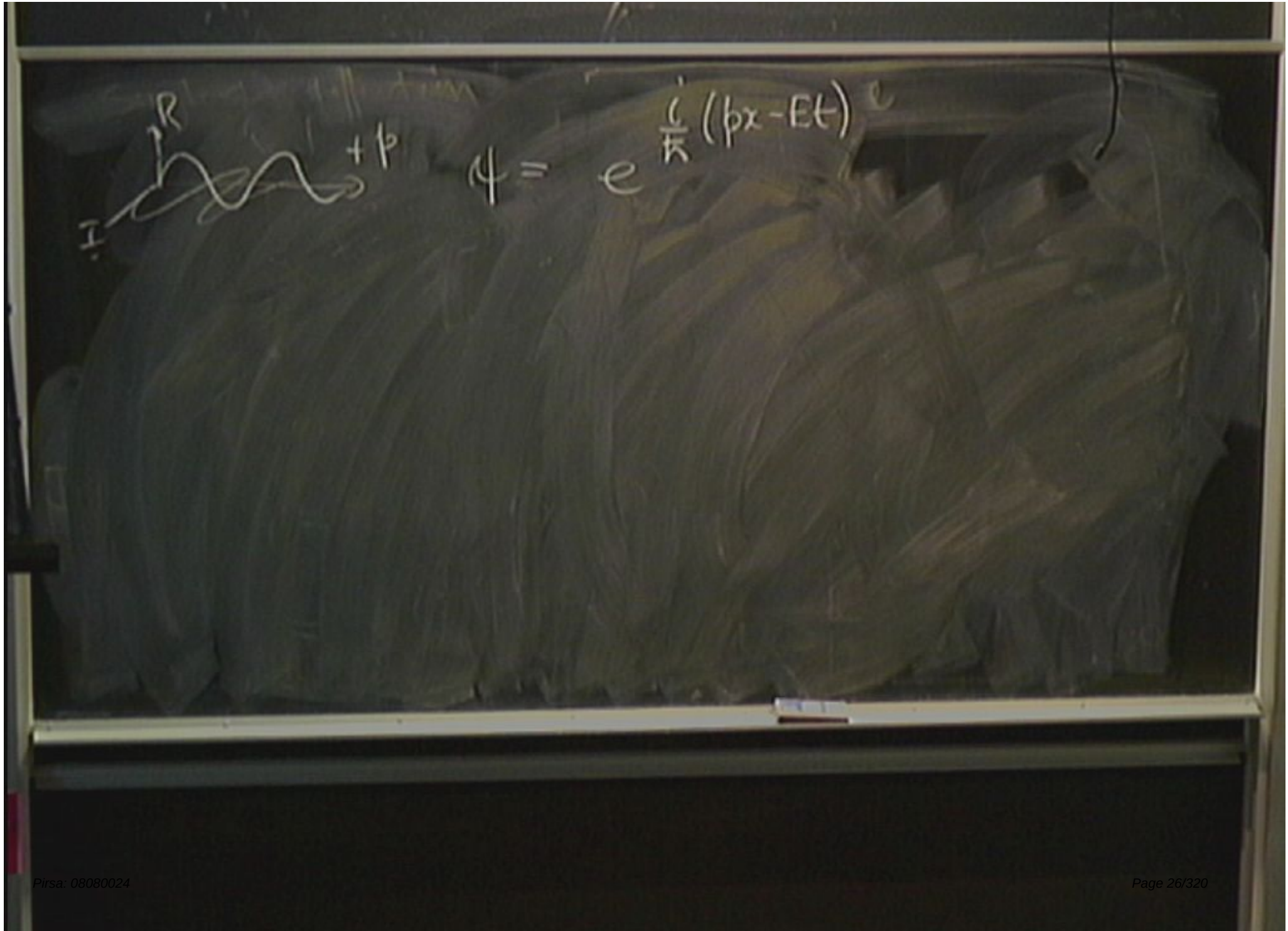
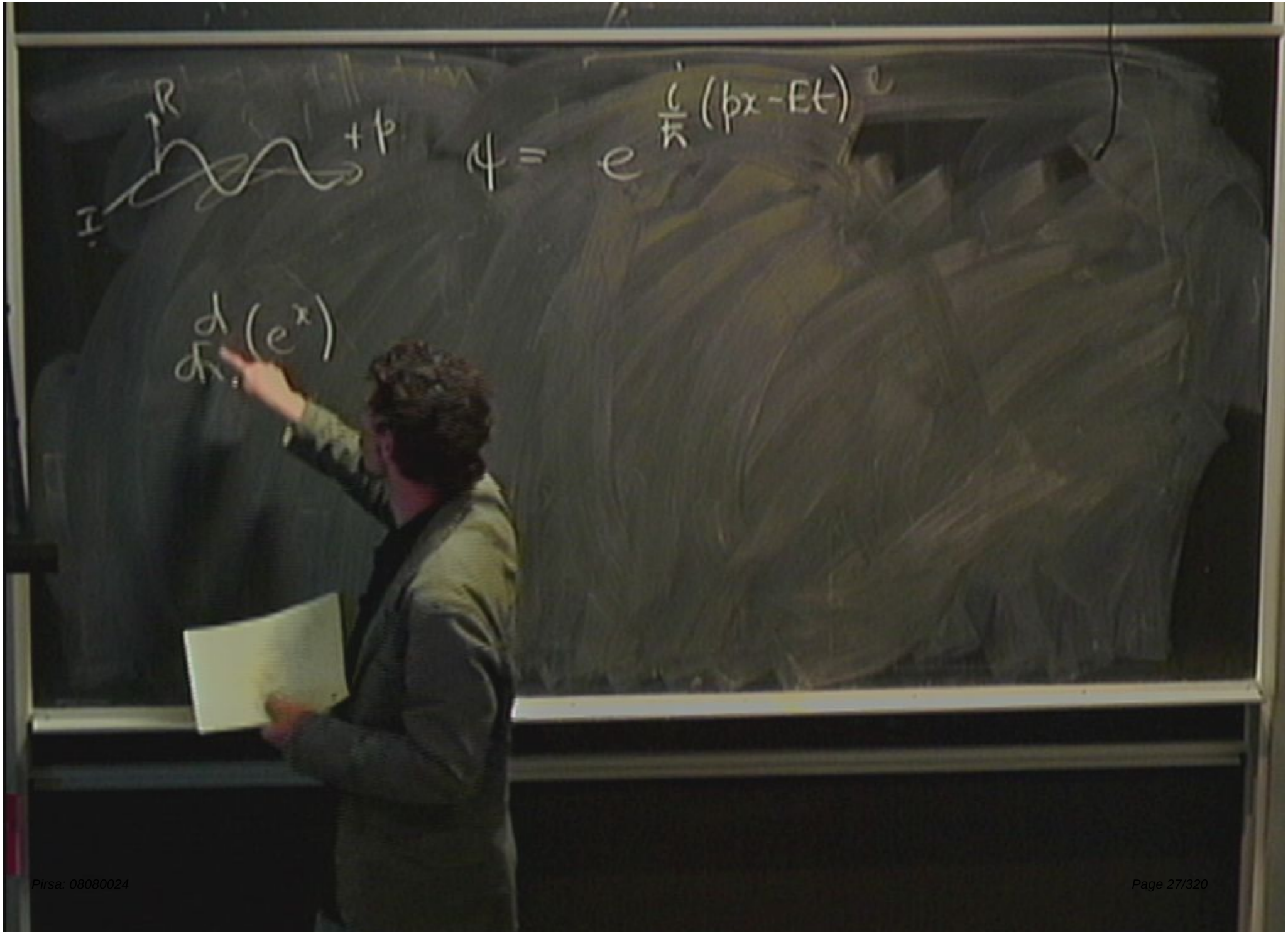
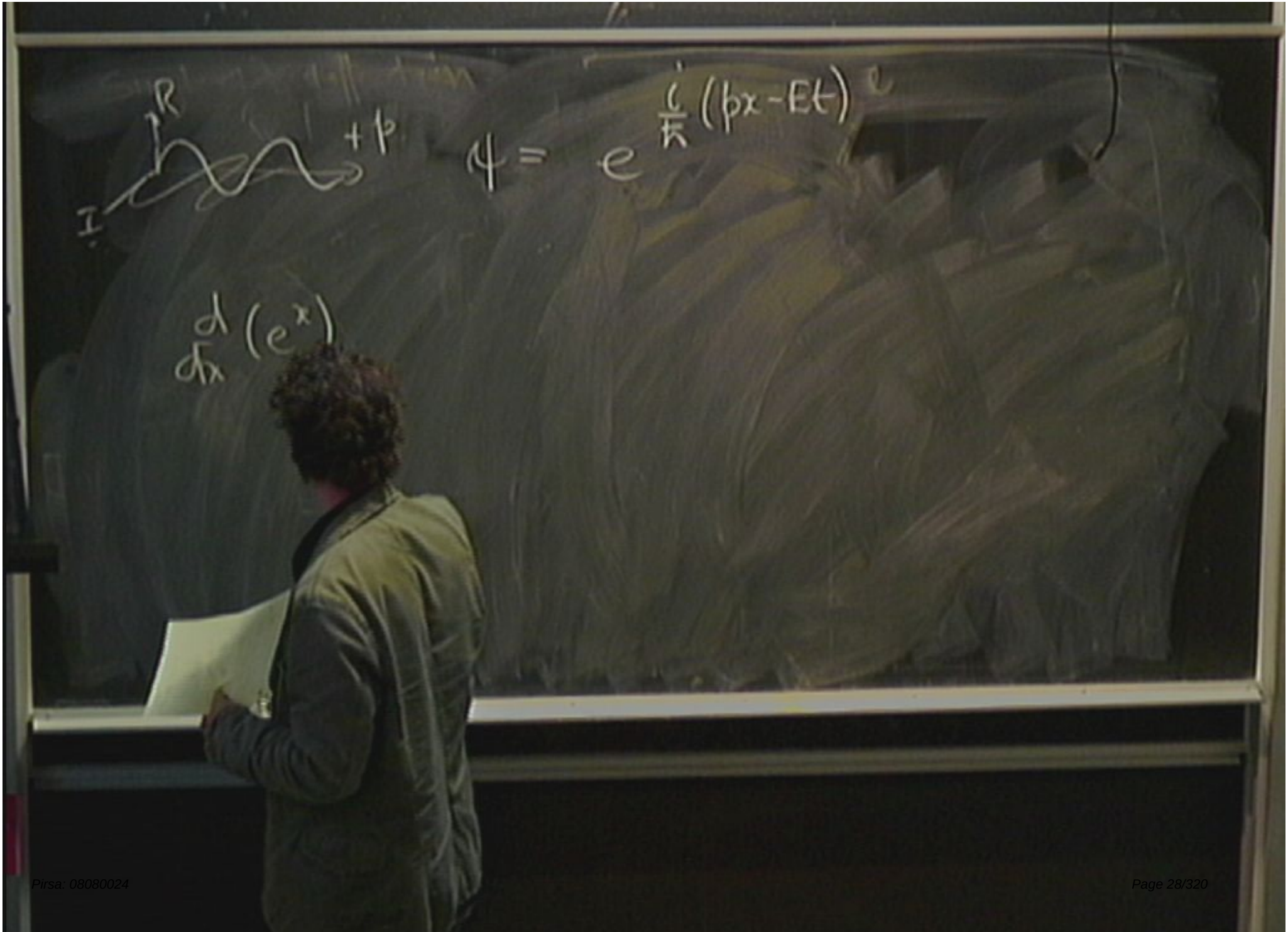
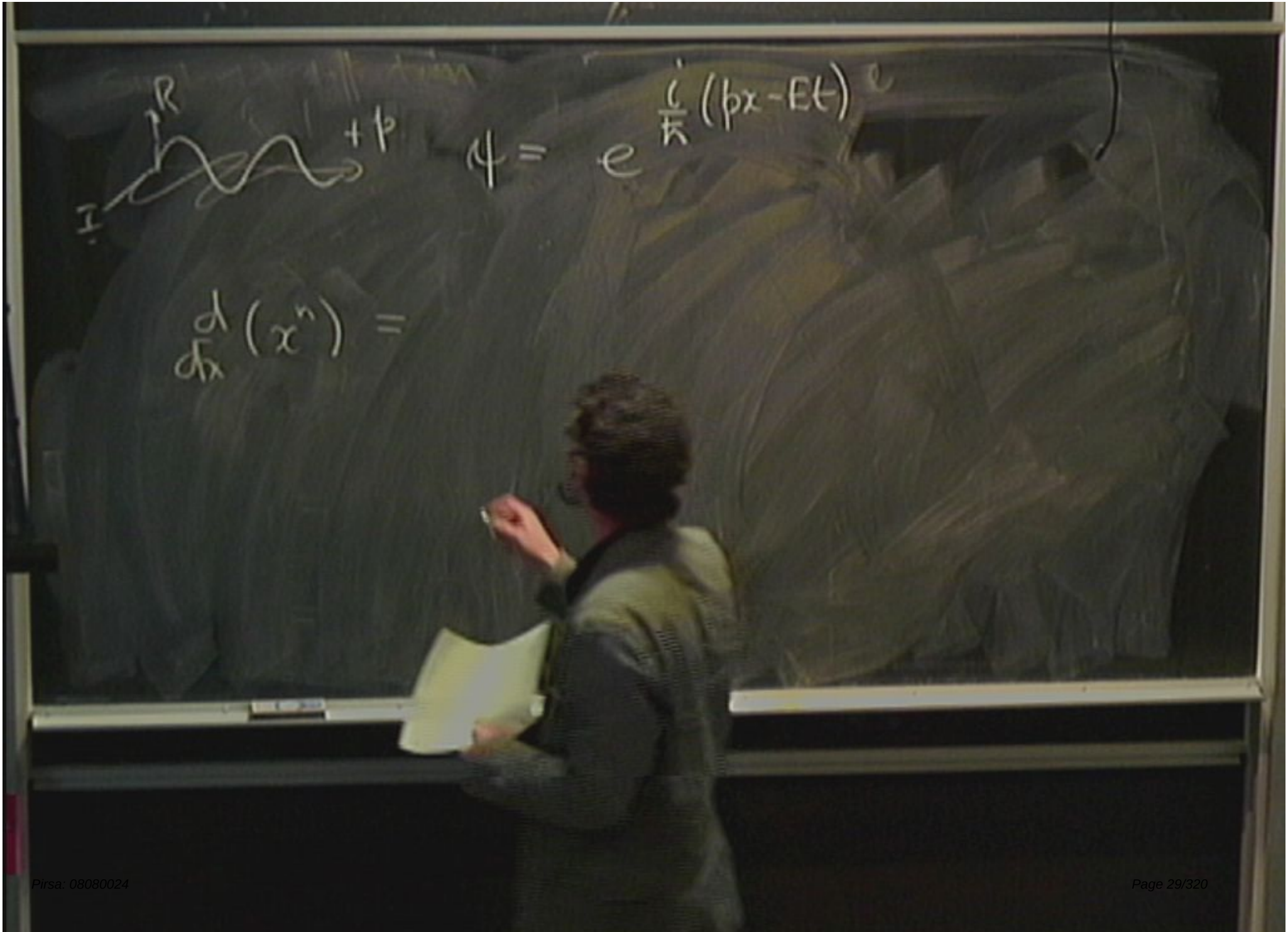
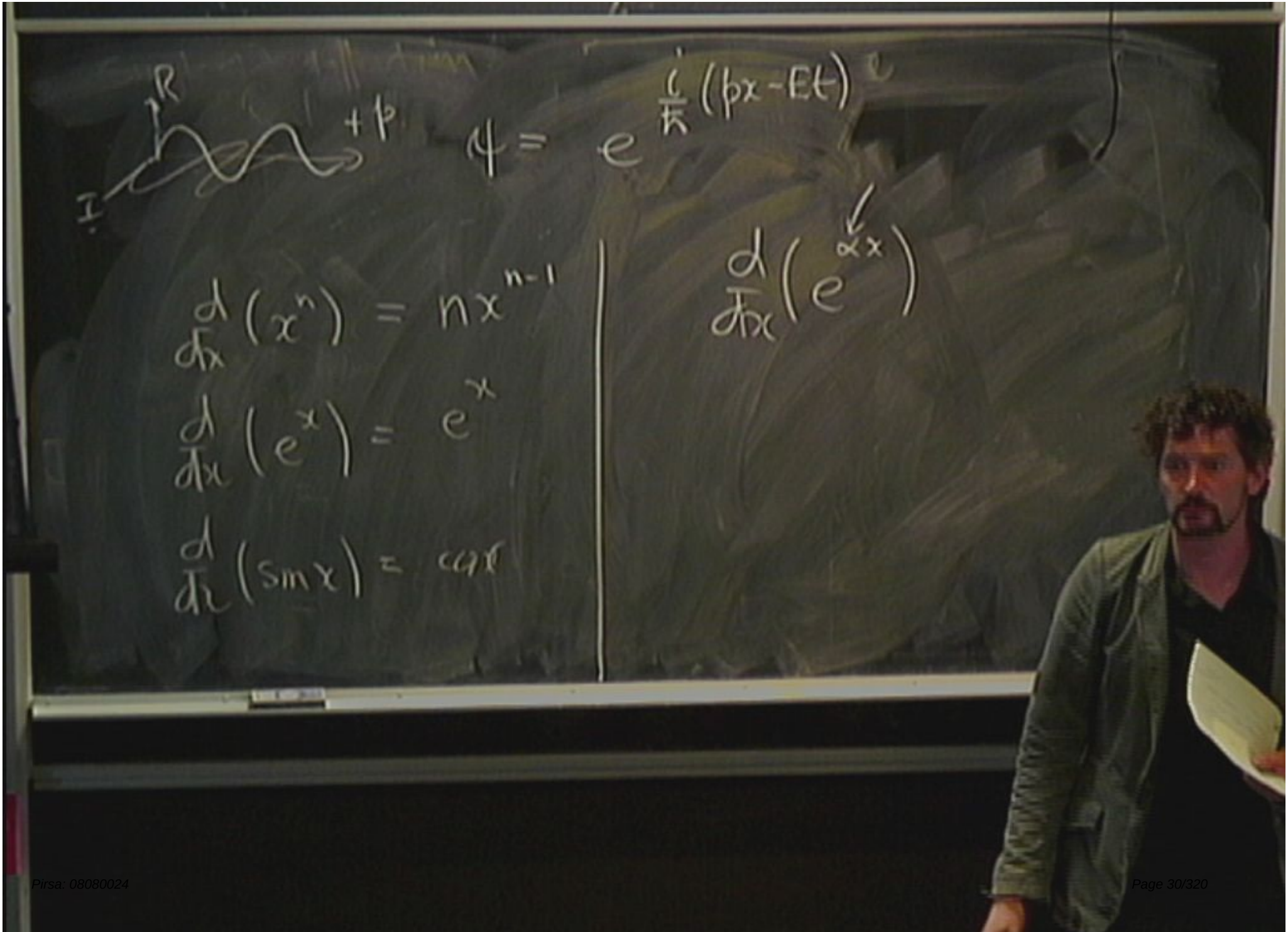

R
+p
I
$\psi = e^{\frac{i}{\hbar}(px - Et)}$

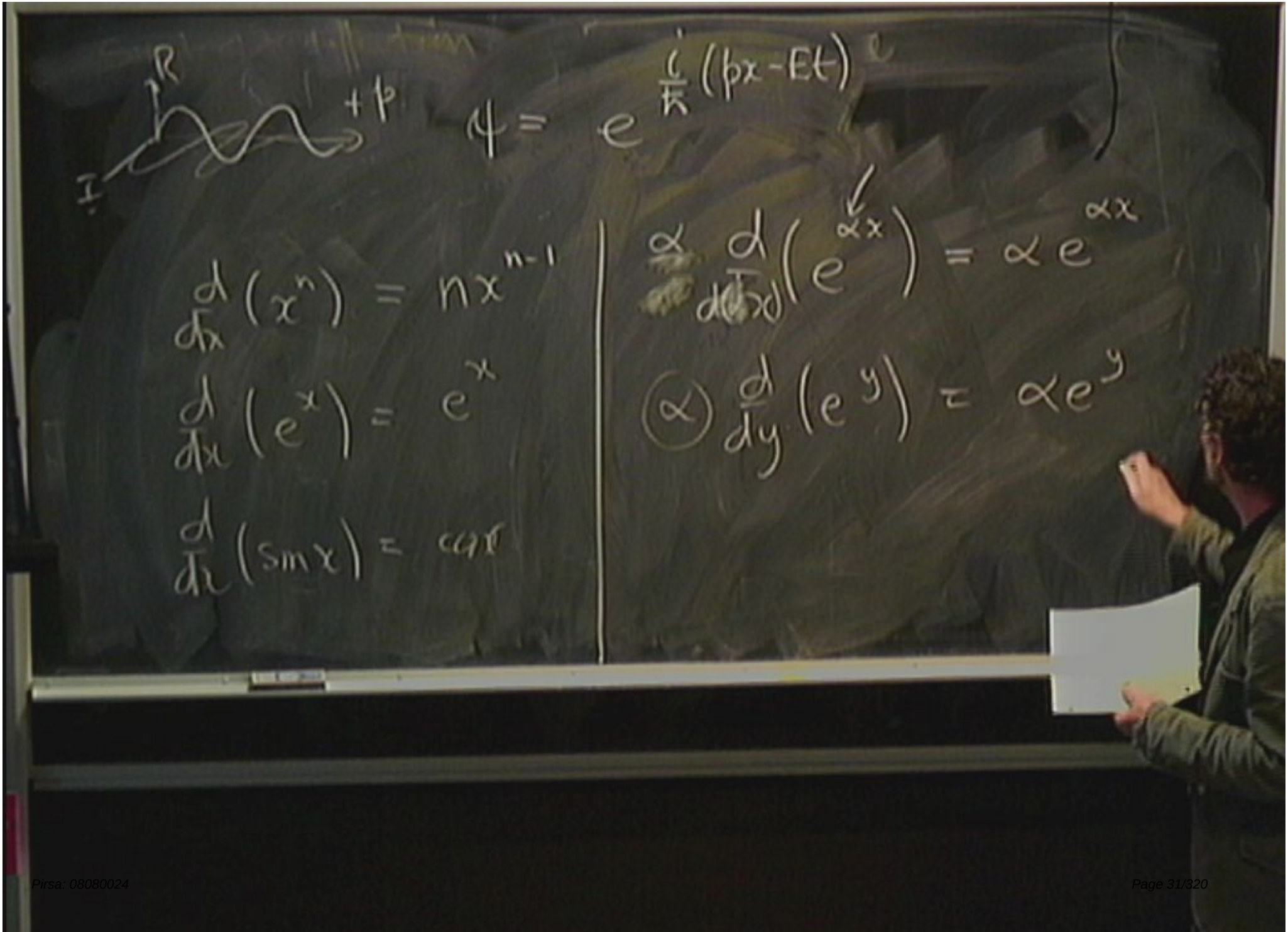

R
I
+p
$\psi = e^{\frac{i}{\hbar}(px - Et)}$

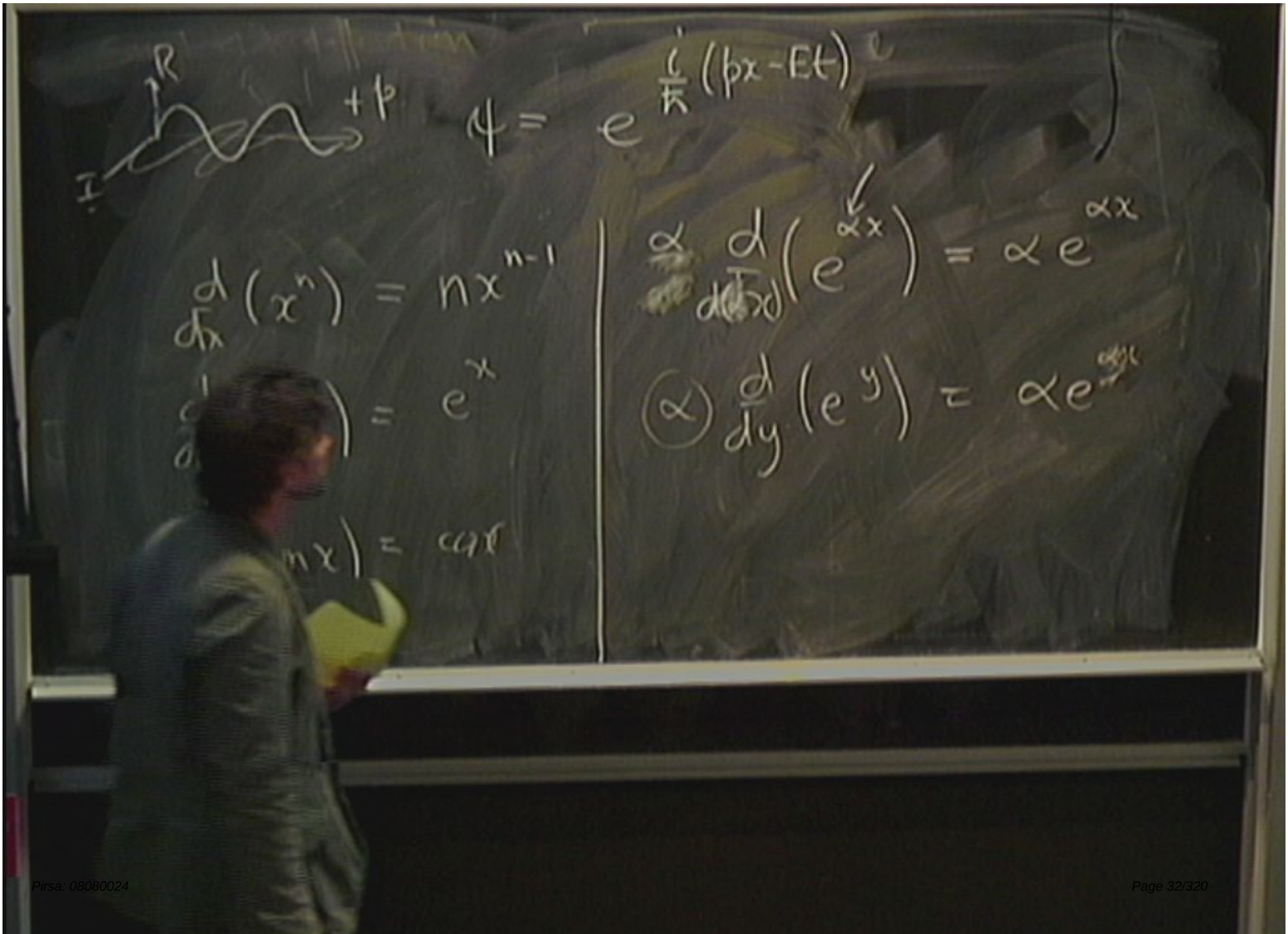

R
+p
I
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$\frac{d}{dx}(e^x)$


R
I
+p
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$\frac{d}{dx}(e^x)$


R
I
+p
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$\frac{d}{dx}(x^n) =$


R
+p
I
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^x) = e^x$
$\frac{d}{dx}(\sin x) = \cos x$
$\frac{d}{dx}(e^{\alpha x})$


R
+p
I
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^x) = e^x$
$\frac{d}{dx}(\sin x) = \cos x$
$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$
$(\alpha)\ \frac{d}{dy}(e^y) = \alpha e^y$


R
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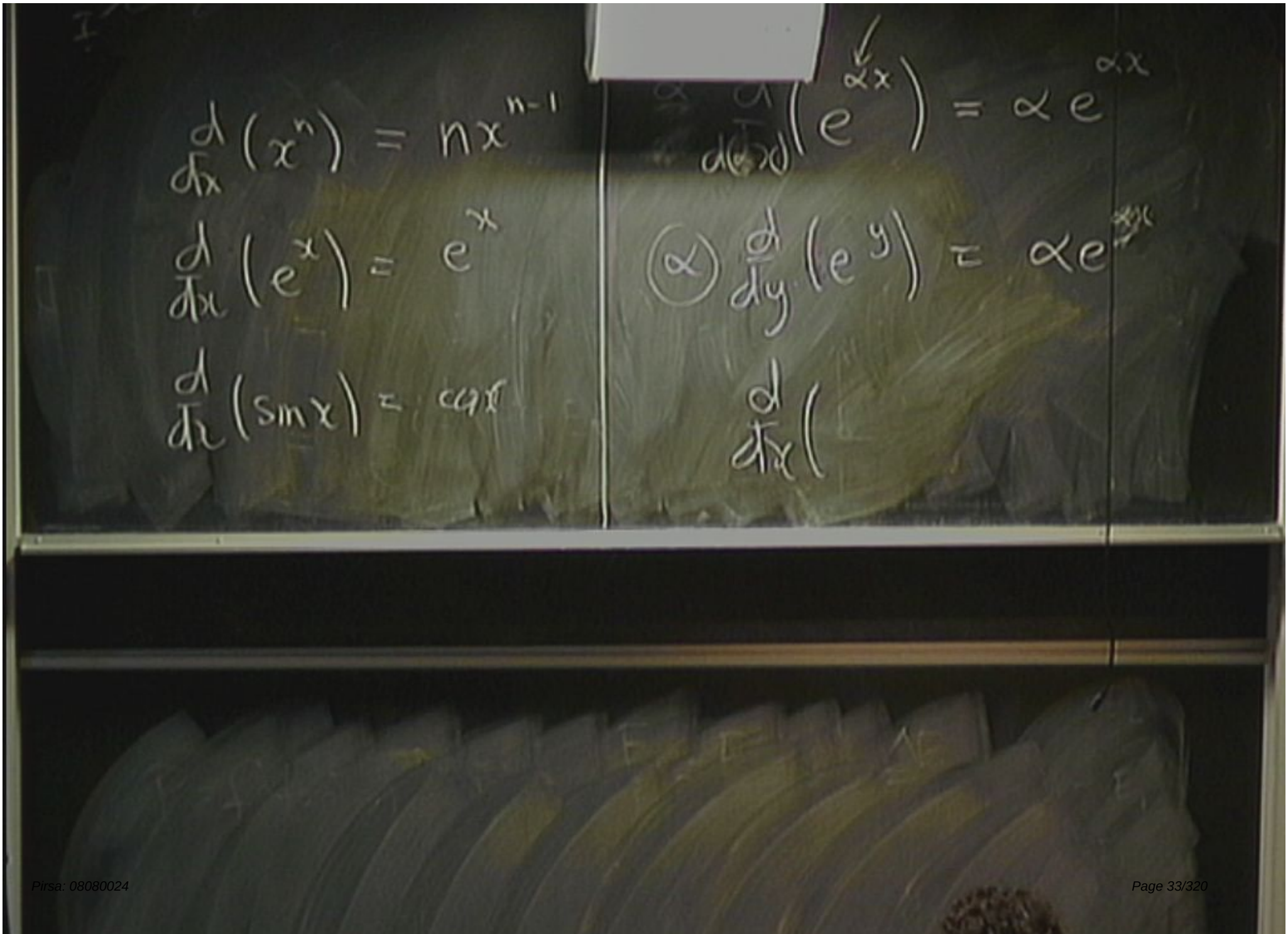
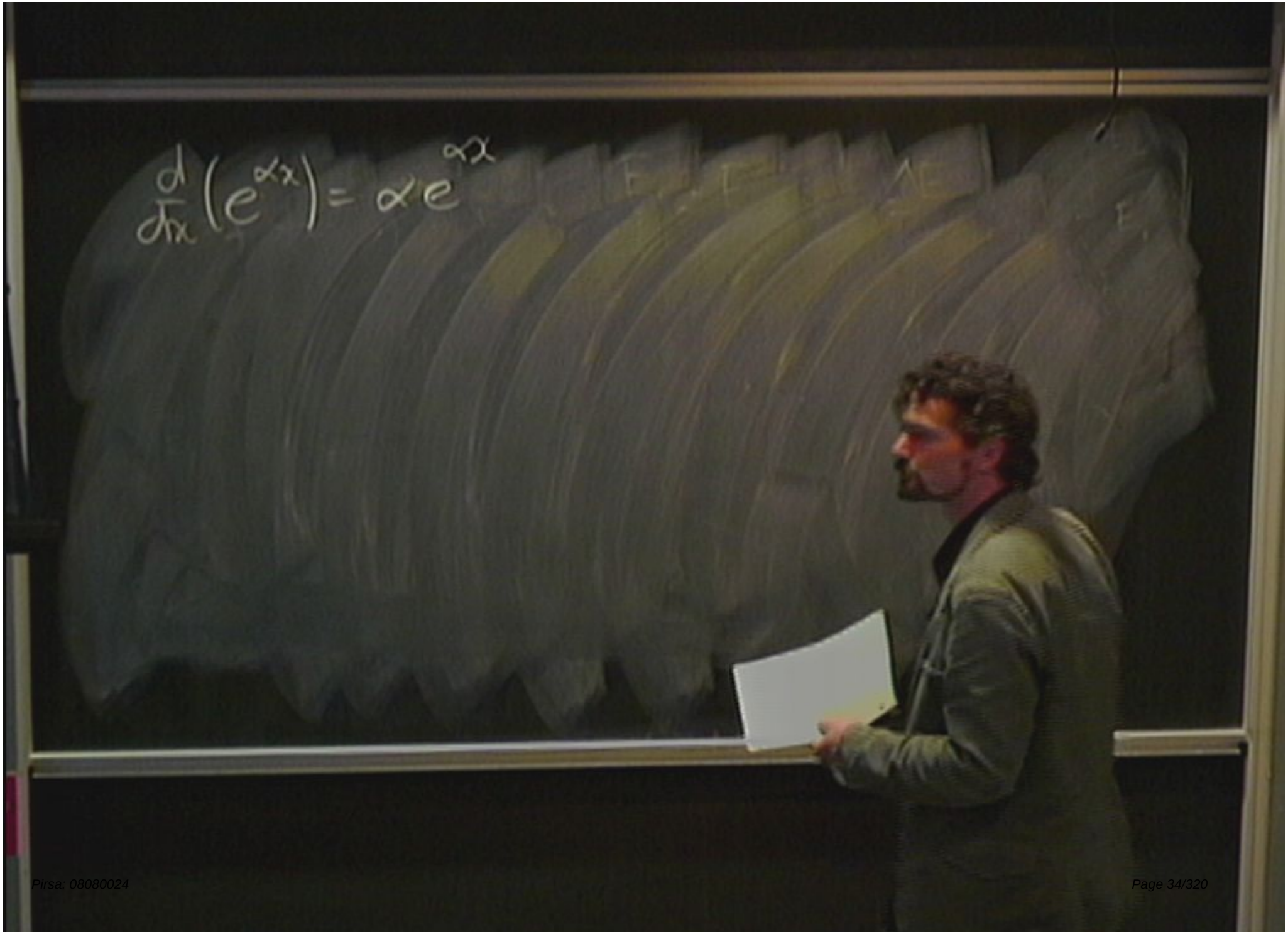
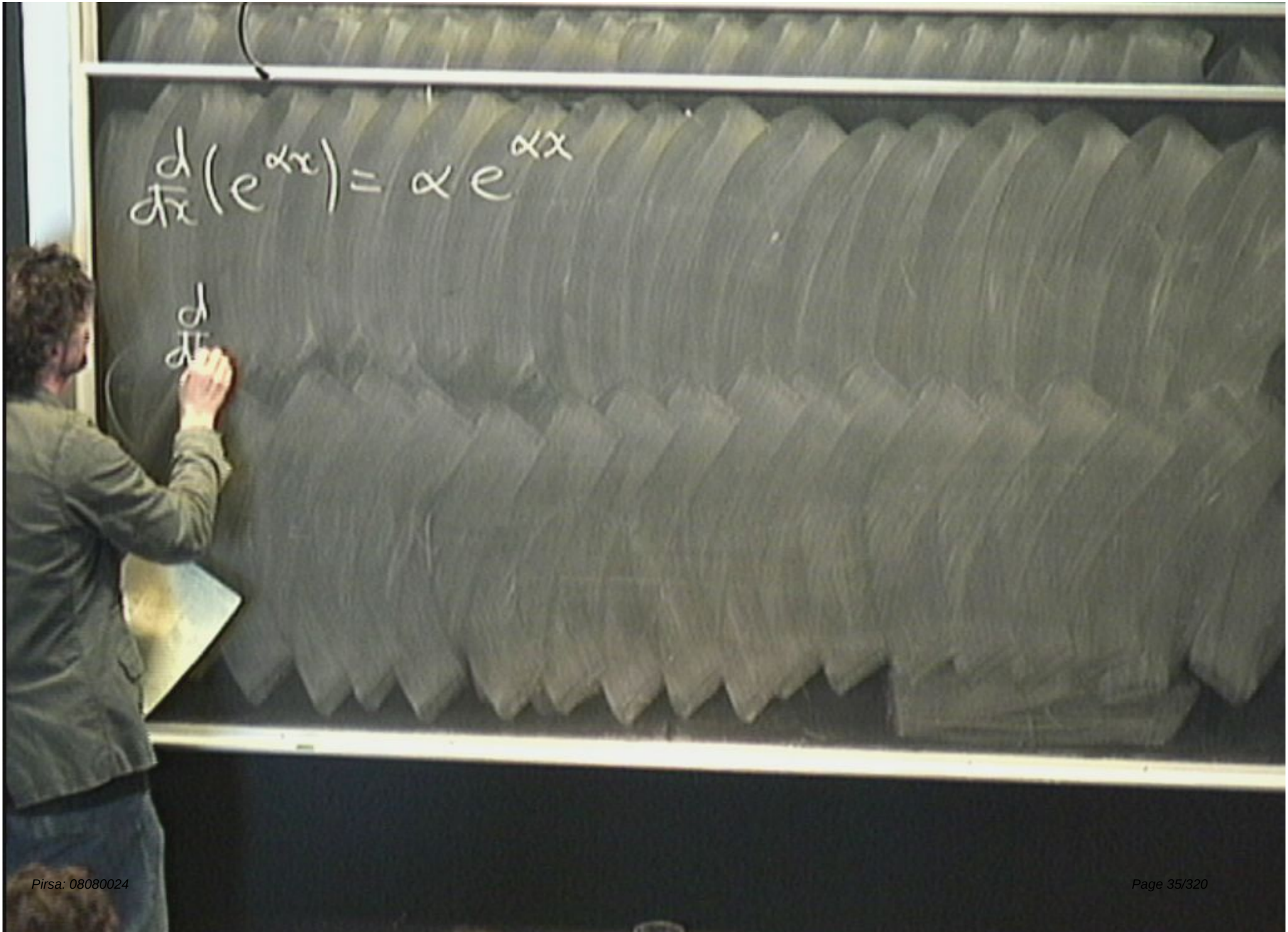
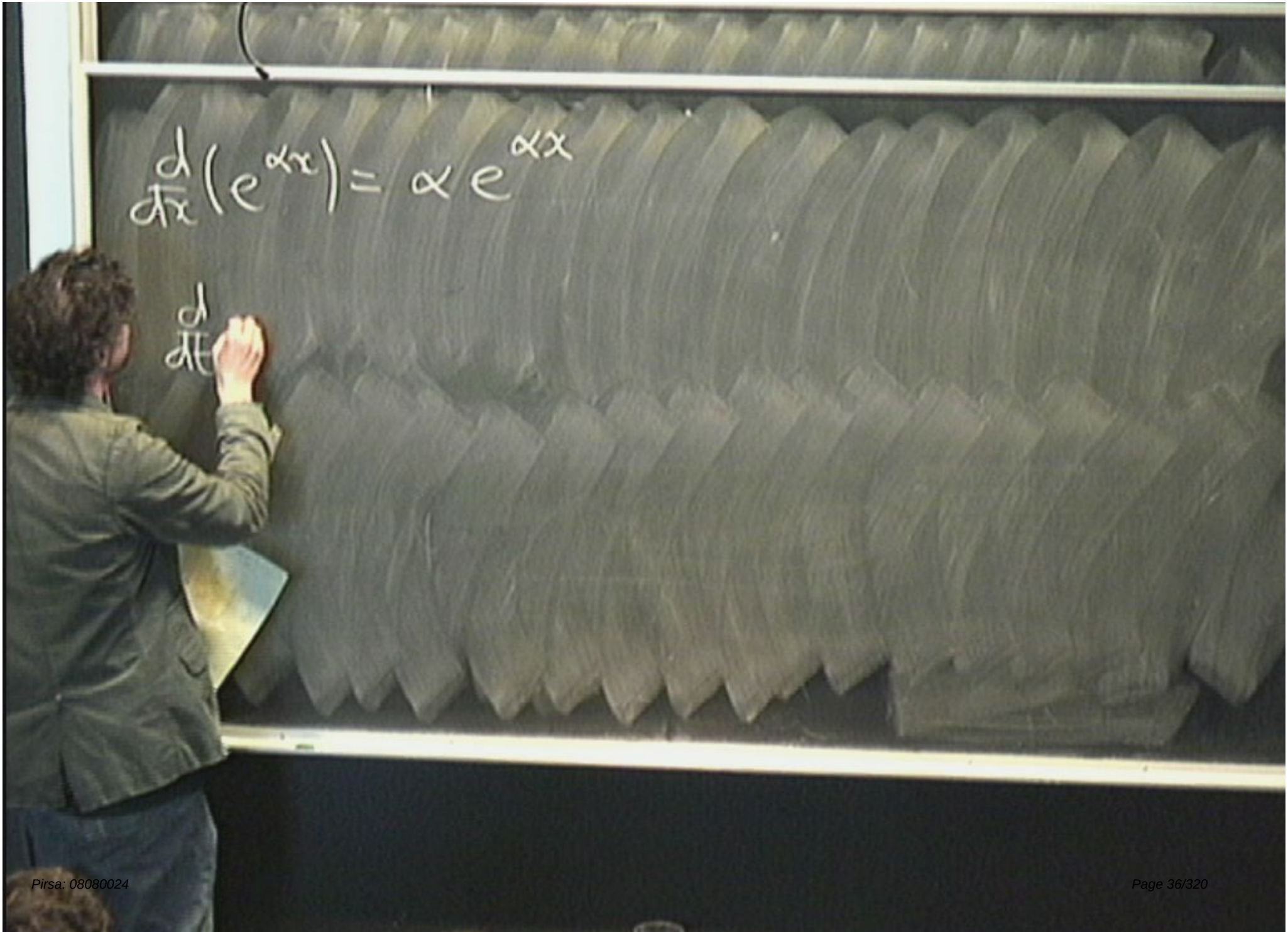
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^x) = e^x$
$\frac{d}{dx}(\sin x) = \cos x$
$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$
$(\alpha)\ \frac{d}{dy}(e^{\alpha y}) = \alpha e^{\alpha y}$


$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^x) = e^x$
$\frac{d}{dx}(\sin x) = \cos x$
$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$(\alpha)\ \frac{d}{dy}(e^y) = \alpha e^{\alpha y}$
$\frac{d}{dx}($

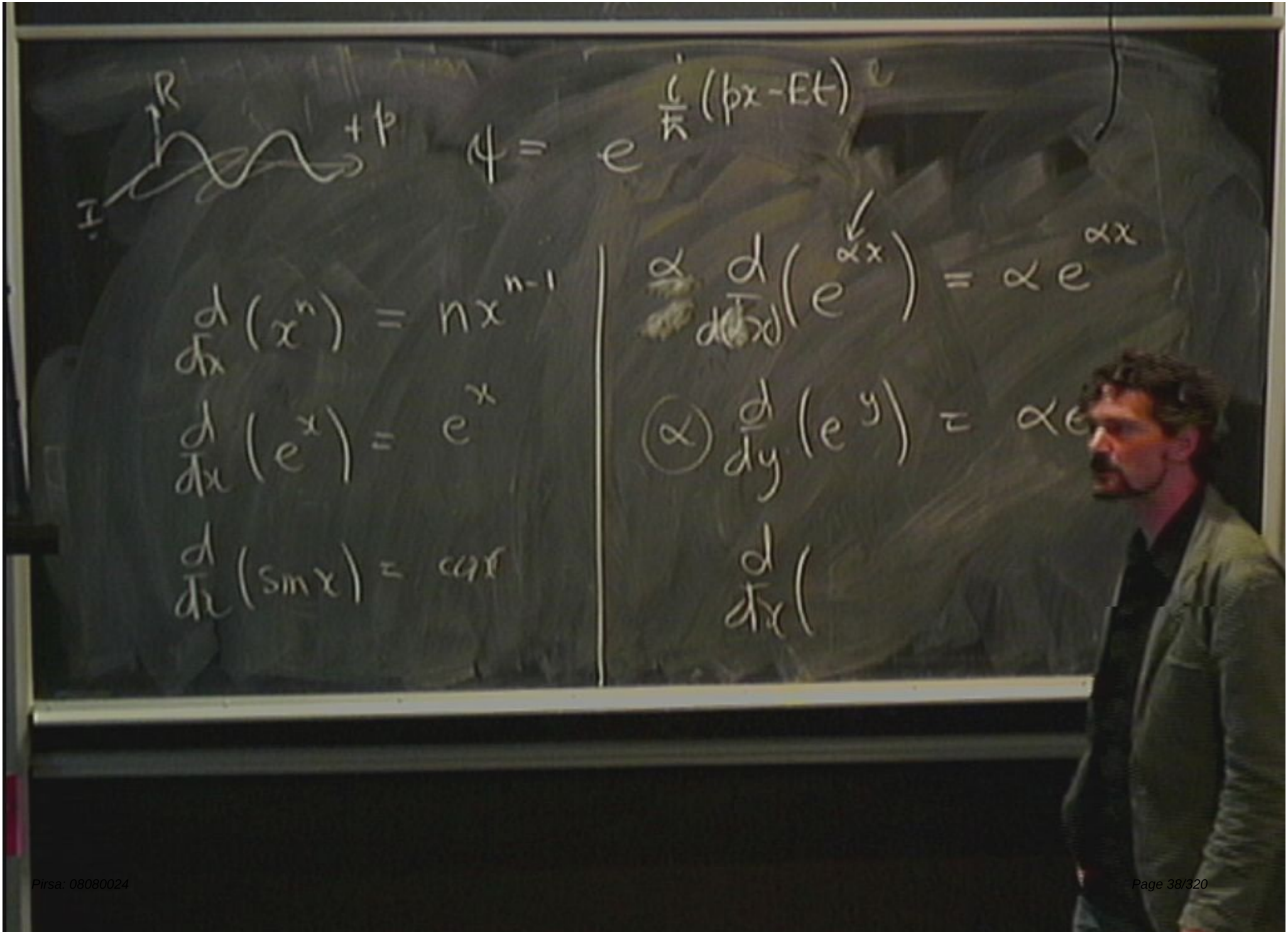

$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$

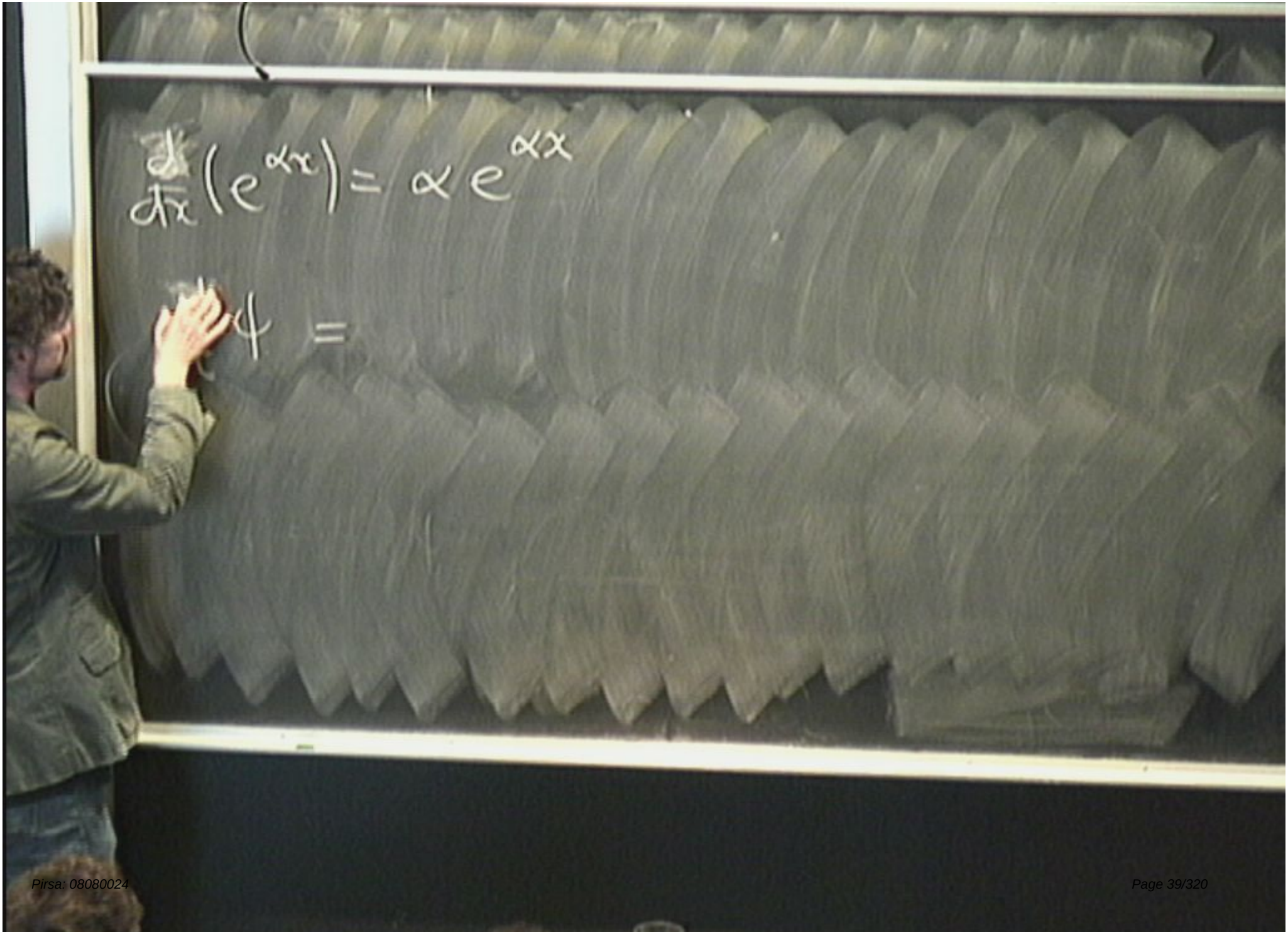

$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$\frac{d}{dx}$

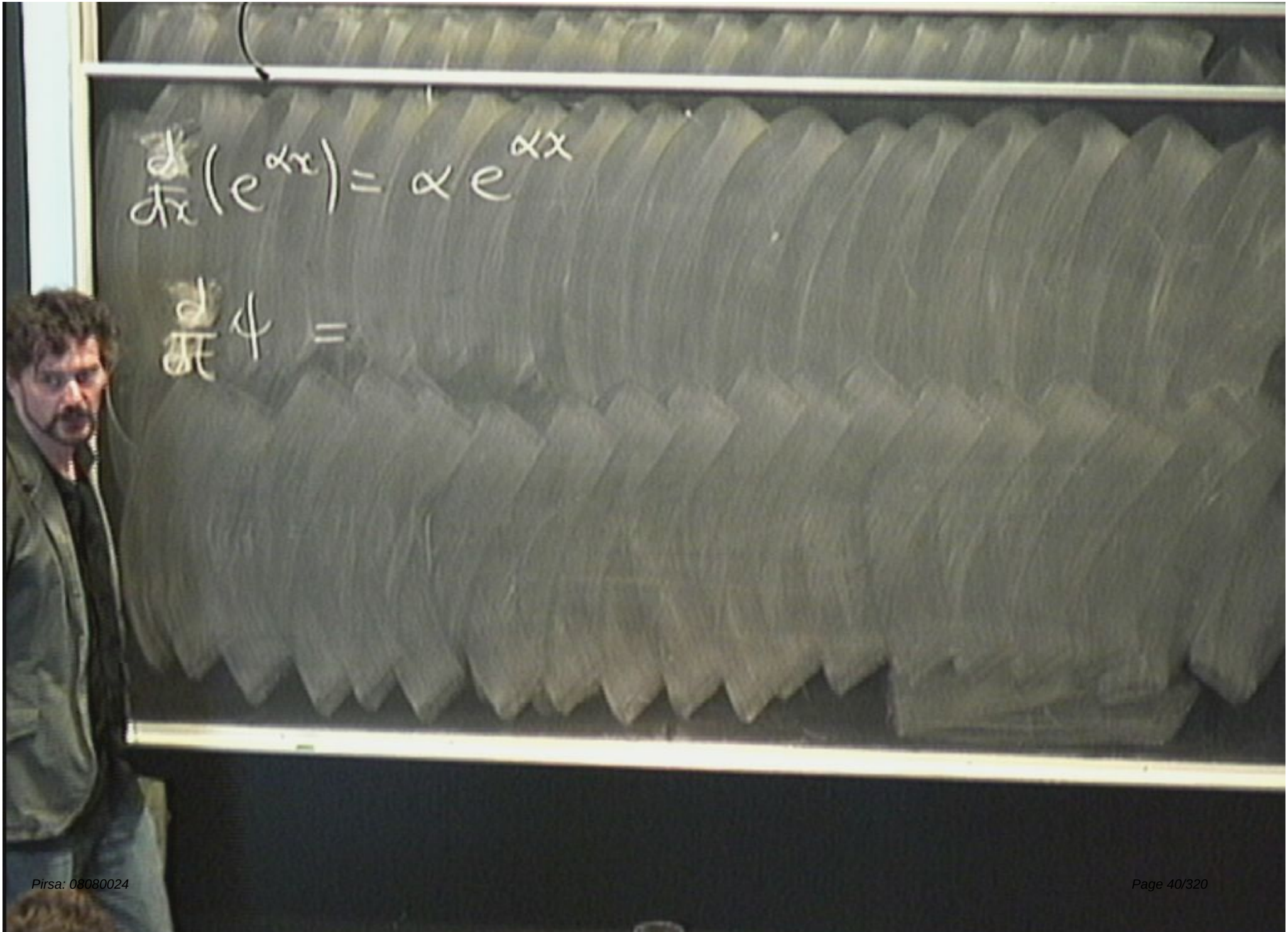

$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$\frac{d}{dt}$

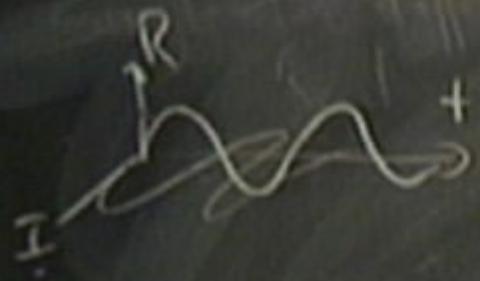
$$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$$

$$\frac{d}{dt}\psi =$$


R
+p
I
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^x) = e^x$
$\frac{d}{dx}(\sin x) = \cos x$
$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$
$\alpha \frac{d}{dy}(e^y) = \alpha e$
$\frac{d}{dx}($


$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$\psi =$


$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$\frac{d}{dt}\psi =$



$$\psi = e^{\frac{i}{\hbar}(px - Et)}$$

$$\frac{d}{dx}(x^n) = nx^{n-1}$$

$$\frac{d}{dx}(e^x) = e^x$$

$$\frac{d}{dx}(\sin x) = \cos x$$

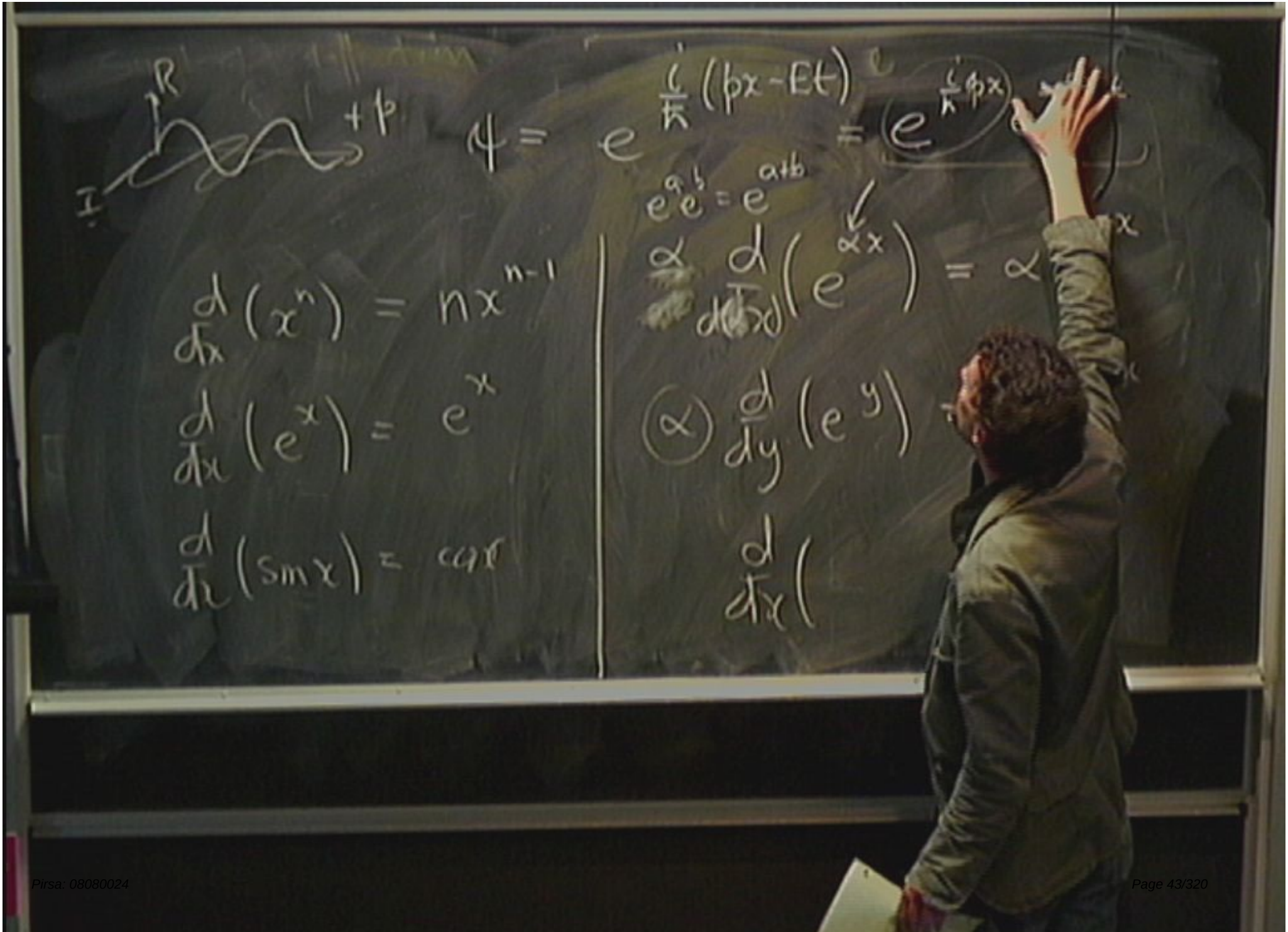
$$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$$

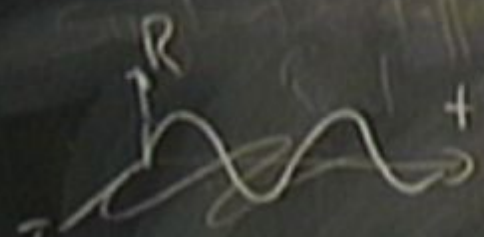
$$(\alpha)\ \frac{d}{dy}(e^y) = \alpha e^{\alpha y}$$

$$\frac{d}{dx}($$

$$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$$

$$\frac{d}{dx}\psi =$$


R
I
+p
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$= e^{\frac{i}{\hbar}px}$
$e^a e^b = e^{a+b}$
$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^x) = e^x$
$\frac{d}{dx}(\sin x) = \cos x$
$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha$
$(\alpha)\ \frac{d}{dy}(e^y)$
$\frac{d}{dx}($



$$\psi = e^{\frac{i}{\hbar}(px - Et)} = e^{\frac{i}{\hbar}px} e^{-\frac{i}{\hbar}Et}$$

$$e^a e^b = e^{a+b}$$

$$\frac{d}{dx}(x^n) = nx^{n-1}$$

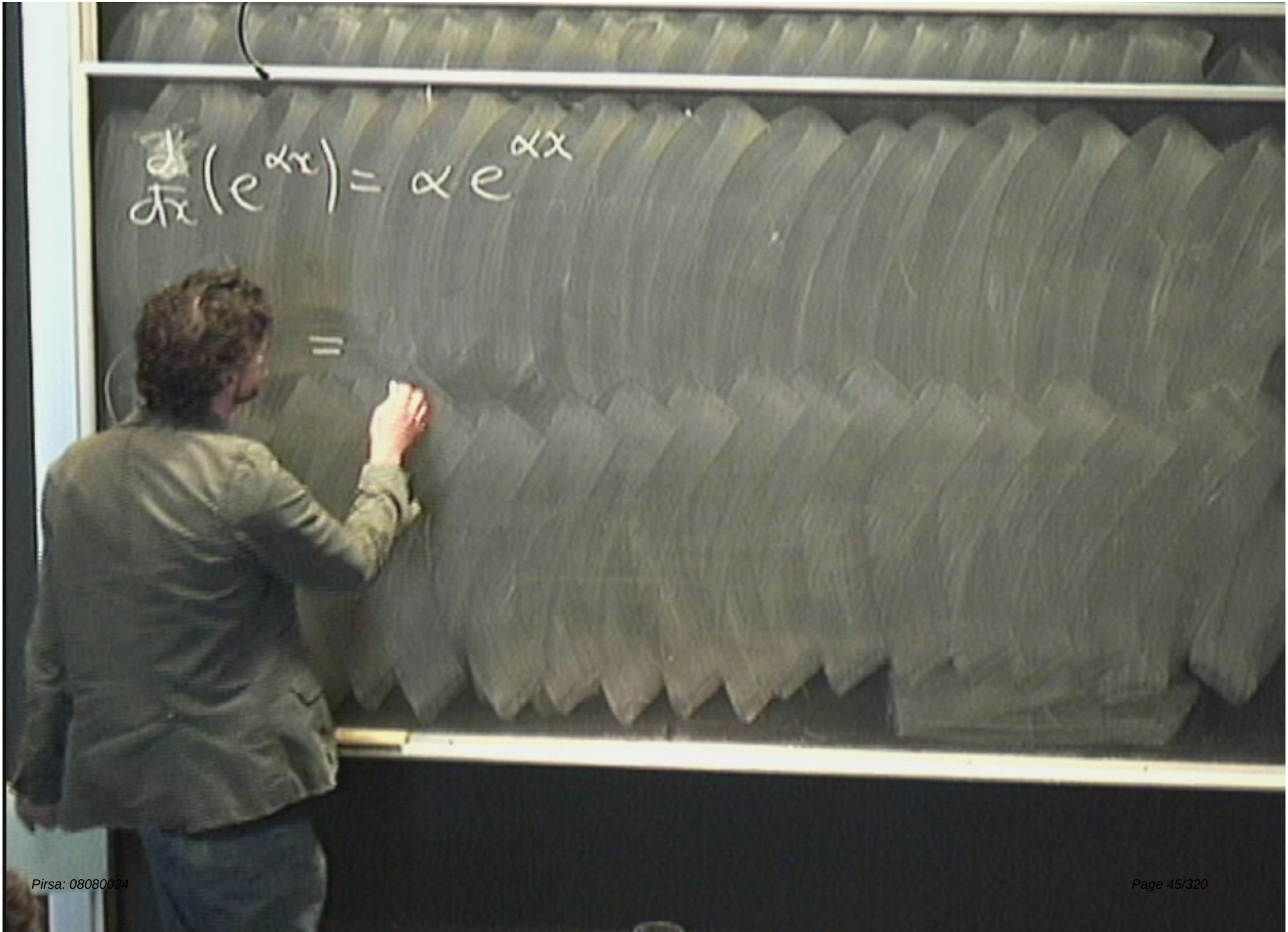
$$\frac{d}{dx}(e^x) = e^x$$

$$\frac{d}{dx}(\sin x) = \cos x$$

$$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$$

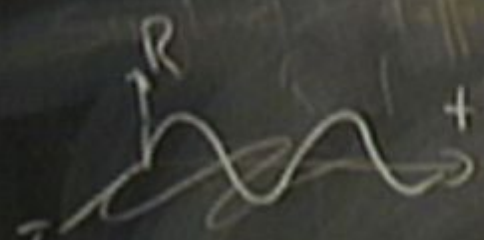
$$(\alpha) \frac{d}{dy}(e^y) = \alpha e^{\alpha y}$$

$$\frac{d}{dx}($$


$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
=

$$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$$

$$\frac{d}{dx}\psi = \frac{i}{\hbar}p\psi$$



$$\psi = e^{\frac{i}{\hbar}(px - Et)} = e^{\frac{i}{\hbar}px} e^{-\frac{i}{\hbar}Et}$$

$$e^a e^b = e^{a+b}$$

$$\frac{d}{dx}(x^n) = nx^{n-1}$$

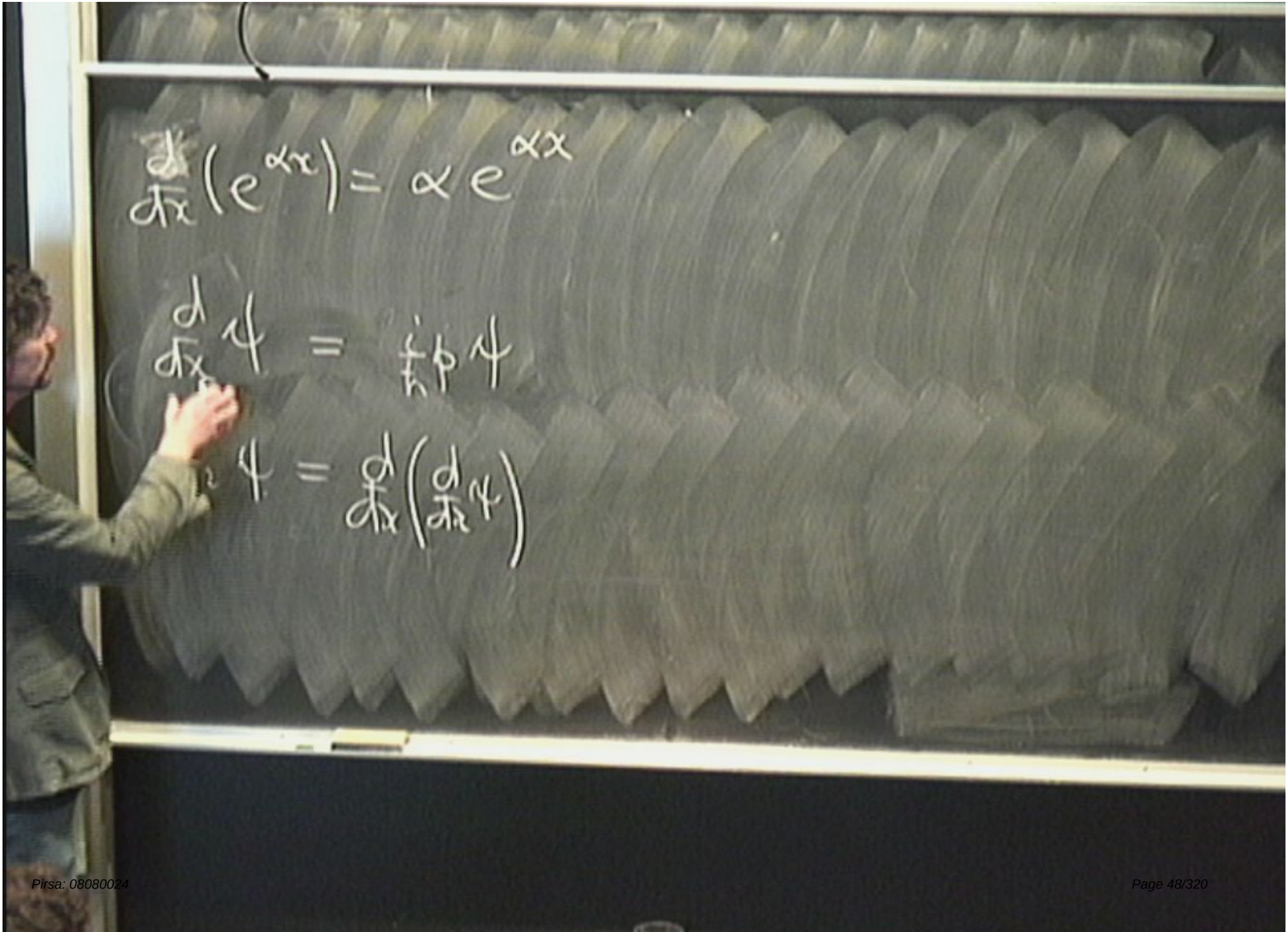
$$\frac{d}{dx}(e^x) = e^x$$

$$\frac{d}{dx}(\sin x) = \cos x$$

$$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$$

$$(\alpha) \frac{d}{dy}(e^y) = \alpha e^{\alpha y}$$

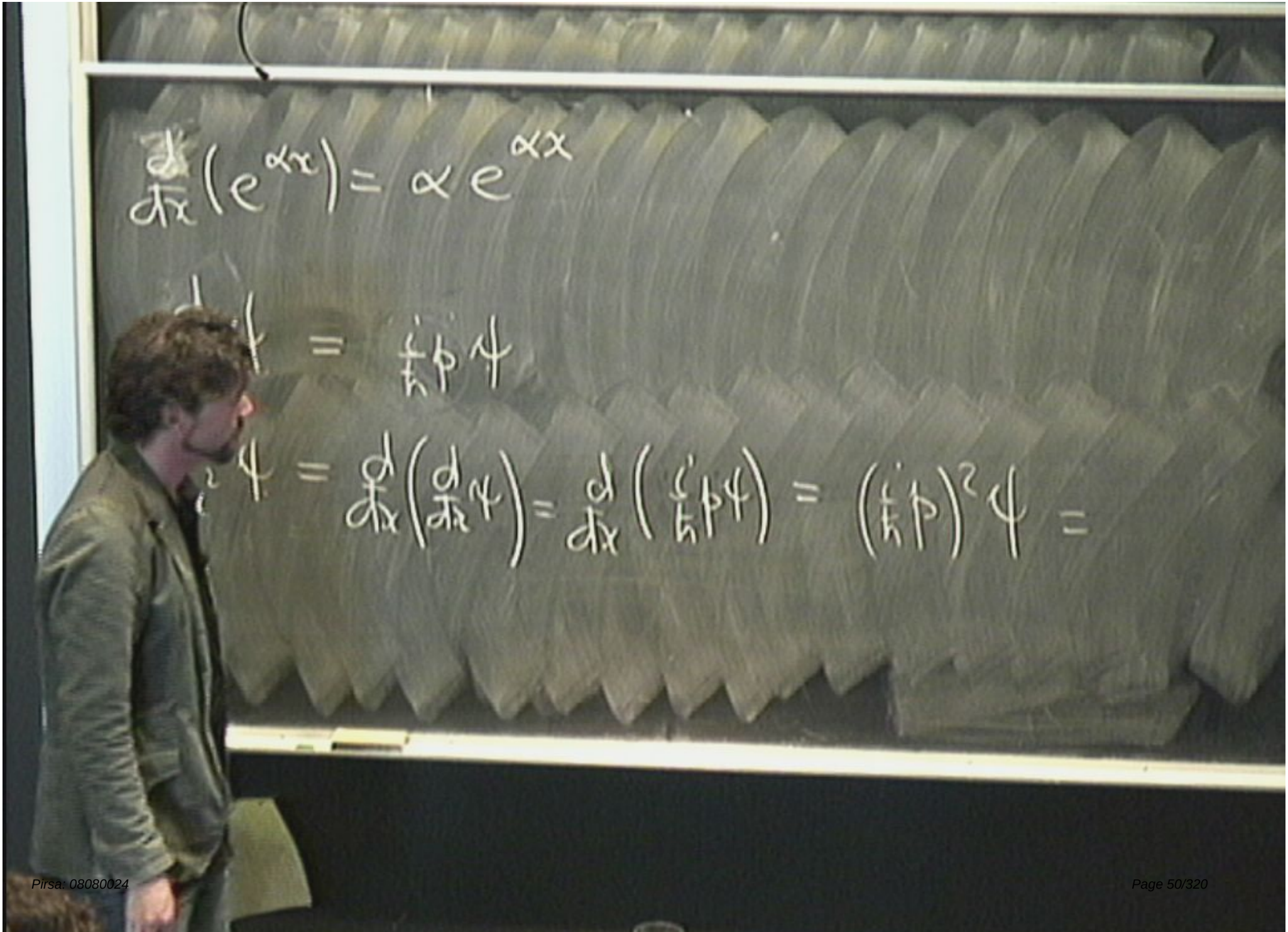
$$\frac{d}{dx}($$


$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$\frac{d}{dx}\psi = ikp\psi$
$\psi = \frac{d}{dx}\left(\frac{d}{dx}\psi\right)$

$$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$$

$$\frac{d}{dx}\psi = \frac{i}{\hbar}p\psi$$

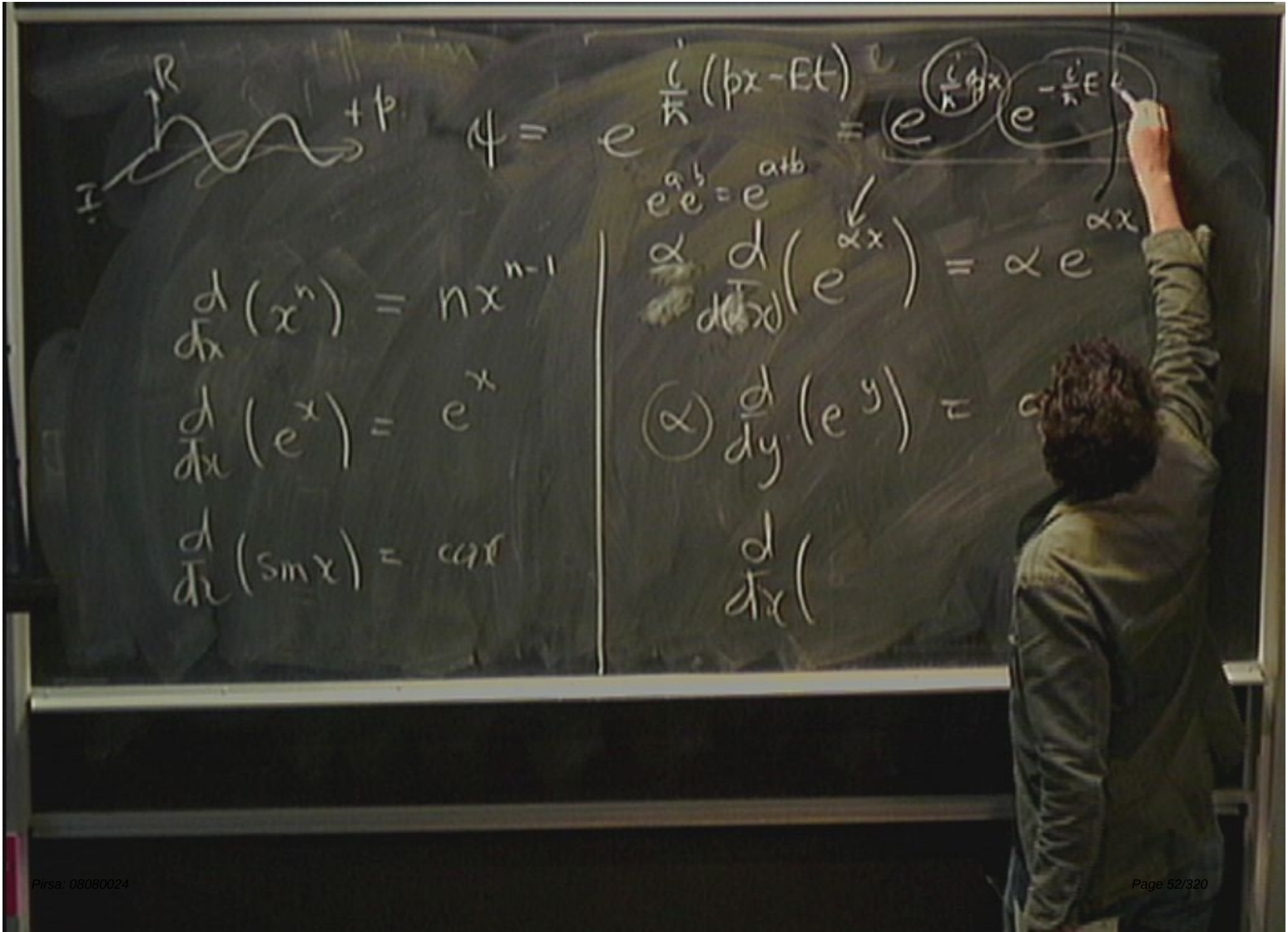
$$\frac{d^2}{dx^2}\psi = \frac{d}{dx}\left(\frac{d}{dx}\psi\right) = \frac{d}{dx}\left(\frac{i}{\hbar}p\psi\right) =$$

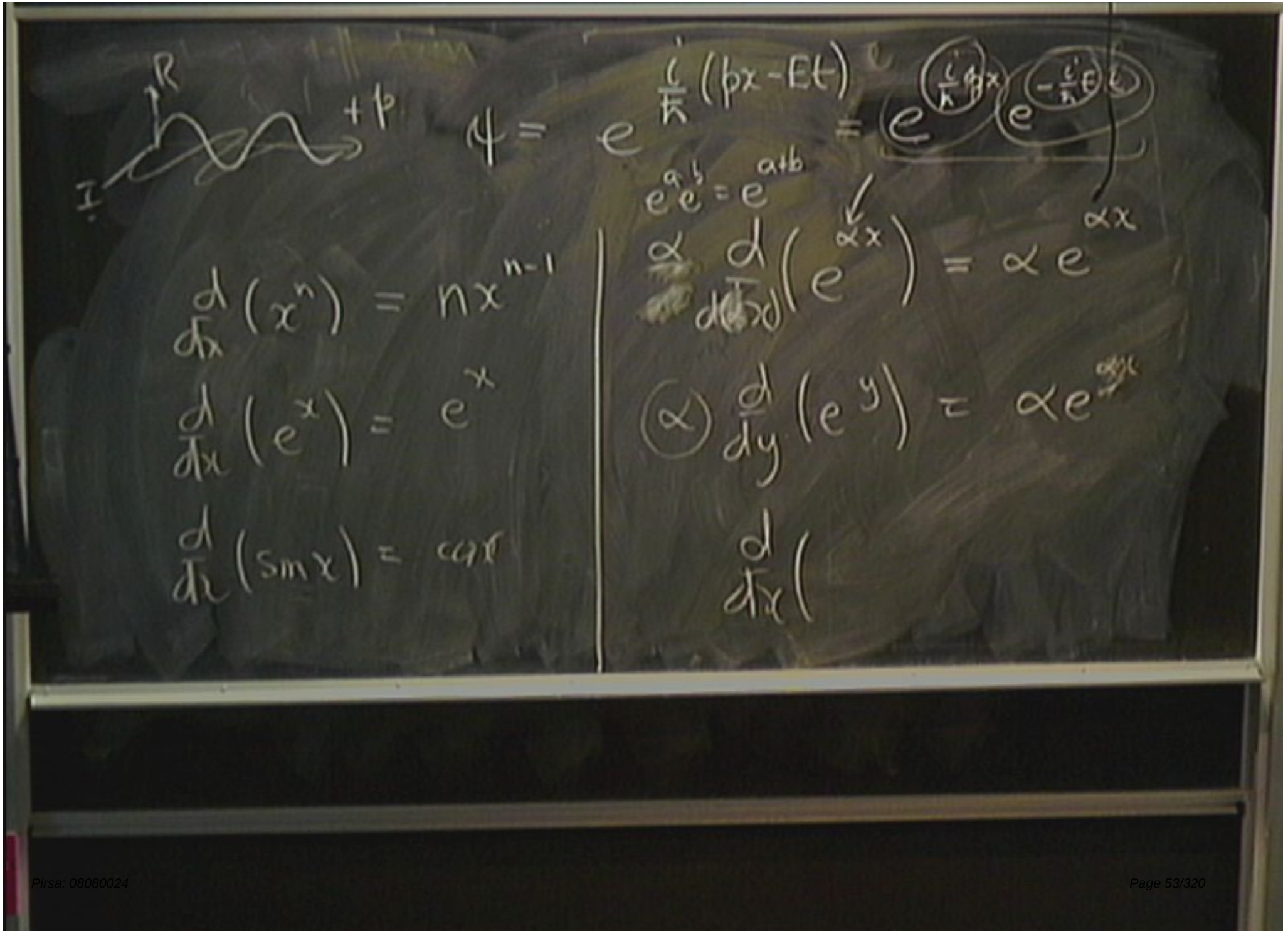

$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$\frac{d}{dx}\psi = \frac{i}{\hbar}p\psi$
$\frac{d^2}{dx^2}\psi = \frac{d}{dx}\left(\frac{d}{dx}\psi\right) = \frac{d}{dx}\left(\frac{i}{\hbar}p\psi\right) = \left(\frac{i}{\hbar}p\right)^2\psi =$

$$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$$

$$\frac{d}{dx}\psi = \frac{i}{\hbar}p\psi$$

$$\frac{d^2}{dx^2}\psi = \frac{d}{dx}\left(\frac{d}{dx}\psi\right) = \frac{d}{dx}\left(\frac{i}{\hbar}p\psi\right) = \left(\frac{i}{\hbar}p\right)^2\psi = -\frac{p^2}{\hbar^2}\psi$$


R
+p
I
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$= e^{\frac{i}{\hbar}px} e^{-\frac{i}{\hbar}Et}$
$e^a e^b = e^{a+b}$
$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^x) = e^x$
$\frac{d}{dx}(\sin x) = \cos x$
$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$
$(\alpha) \frac{d}{dy}(e^y) = \alpha$
$\frac{d}{dx}($


R
+p
I
$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$= e^{\frac{i}{\hbar}px} e^{-\frac{i}{\hbar}Et}$
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$\alpha \frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$(\alpha) \frac{d}{dy}(e^y) = \alpha e^{\alpha y}$
$\frac{d}{dx}($

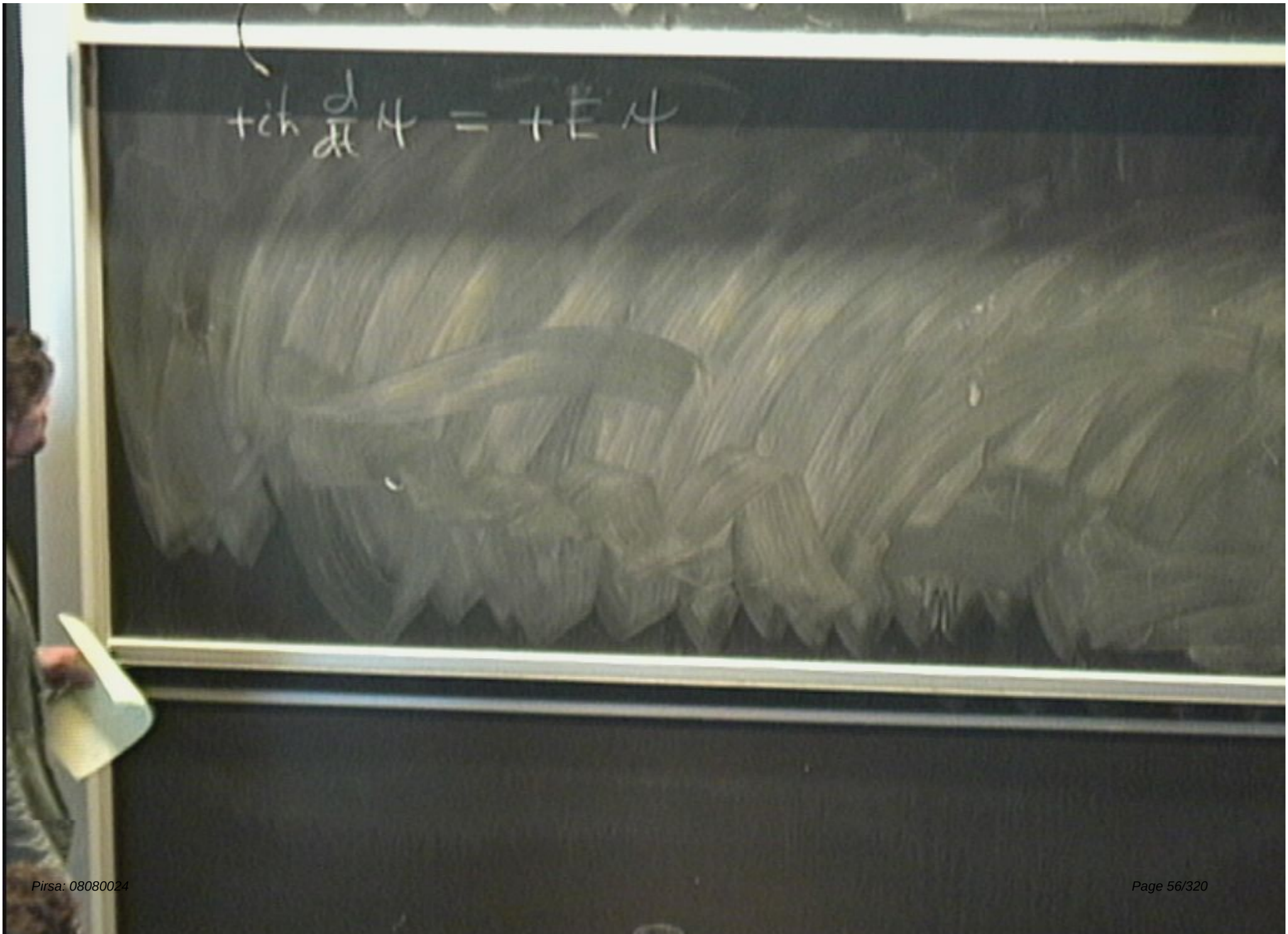
$$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$$

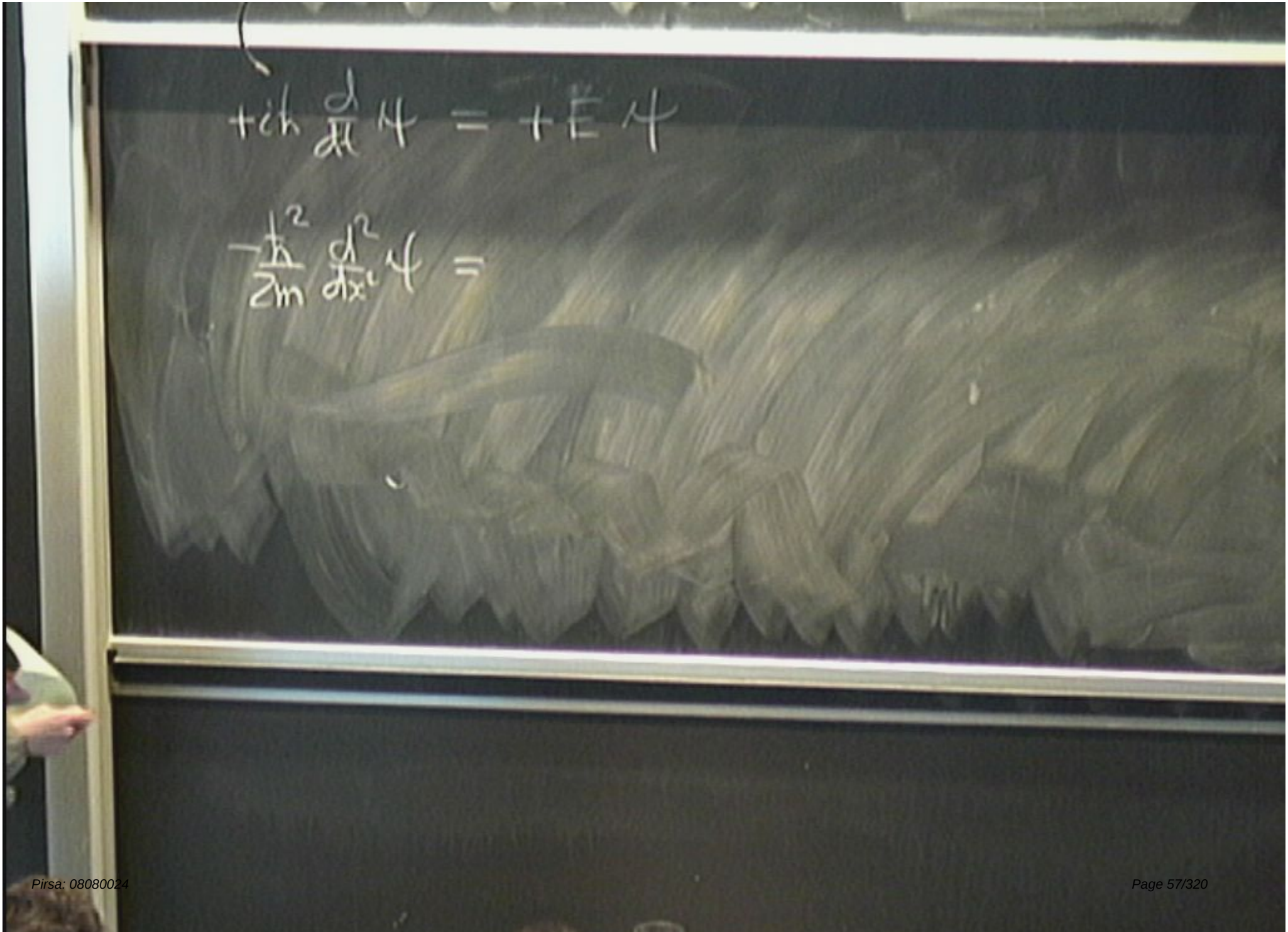
$$\frac{d}{dx}\psi = \frac{i}{\hbar}p\psi$$

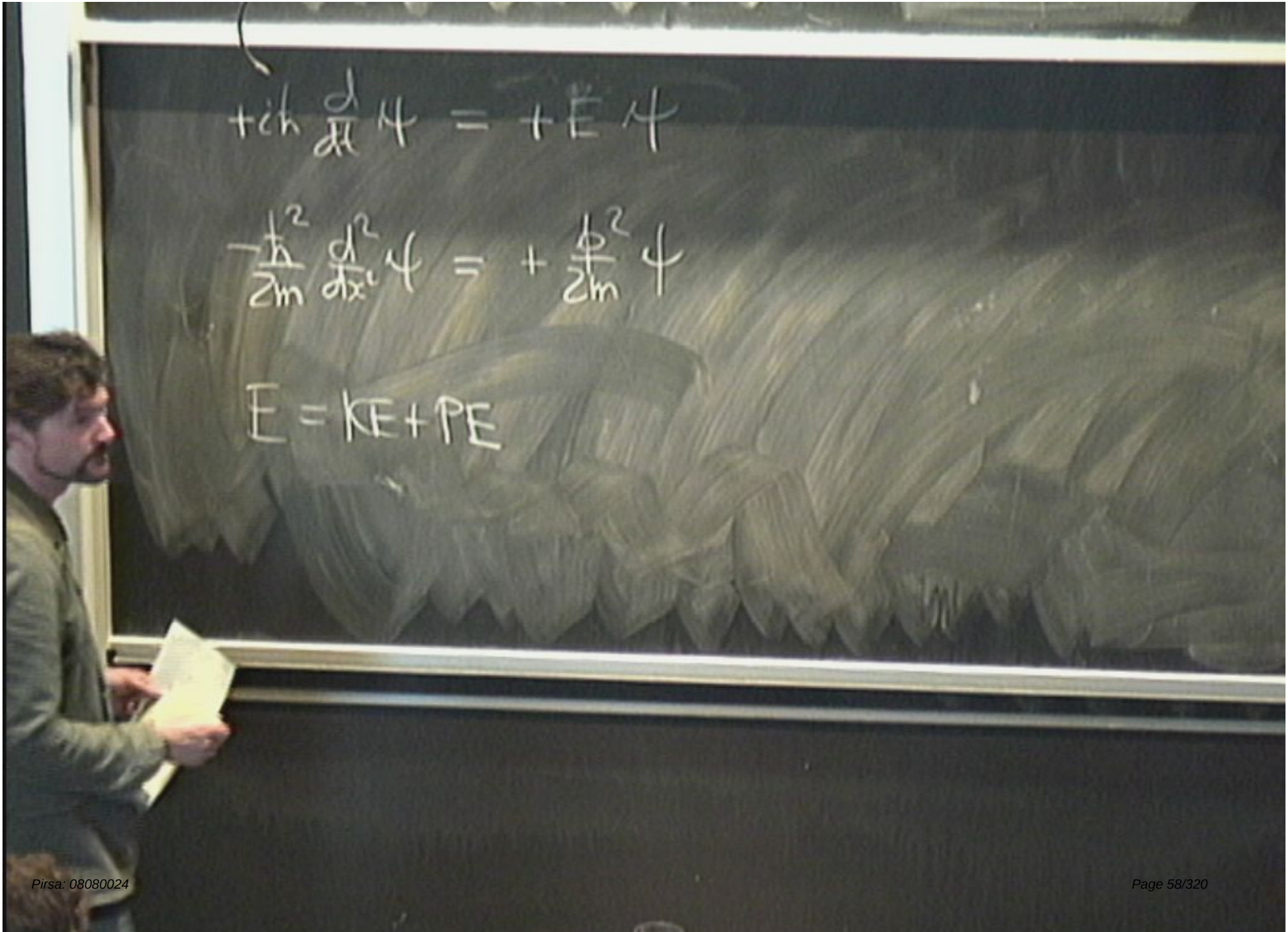
$$\frac{d^2}{dx^2}\psi = \frac{d}{dx}\left(\frac{d}{dx}\psi\right) = \frac{d}{dx}\left(\frac{i}{\hbar}p\psi\right) = \left(\frac{i}{\hbar}p\right)^2\psi = -\frac{p^2}{\hbar^2}\psi$$

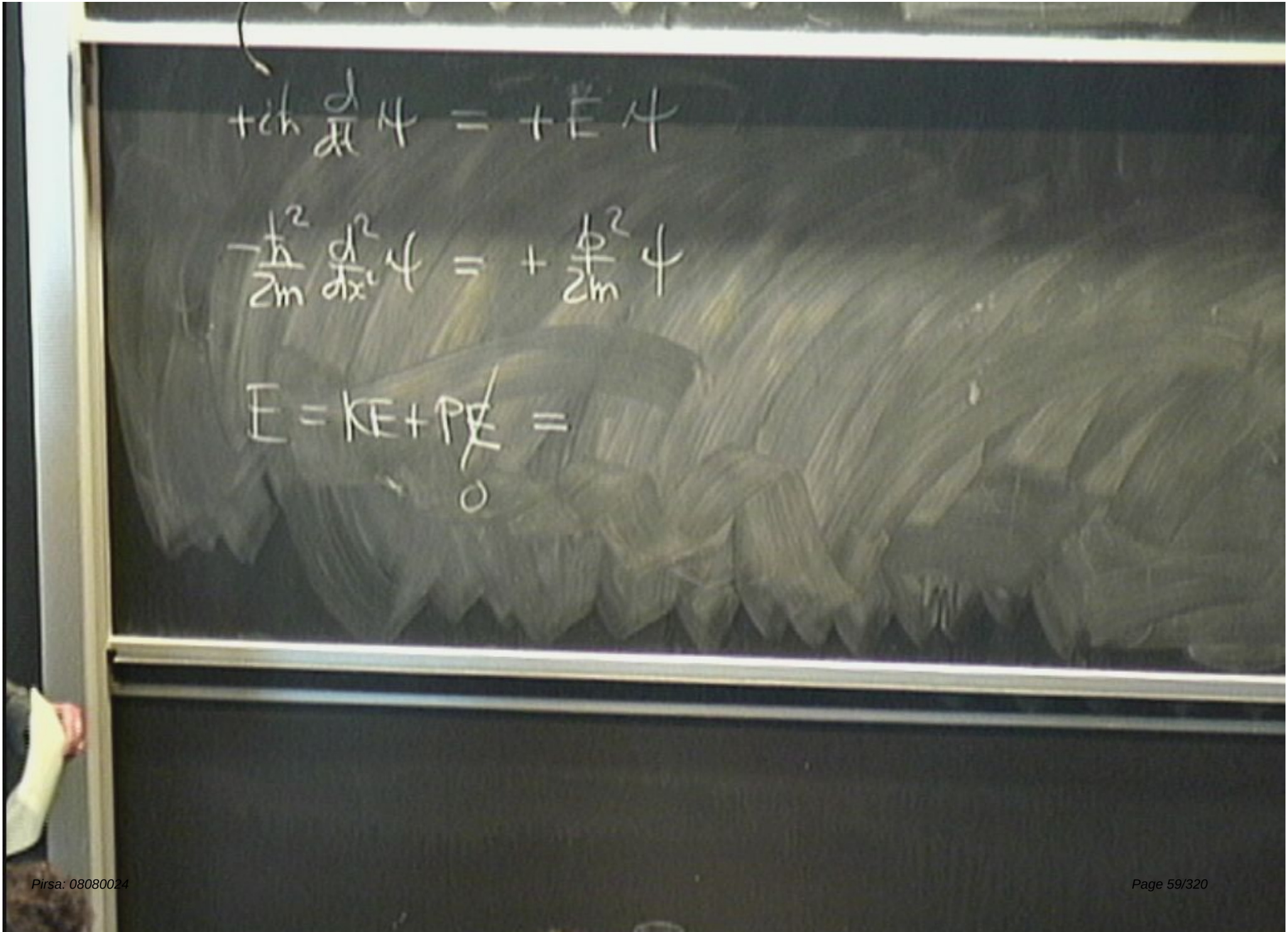
$$\frac{d}{dt}\psi = -\frac{i}{\hbar}E\psi$$

$-ih\frac{d}{dt}H =$


$+ih\frac{d}{dt}\psi = +\hat{E}\psi$


$+i\hbar \frac{\partial}{\partial t} \Psi = +E\Psi$
$-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} \Psi =$


$+i\hbar \frac{\partial}{\partial t} \Psi = +E\Psi$
$-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} \Psi = +\frac{p^2}{2m} \Psi$
$E = KE + PE$


$+i\hbar \frac{\partial}{\partial t} \Psi = +E\Psi$
$-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} \Psi = +\frac{p^2}{2m} \Psi$
$E = KE + PE = 0$

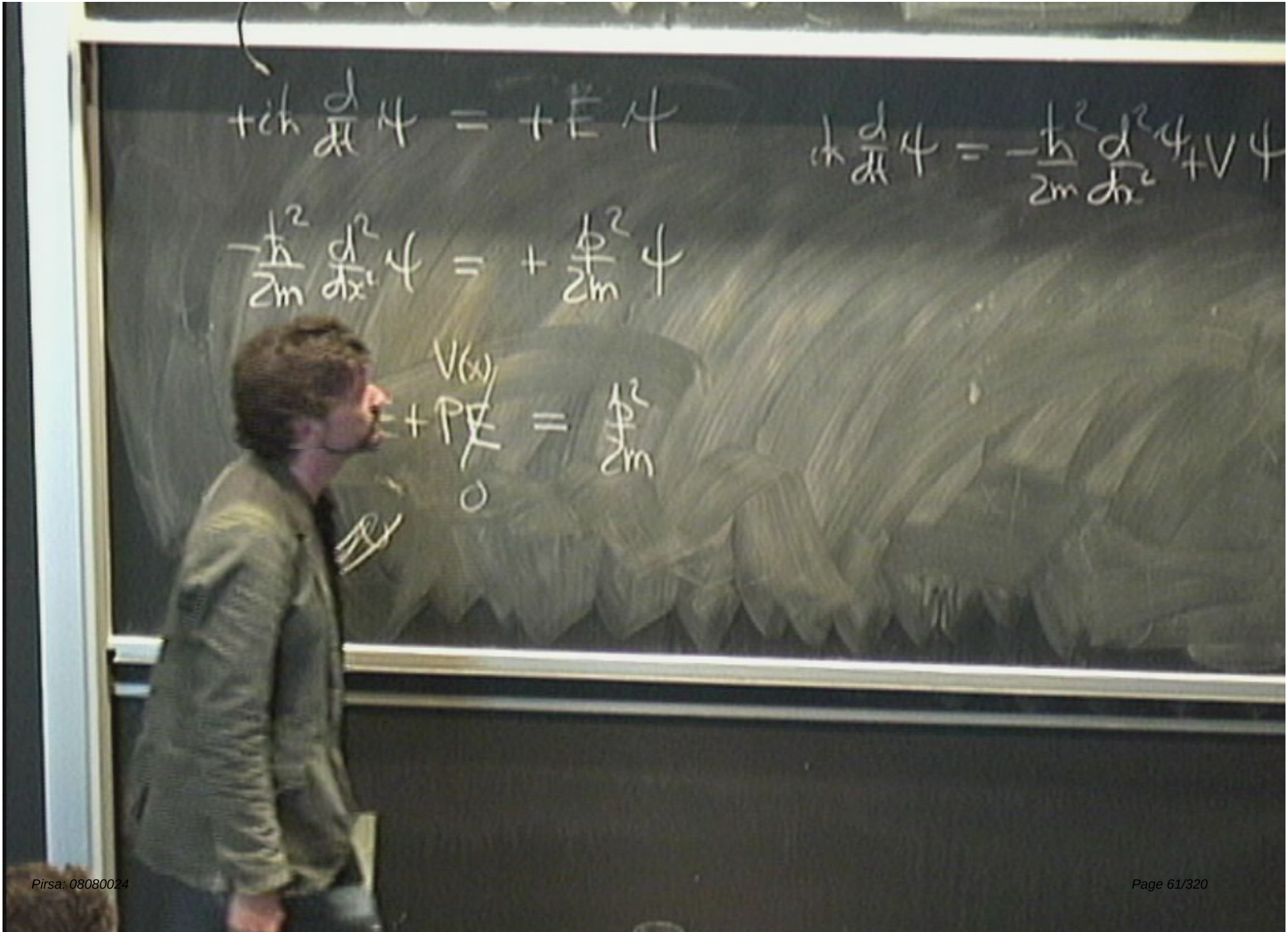
$$+ih\frac{d}{dt}\Psi = +E\Psi$$

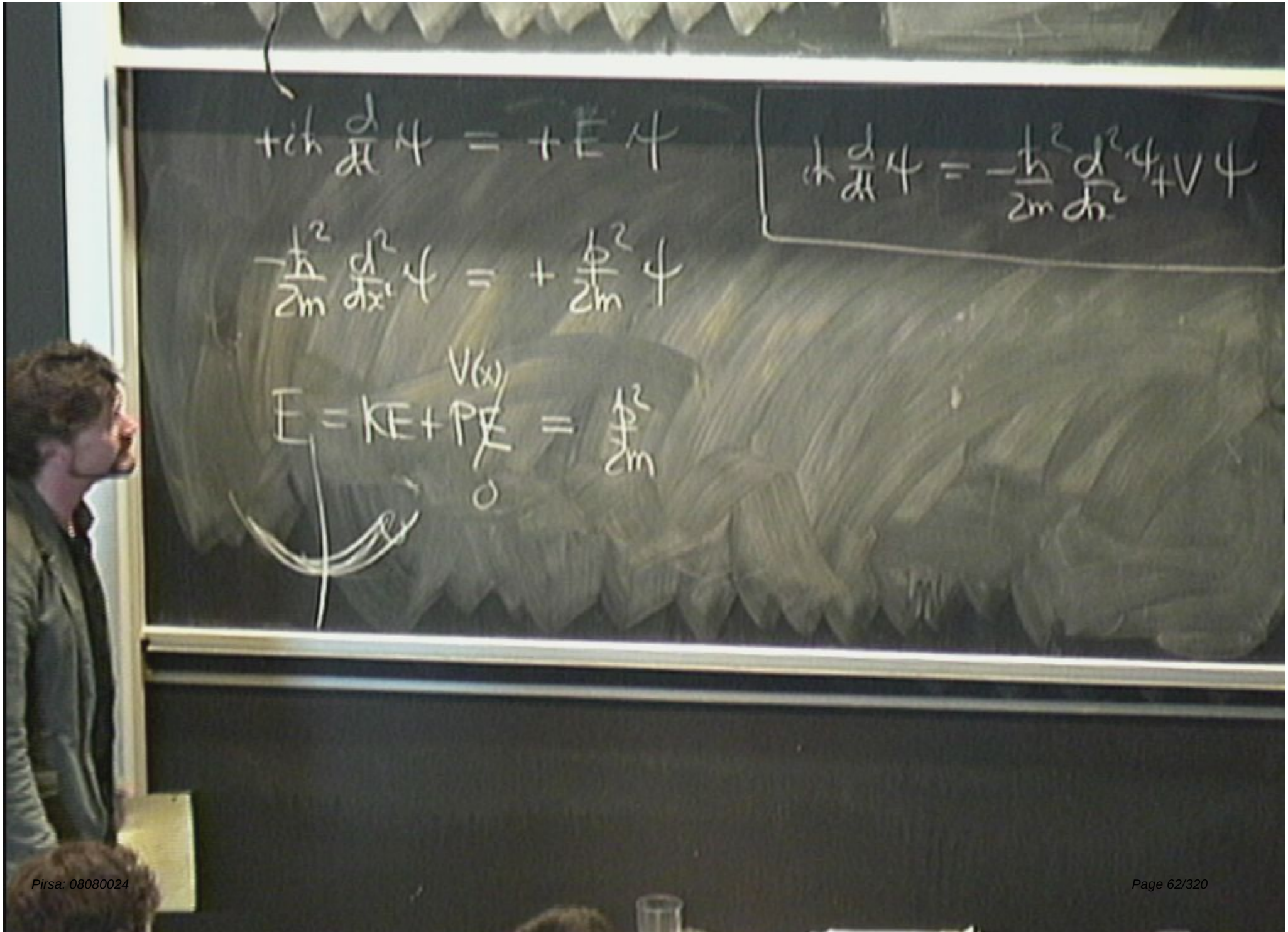
$$ih\frac{d}{dt}\Psi = -\frac{h^2}{2m}\frac{d^2}{dx^2}\Psi$$

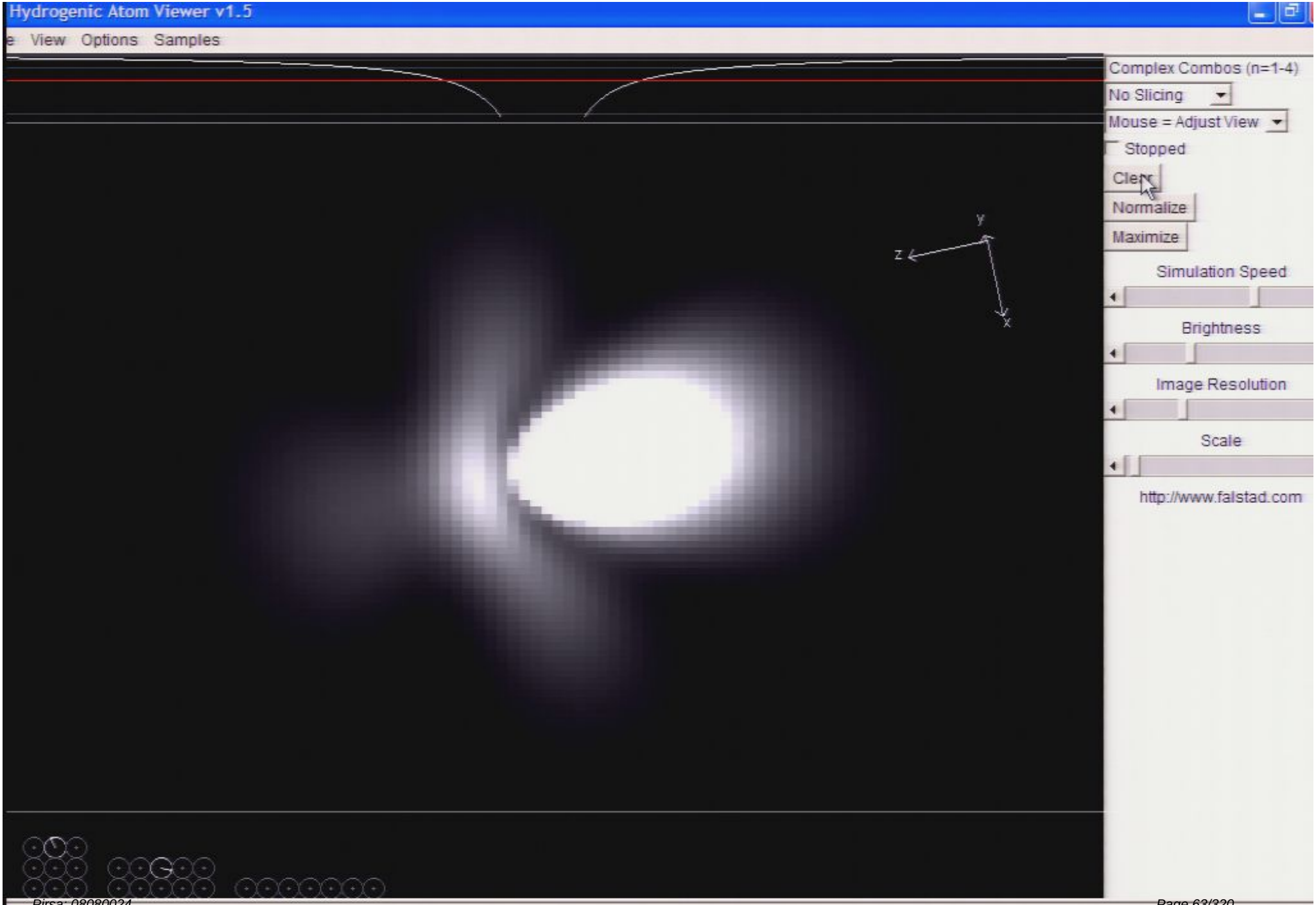
$$-\frac{h^2}{2m}\frac{d^2}{dx^2}\Psi = +\frac{p^2}{2m}\Psi$$

$$E = KE + \cancel{PE} = \frac{p^2}{2m}$$

$$0$$


$+i\hbar \frac{d}{dt}\Psi = +E\Psi$
$i\hbar \frac{d}{dt}\Psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\Psi + V\Psi$
$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\Psi = +\frac{p^2}{2m}\Psi$
V(x)
$E + PE = \frac{p^2}{2m}$
0


$+i\hbar \frac{d}{dt}\Psi = +E\Psi$
$i\hbar \frac{d}{dt}\Psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\Psi + V\Psi$
$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\Psi = +\frac{p^2}{2m}\Psi$
$E = KE + PE = \frac{p^2}{2m}$
V(x)
0


Hydrogenic Atom Viewer v1.5
e View Options Samples
Complex Combos (n=1-4)
No Slicing
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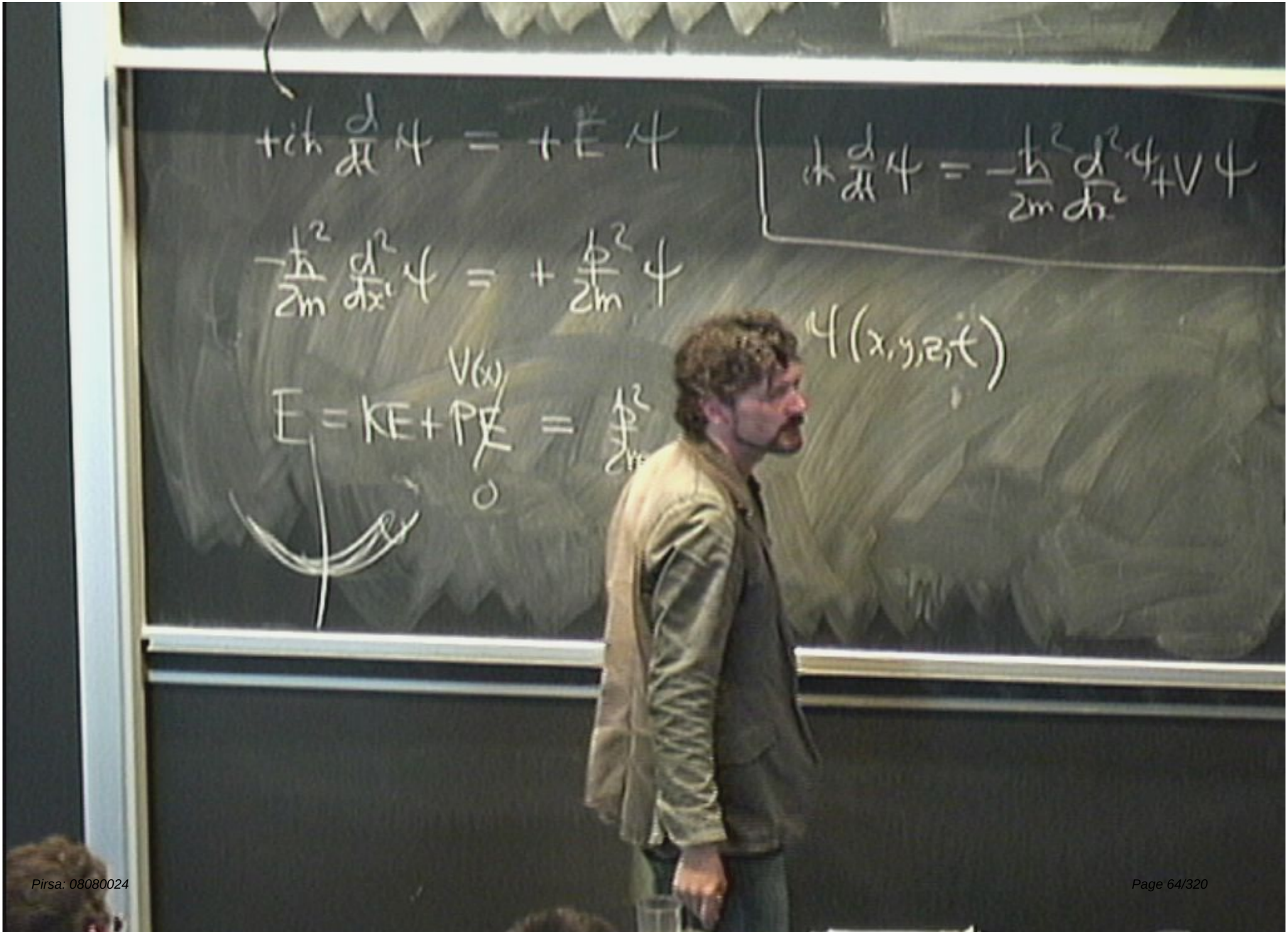
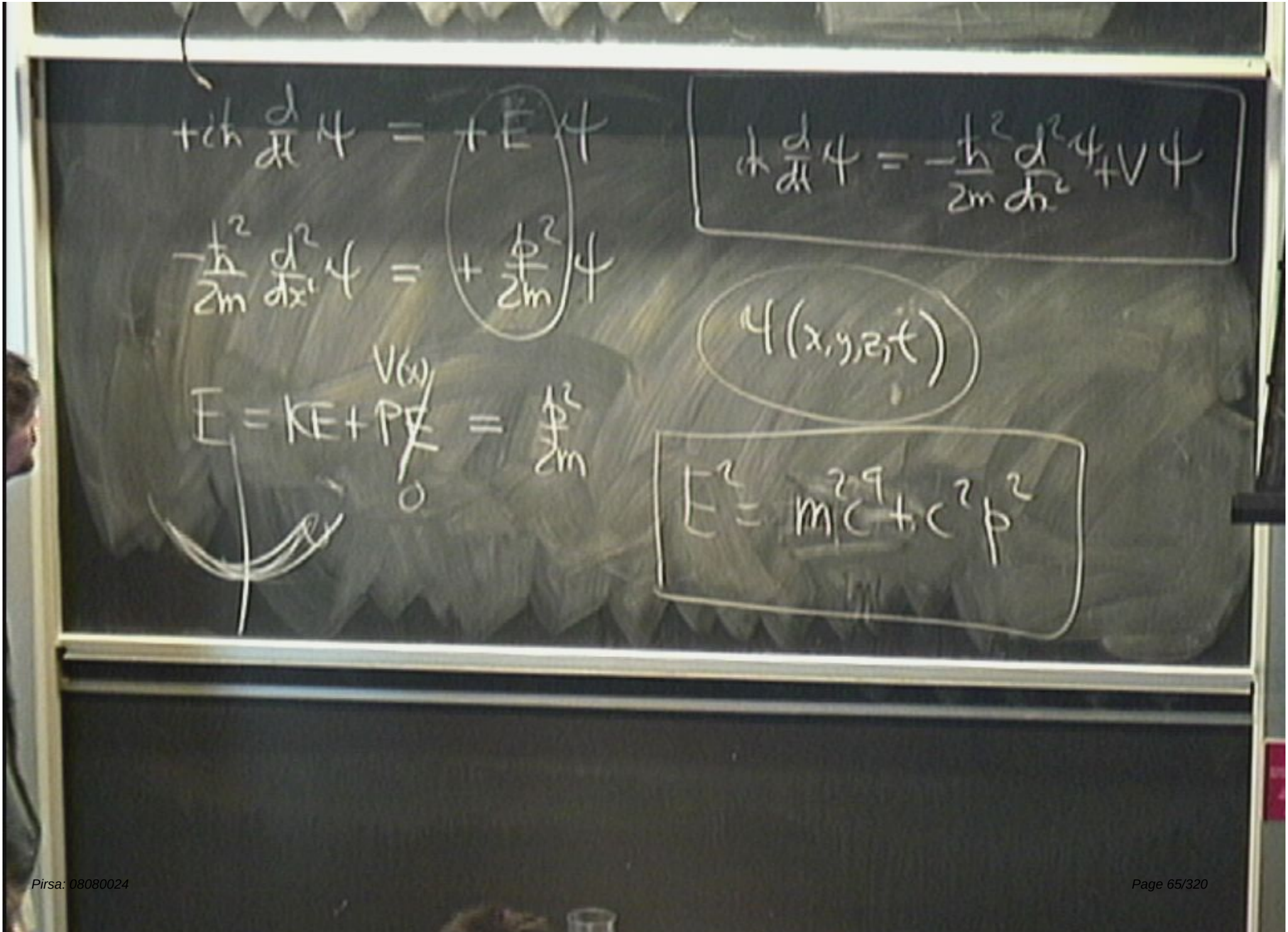
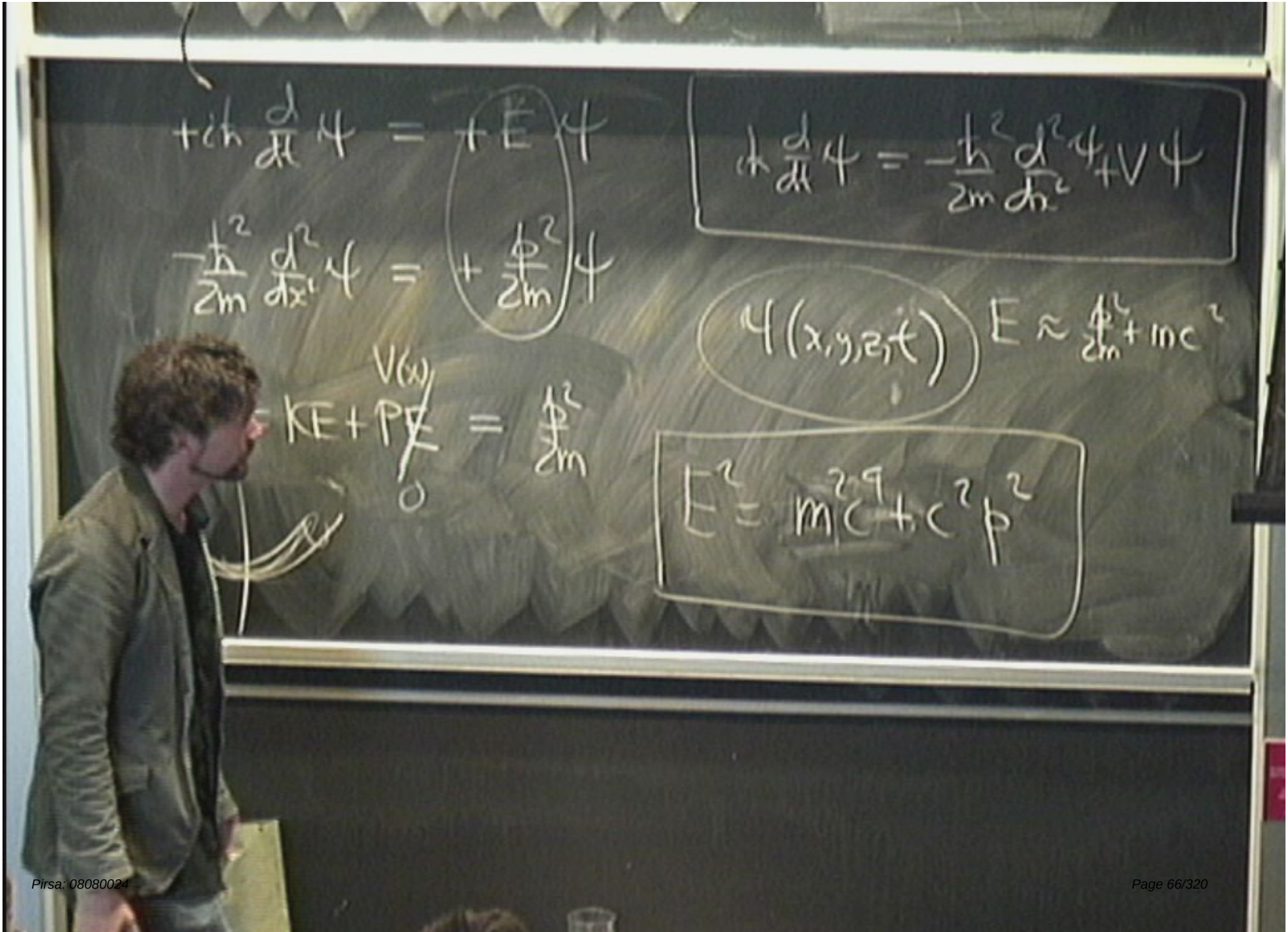
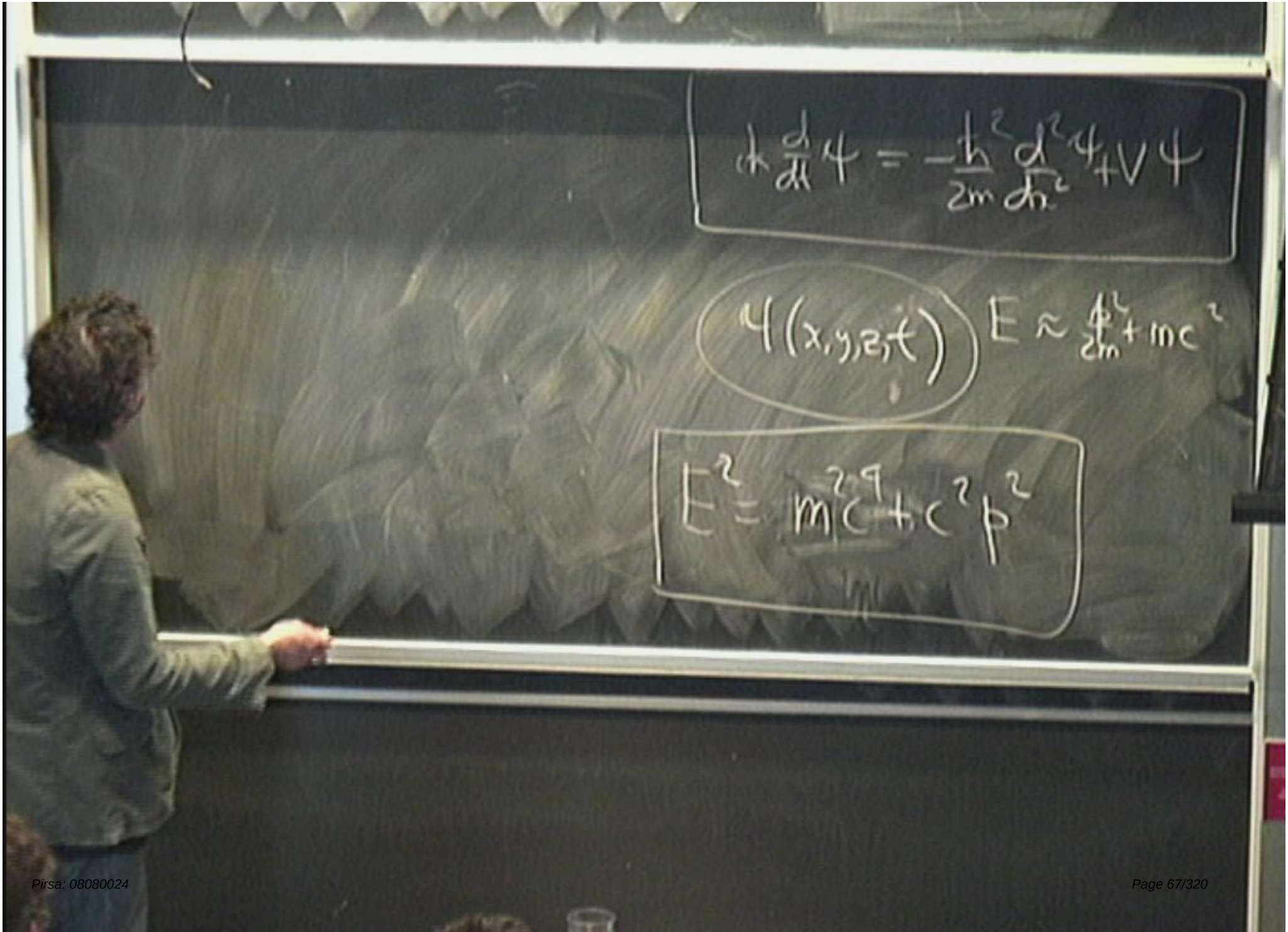

$+i\hbar \frac{\partial}{\partial t}\Psi = +E\Psi$
$i\hbar \frac{\partial}{\partial t}\Psi = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\Psi + V\Psi$
$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\Psi = +\frac{p^2}{2m}\Psi$
$\Psi(x,y,z,t)$
$E = KE + \overset{V(x)}{PE} = \frac{p^2}{2m}$
0


$+i\hbar \frac{d}{dt}\psi = +E\psi$
$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi = +\frac{p^2}{2m}\psi$
$E = KE + PE = \frac{p^2}{2m}$
$V(x)$
0
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
$\psi(x,y,z,t)$
$E^2 = m^2c^4 + c^2p^2$


$+i\hbar \frac{d}{dt}\psi = +E\psi$
$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi = +\frac{p^2}{2m}\psi$
$KE + PE = \frac{p^2}{2m}$
$V(x)$
0
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = m^2c^4 + c^2p^2$


$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
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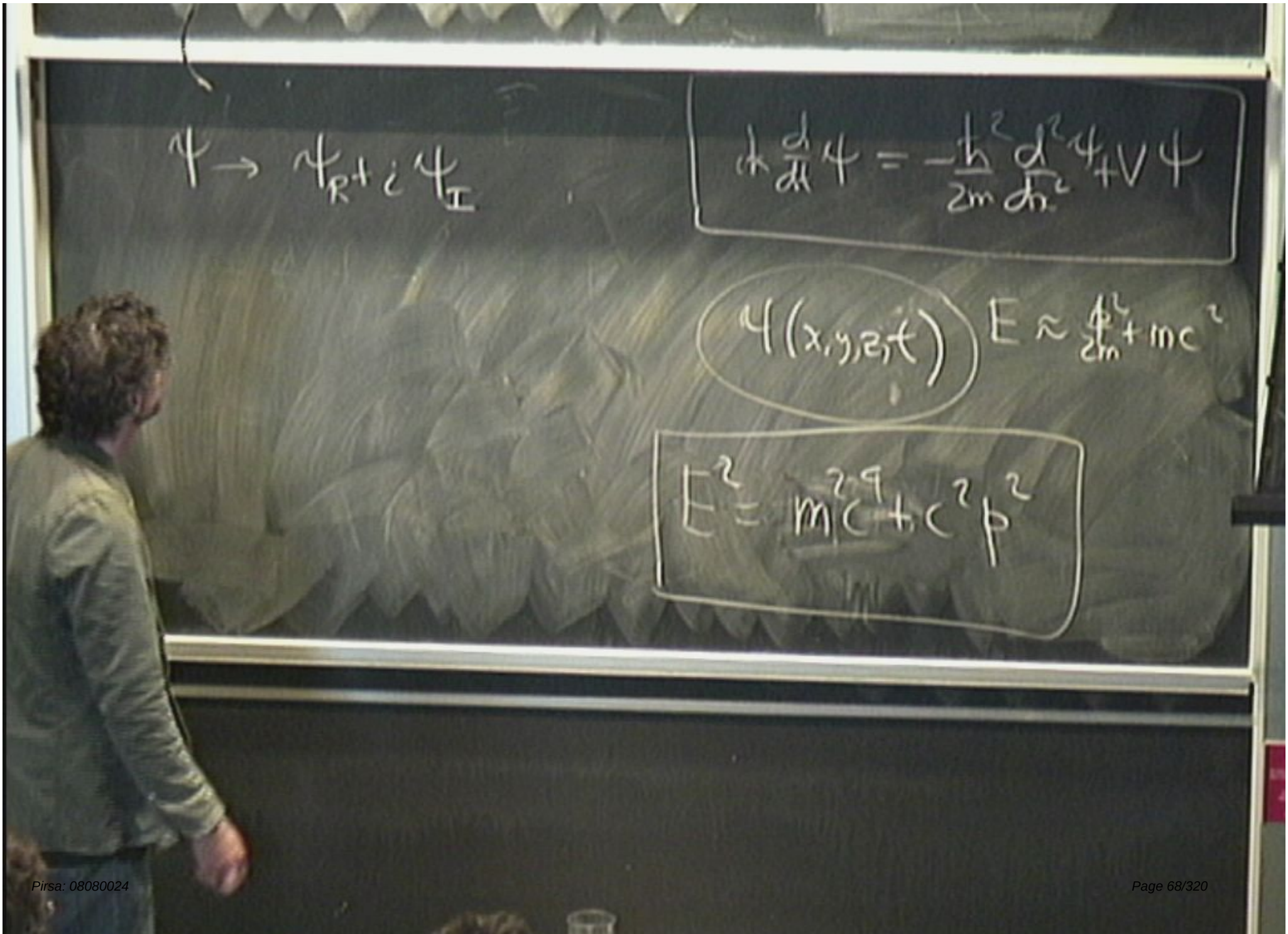
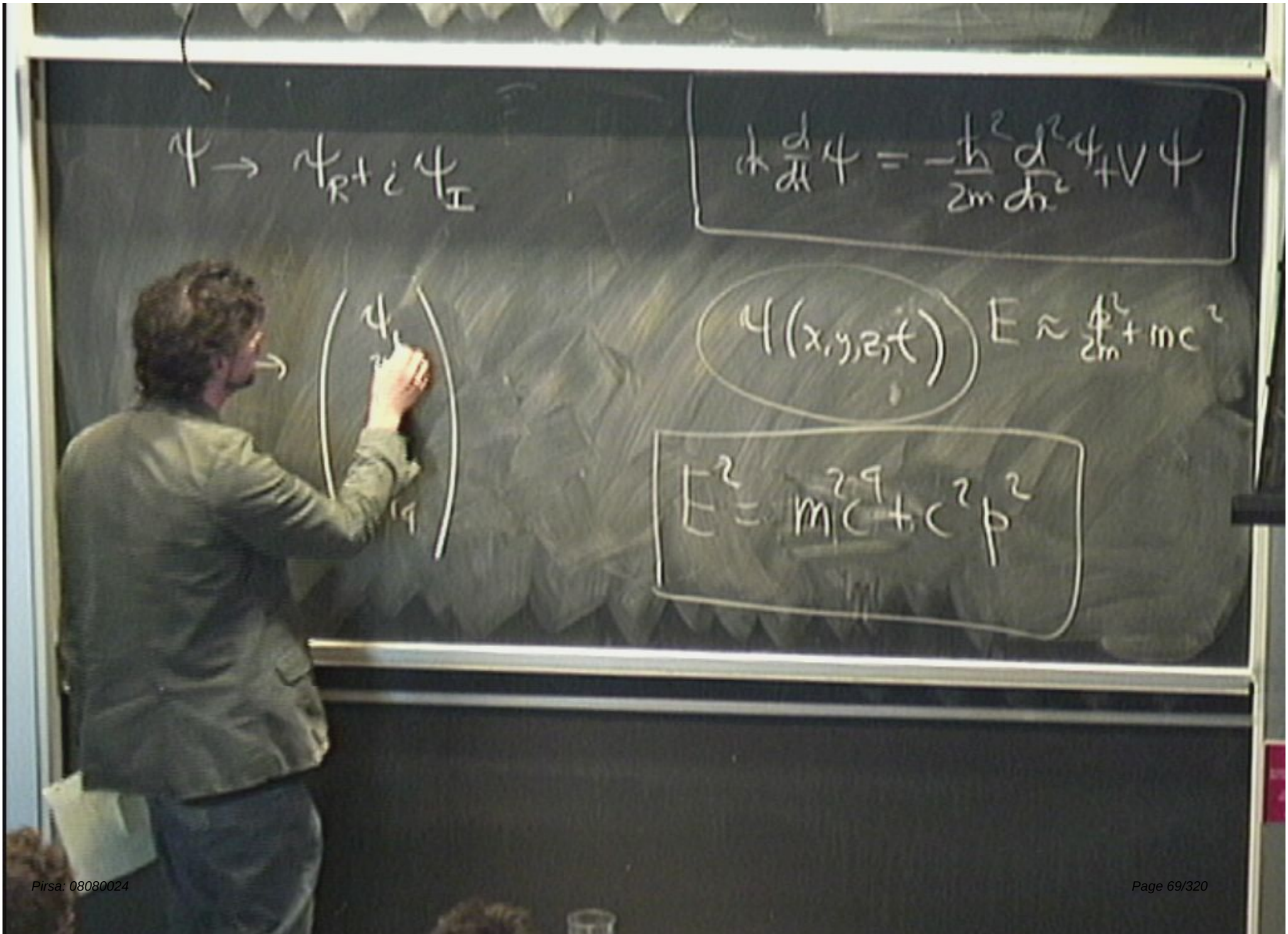
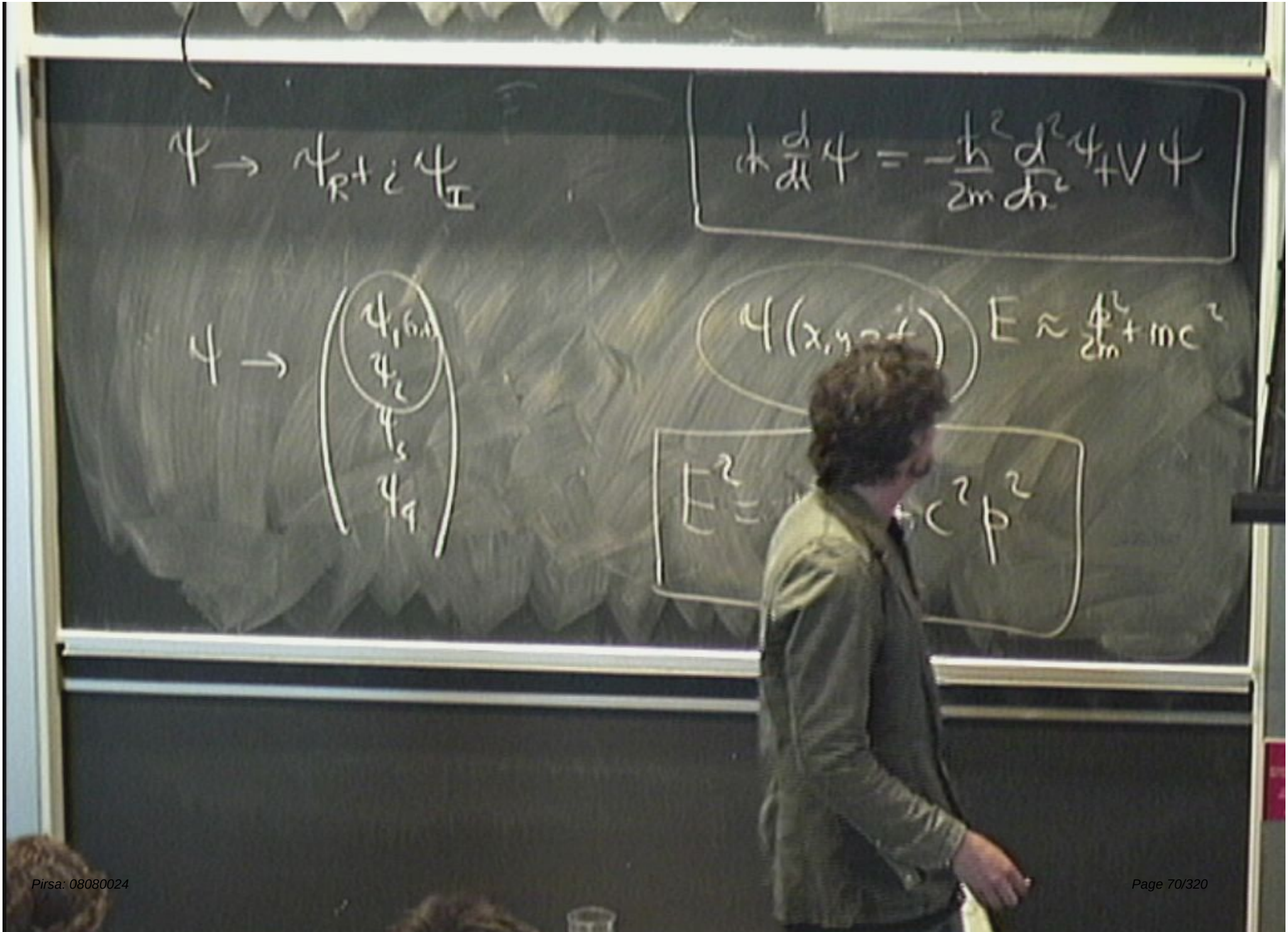

$\psi \to \psi_R + i\psi_I$
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = m^2c^4 + c^2p^2$


$\psi \to \psi_R + i\psi_I$
$\to \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = m^2c^4 + c^2p^2$


$\psi \to \psi_R + i\psi_I$
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
$\psi \to \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = (mc^2)^2 + c^2p^2$

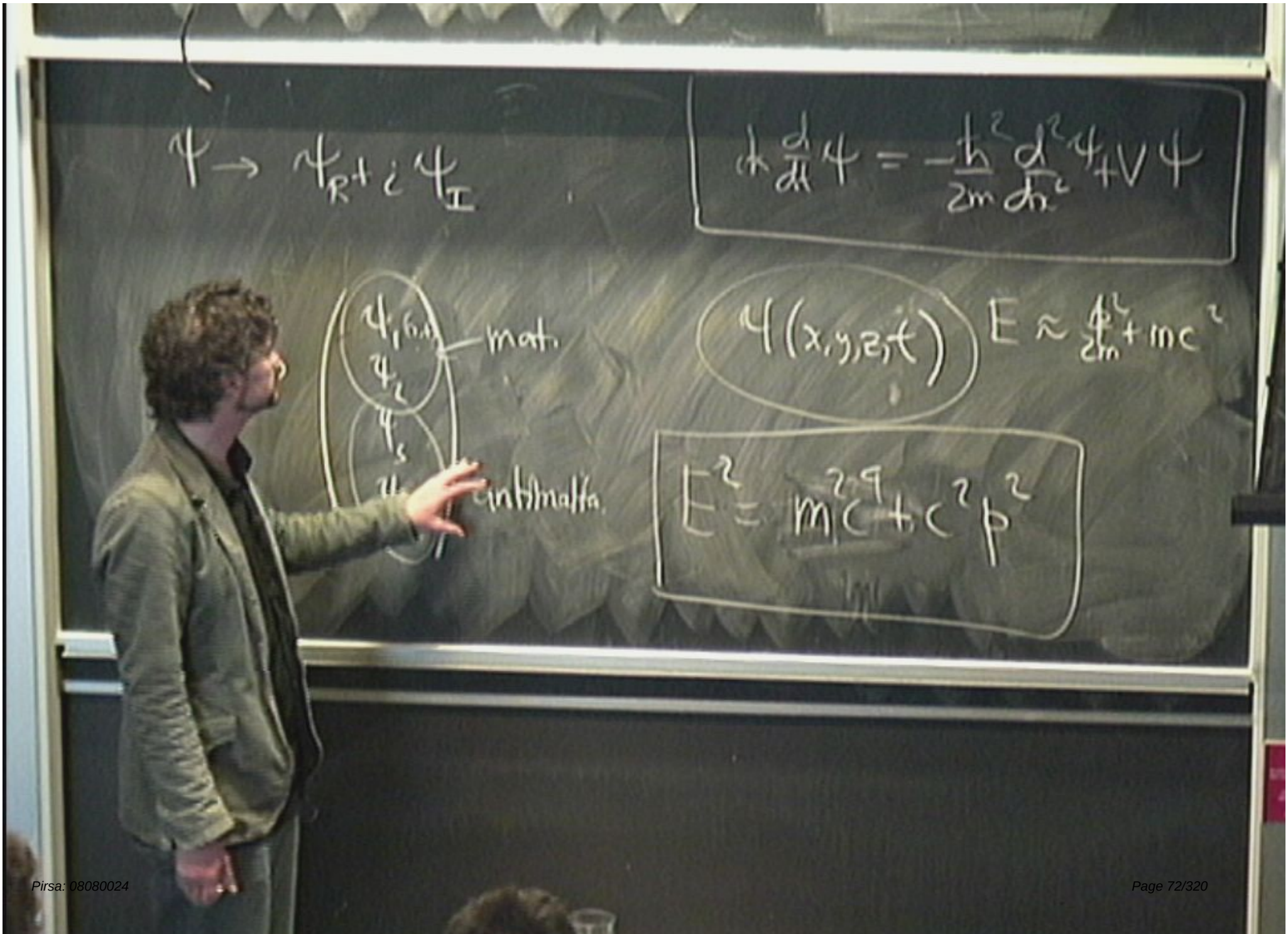
$\psi \to \psi_R + i\psi_I$

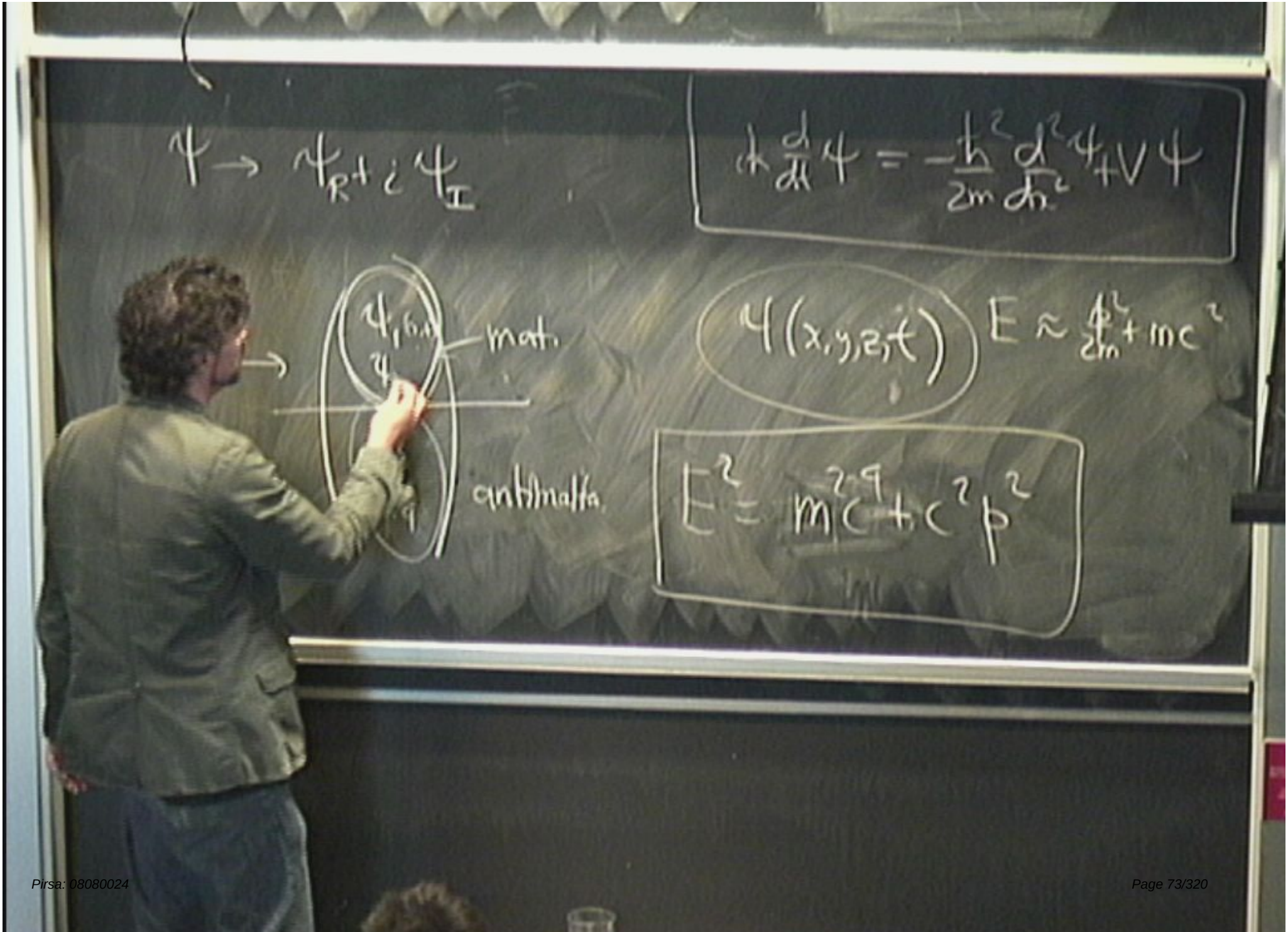
$$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$$

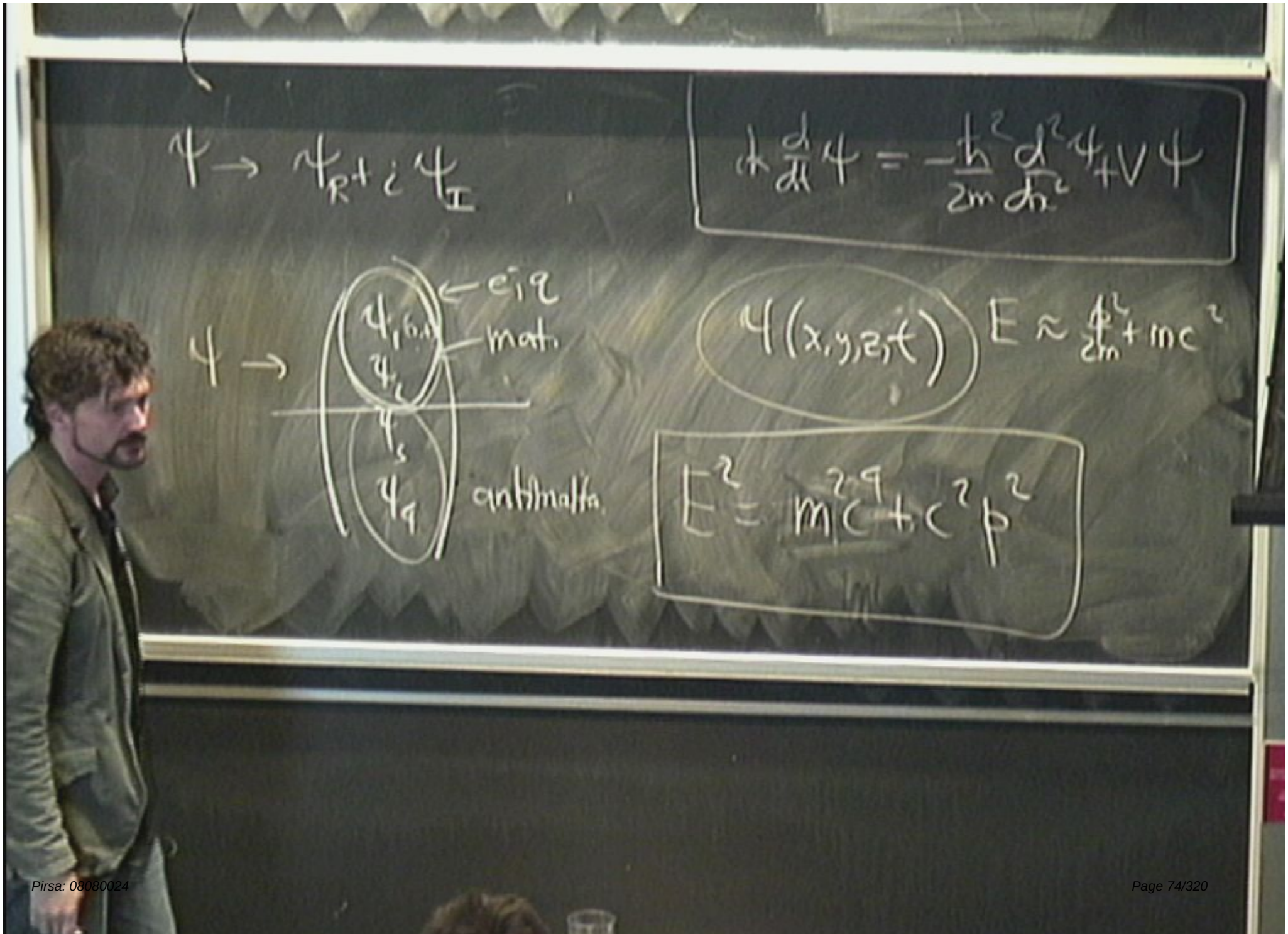
$\psi \to$ (ψ_1 ψ_2 ψ_3 ψ_4)

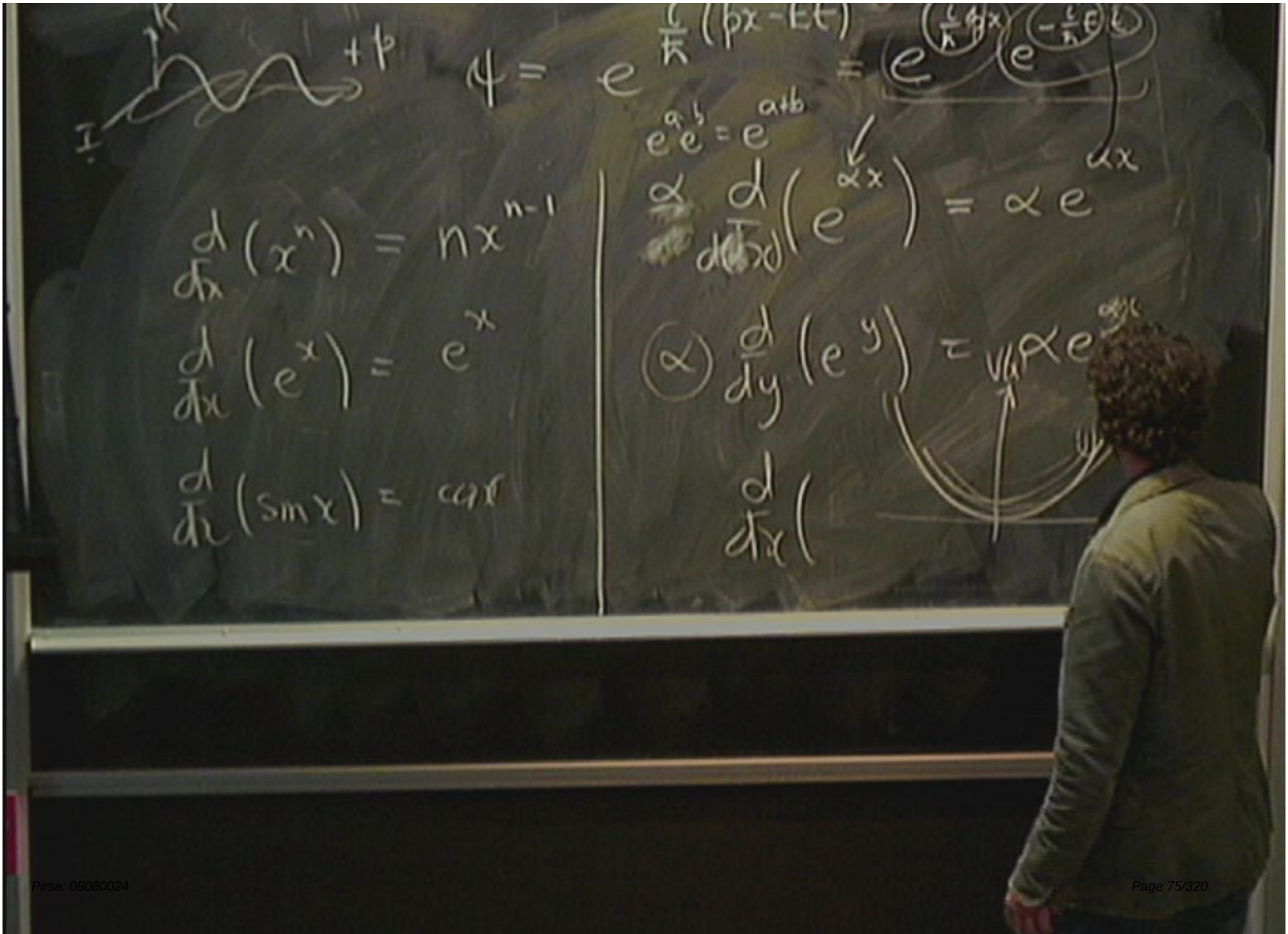
$\psi(x,y,z,t)$ $\quad E \approx \frac{p^2}{2m} + mc^2$

$$E^2 = m^2c^4 + c^2p^2$$


$\psi \to \psi_R + i\psi_I$
$ih\frac{d}{dt}\psi = -\frac{h^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
ψ_1
ψ_2
ψ_3
mat.
antimateria
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = m^2c^4 + c^2p^2$


$\psi \to \psi_R + i\psi_I$
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
ψ_{hyd}
ψ
matt.
antimatt.
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = m^2c^4 + c^2p^2$


$\psi \to \psi_R + i\psi_I$
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
$\psi \to$
$\psi_{1,2,3}$
ψ_4
ψ_5
ψ_6
$\leftarrow e, q$
matt.
antimatt.
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = m^2c^4 + c^2p^2$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$e^a e^b = e^{a+b}$
$\frac{d}{dx}(x^n) = nx^{n-1}$
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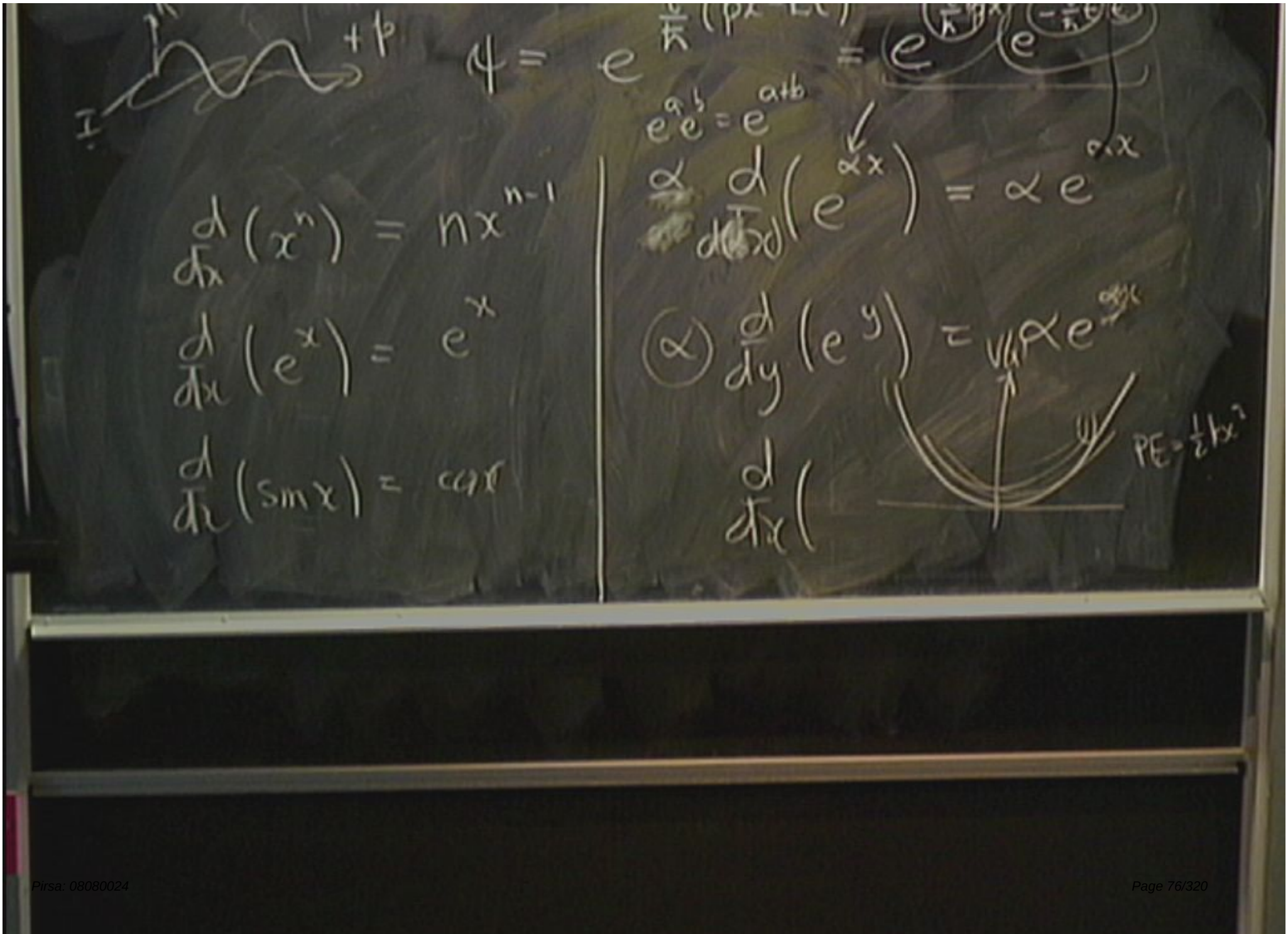
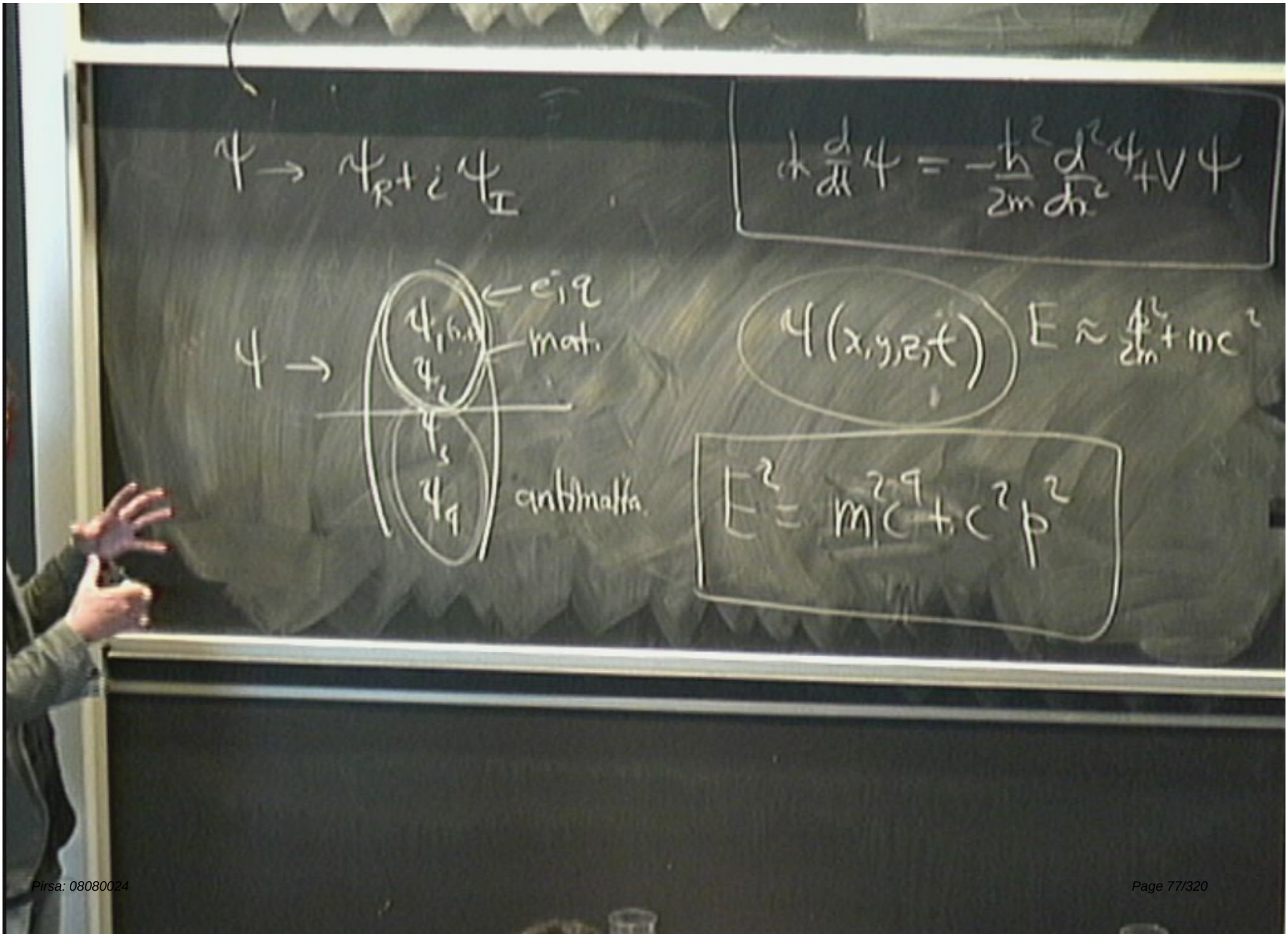
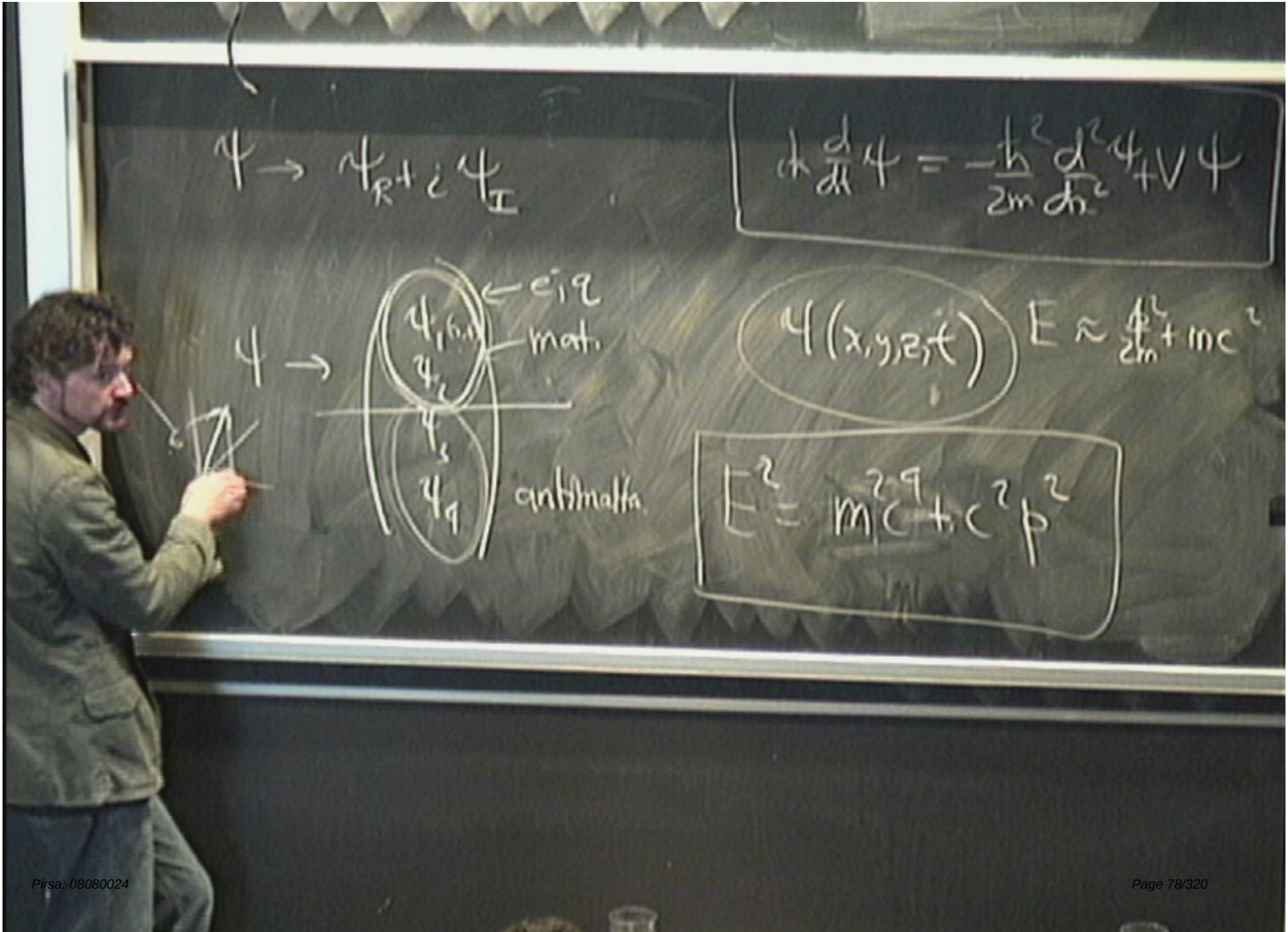
$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$
(α) $\frac{d}{dy}(e^{\alpha y}) = \alpha e^{\alpha y}$
$\frac{d}{dx}($

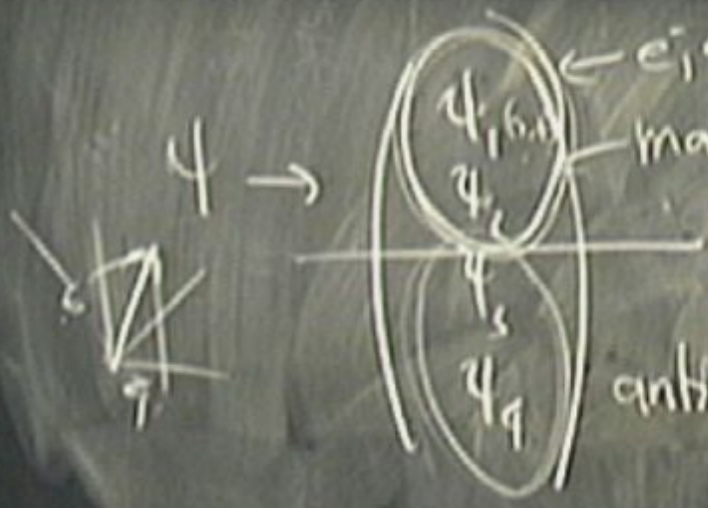

$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^x) = e^x$
$\frac{d}{dx}(\sin x) = \cos x$
$e^a e^b = e^{a+b}$
$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
$\frac{d}{dy}(e^{\alpha y}) = \alpha e^{\alpha y}$
$PE = \frac{1}{2}kx^2$


$\psi \to \psi_R + i\psi_I$
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
$\psi \to$
ψ_1
ψ_2
ψ_3
ψ_4
← e, q
mat.
antimatter
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = m^2c^4 + c^2p^2$


$\psi \to \psi_R + i\psi_I$
$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$
$\psi \to$
$\leftarrow e, q$
ψ_1
ψ_2
ψ_3
ψ_4
mat.
antimatter
$\psi(x,y,z,t)$
$E \approx \frac{p^2}{2m} + mc^2$
$E^2 = m^2c^4 + c^2p^2$

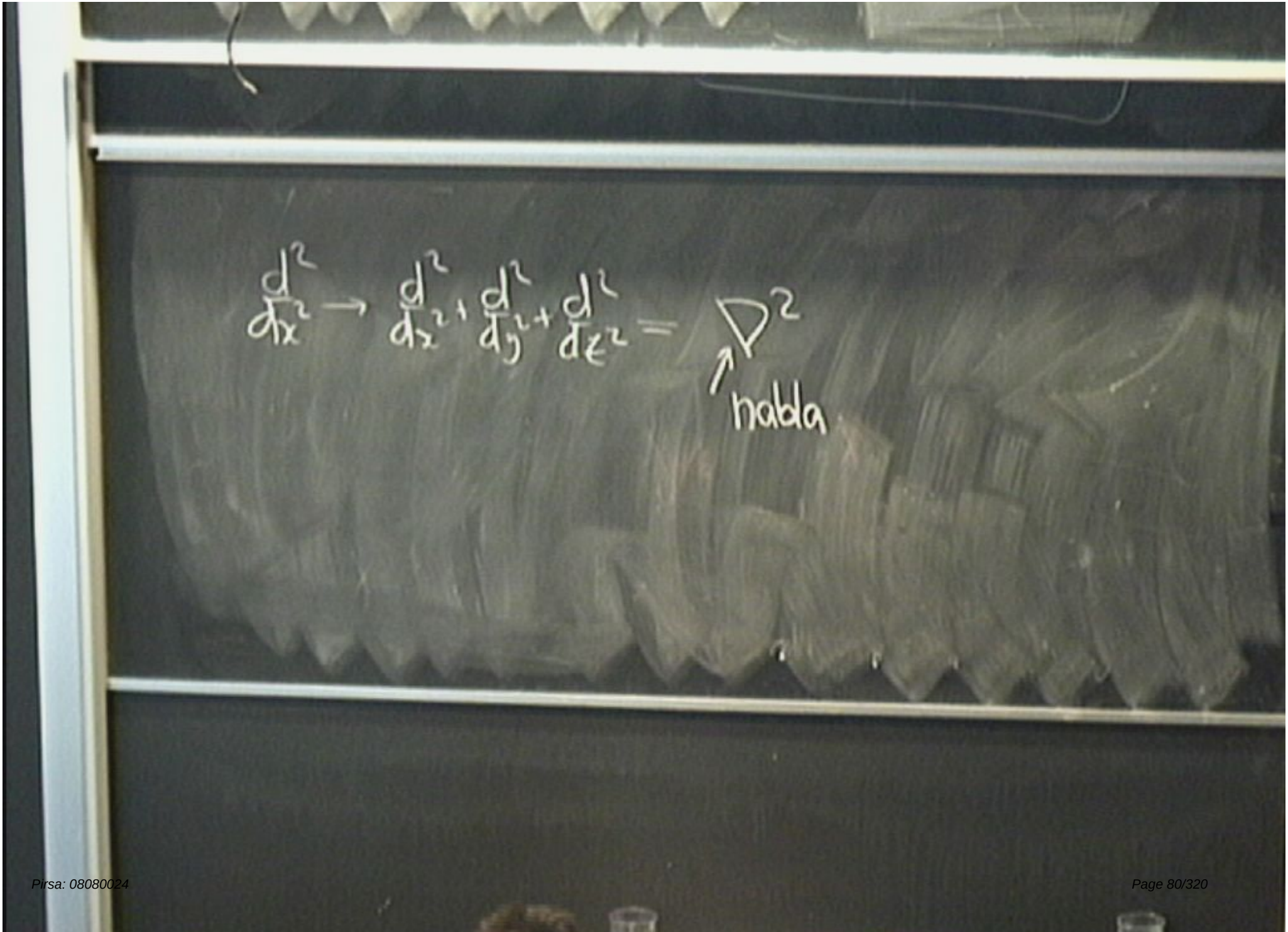
$\psi \to \psi_R + i\psi_I$

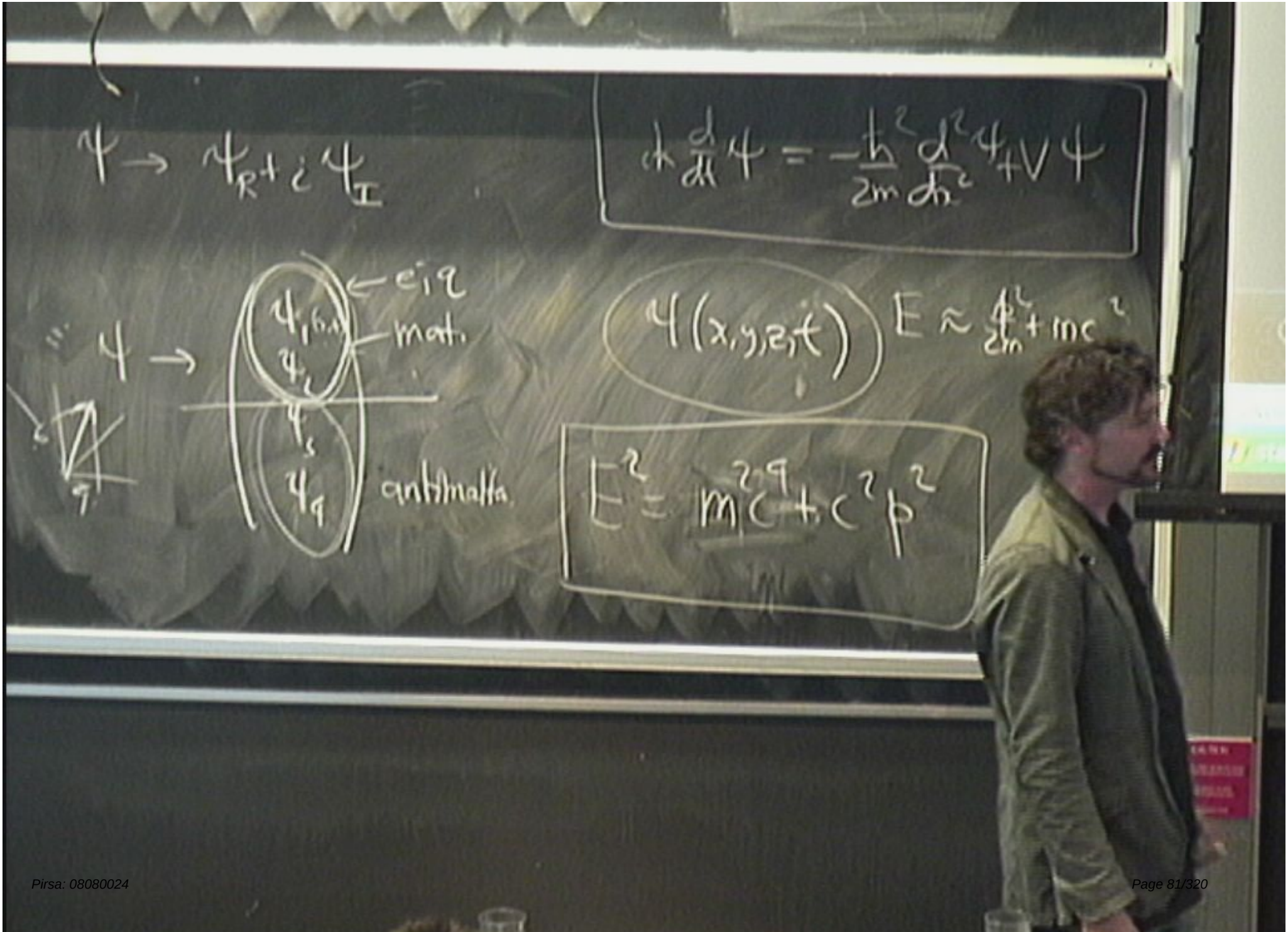
$$i\hbar \frac{d}{dt}\psi = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi + V\psi$$

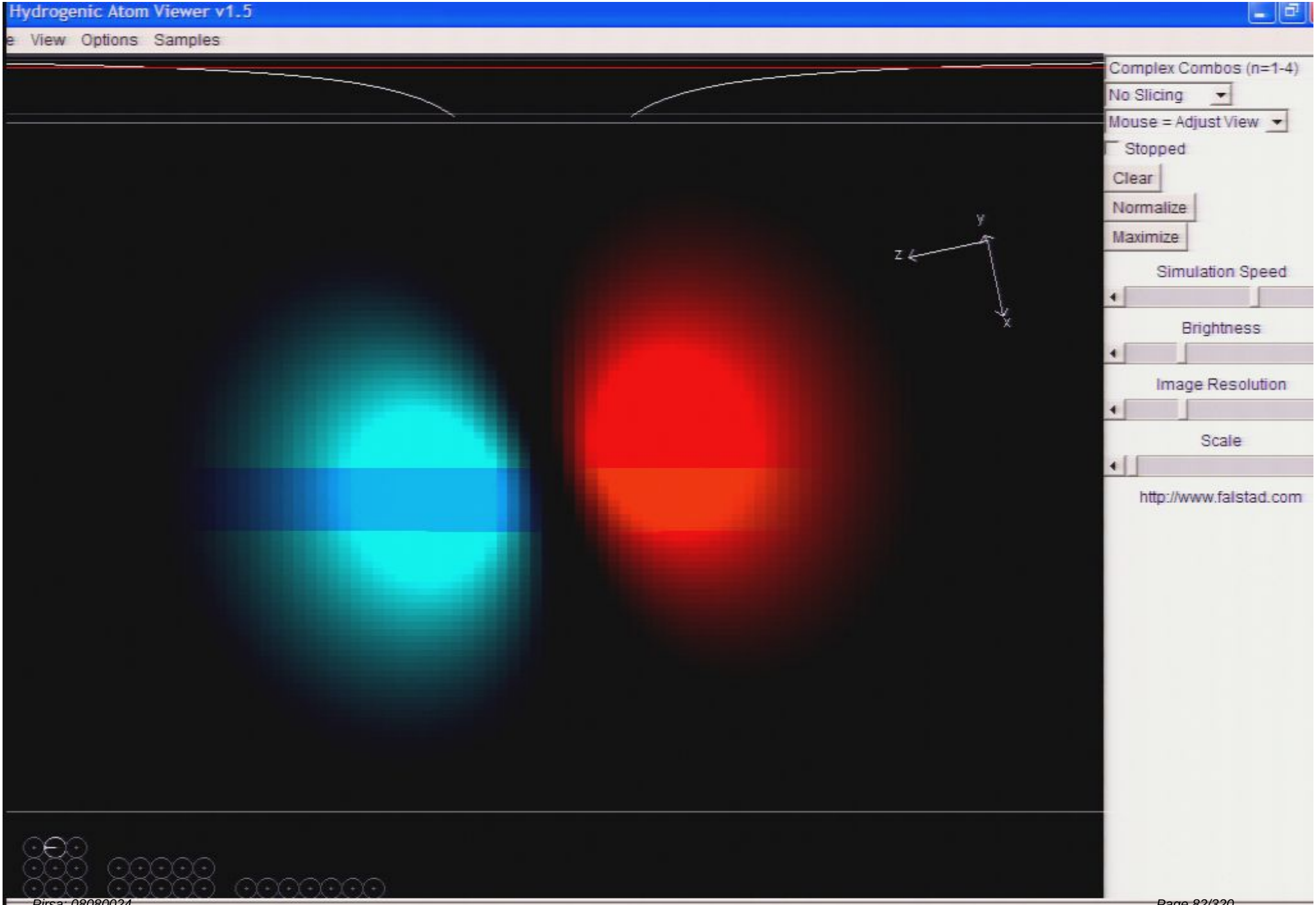


$\psi(x,y,z,t)$ $E \approx \frac{p^2}{2m} + mc^2$

$$E^2 = m^2c^4 + c^2p^2$$


$\frac{d^2}{dx^2} \rightarrow \frac{d^2}{dx^2} + \frac{d^2}{dy^2} + \frac{d^2}{dz^2} = \nabla^2$
nabla


ψ → ψ_R + i ψ_I
iħ d/dt ψ = −ħ²/2m d²/dx² ψ + V ψ
ψ → ψ_1 ψ_2 ψ_3 ψ_4
← e, q
mat.
antimatta
ψ(x,y,z,t)
E ≈ p²/2m + mc²
E² = m²c⁴ + c²p²


Hydrogenic Atom Viewer v1.5
e View Options Samples
Complex Combos (n=1-4)
No Slicing
Mouse = Adjust View
Stopped
Clear
Normalize
Maximize
Simulation Speed
Brightness
Image Resolution
Scale
http://www.falstad.com
y
z
x
a Applet Window

$\psi = e^{ikx}$

$e^a e^b = e^{a+b}$

$\frac{d}{dx}(x^n) = nx^{n-1}$

$\frac{d}{dx}(e^x) = e^x$

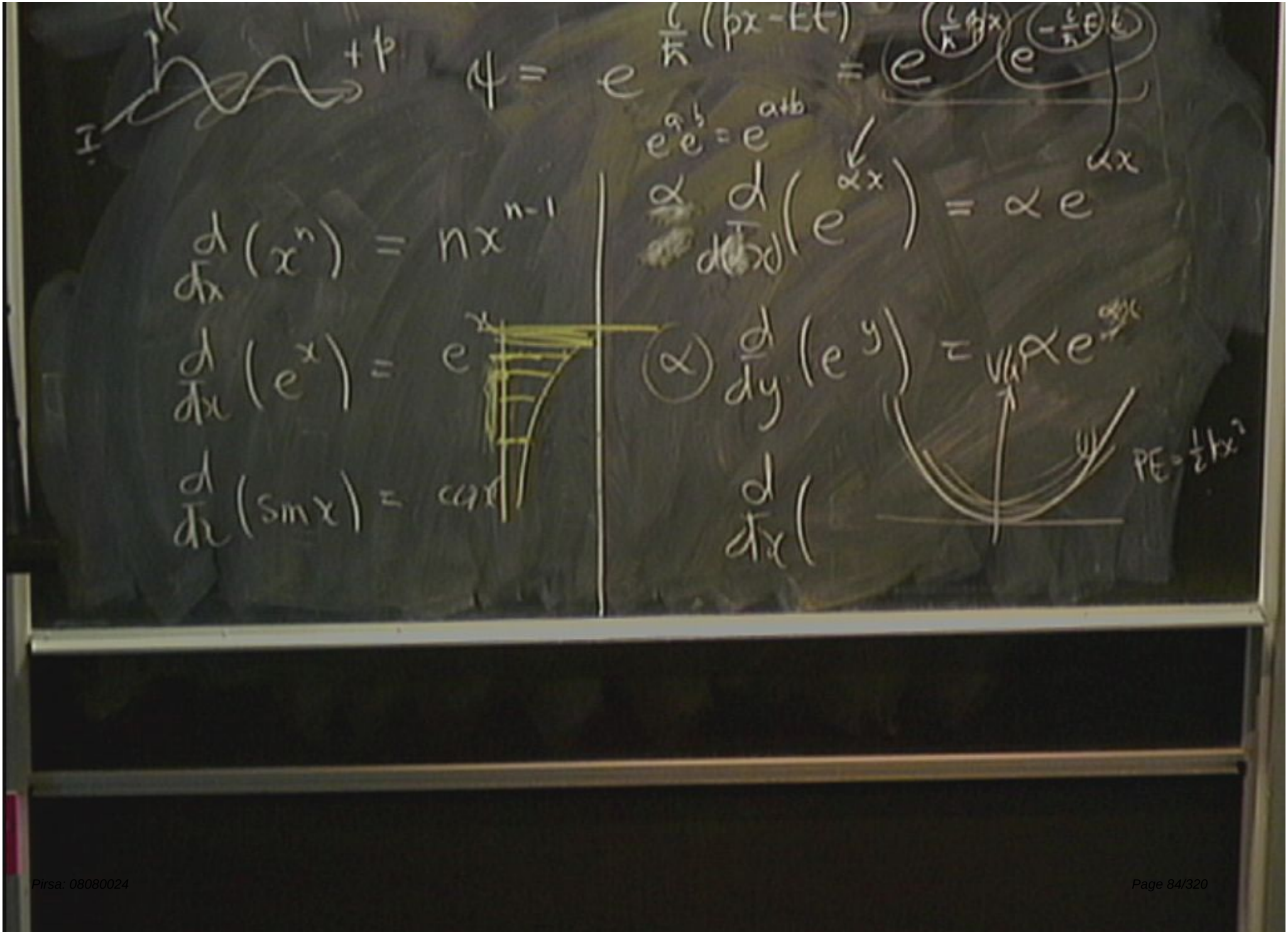
$\frac{d}{dx}(\sin x) = \cos x$

$\alpha \frac{d}{d(\alpha x)}(e^{\alpha x}) = \alpha e^{\alpha x}$

$\alpha \frac{d}{dy}(e^y) = \alpha e^{\alpha x}$

$\frac{d}{dx}($

$PE = \frac{1}{2}kx^2$


$\psi = e^{\frac{i}{\hbar}(px - Et)}$
$= e^{\frac{i}{\hbar}px} e^{-\frac{i}{\hbar}Et}$
$e^a e^b = e^{a+b}$
$\frac{d}{dx}(x^n) = nx^{n-1}$
$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
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What's Inside the Tube?

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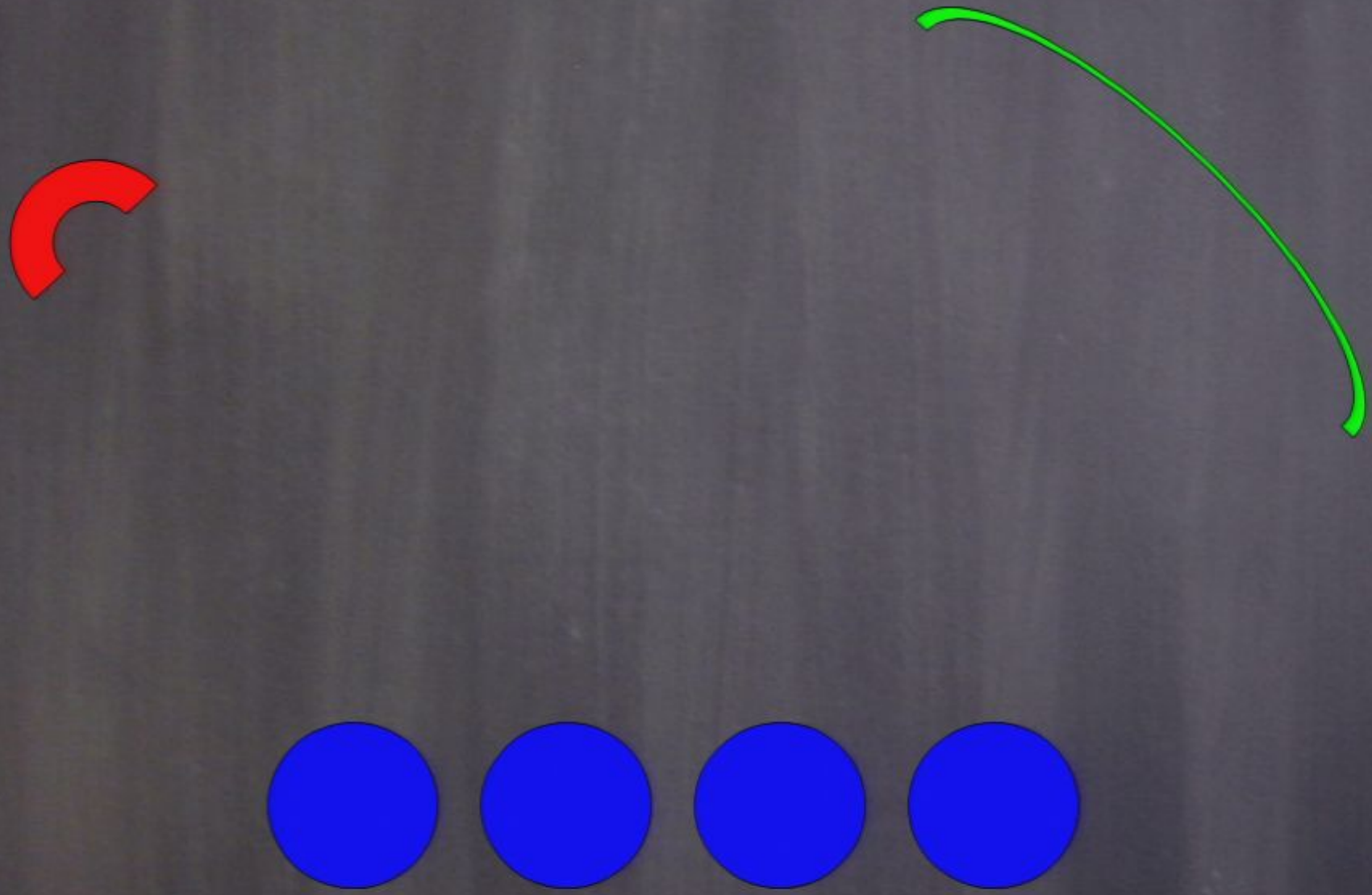

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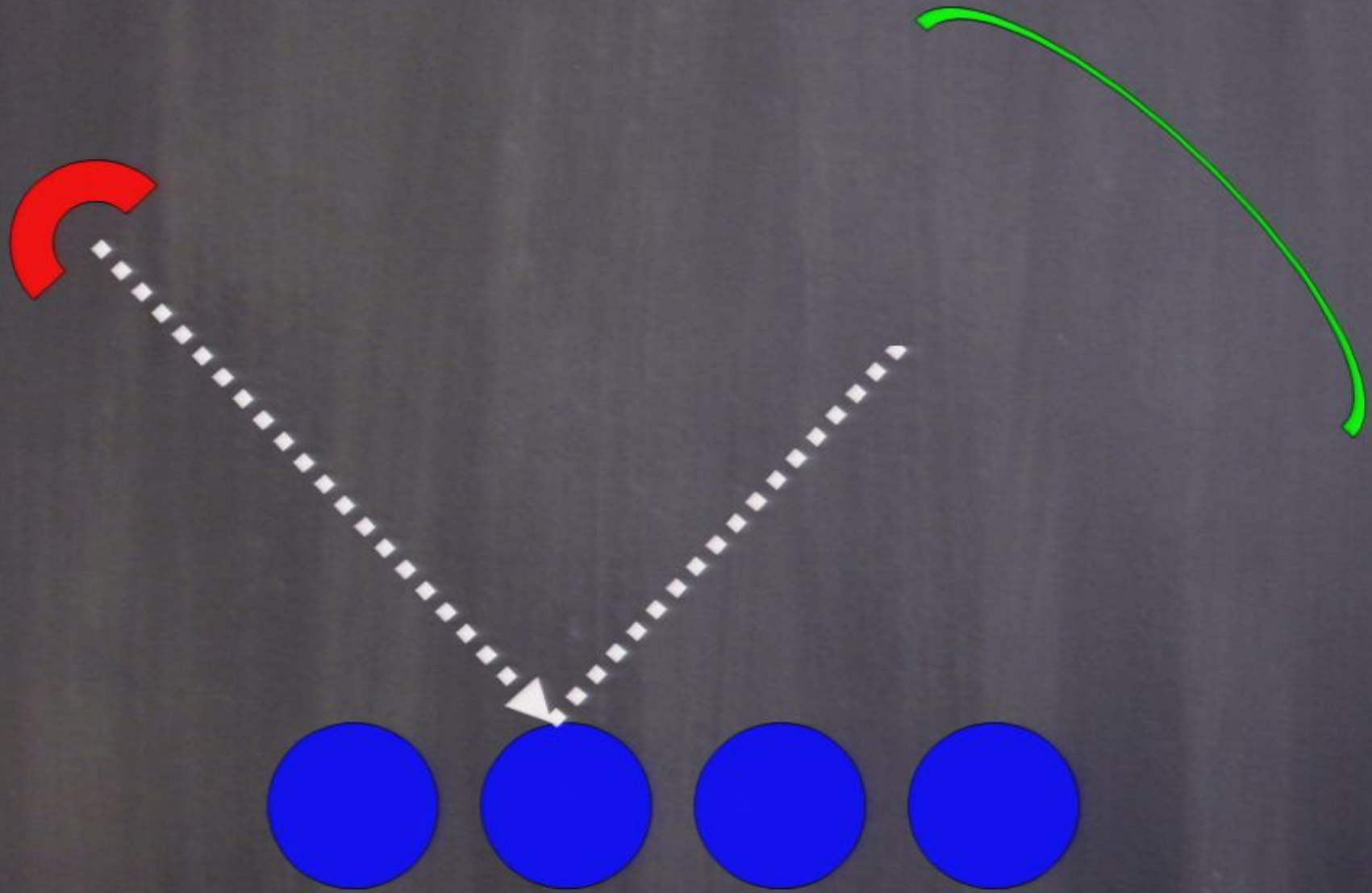

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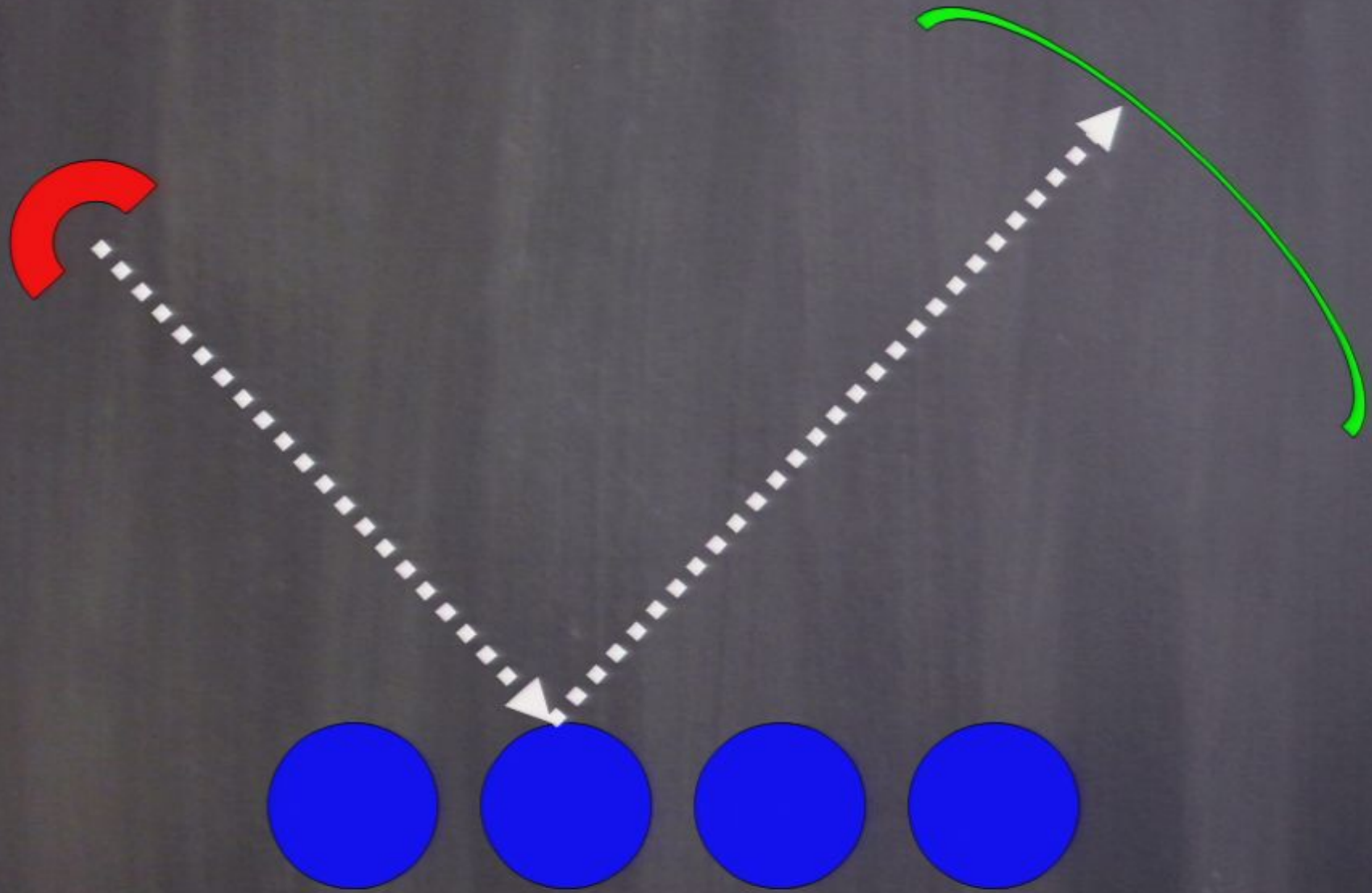

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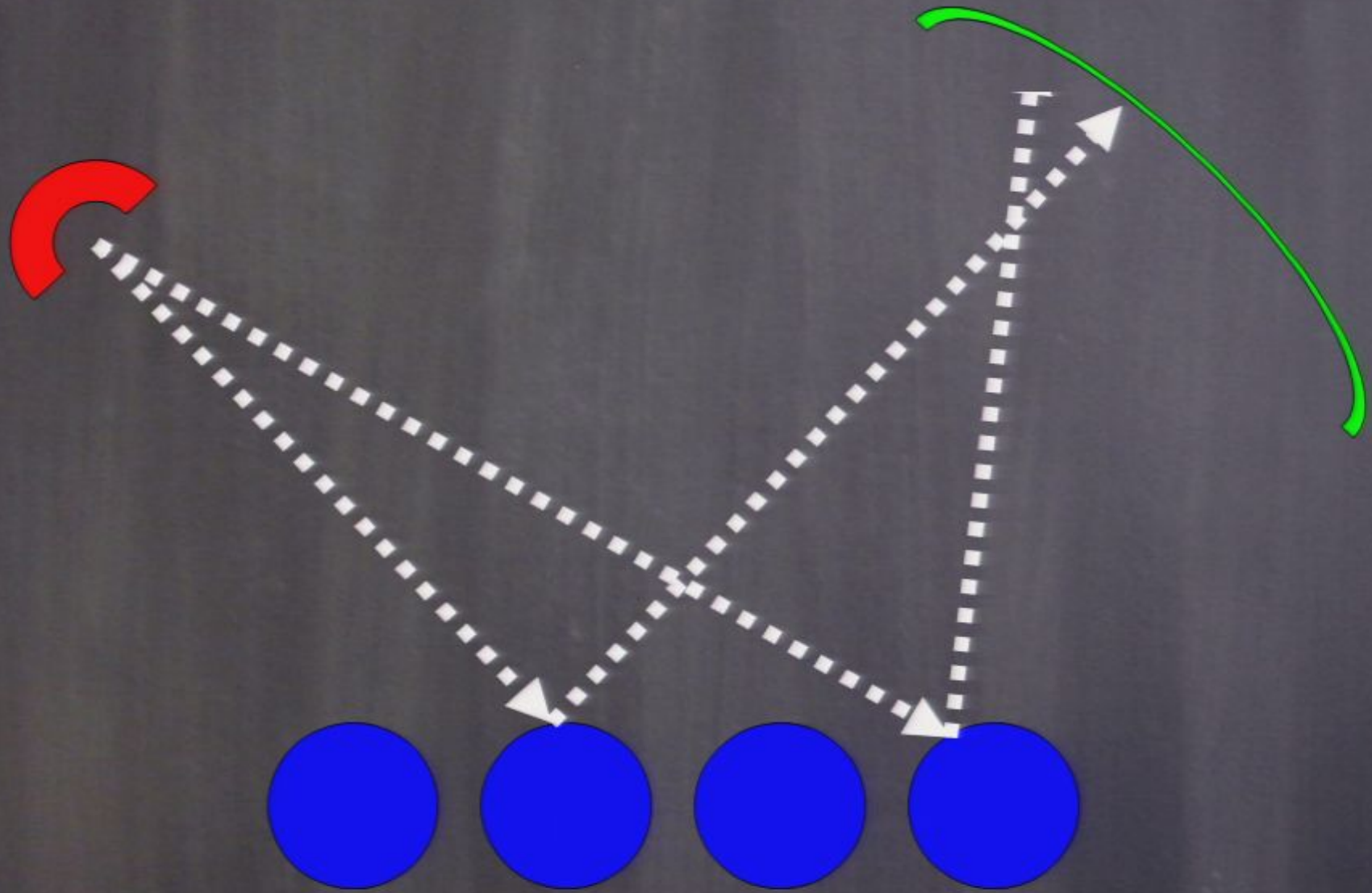

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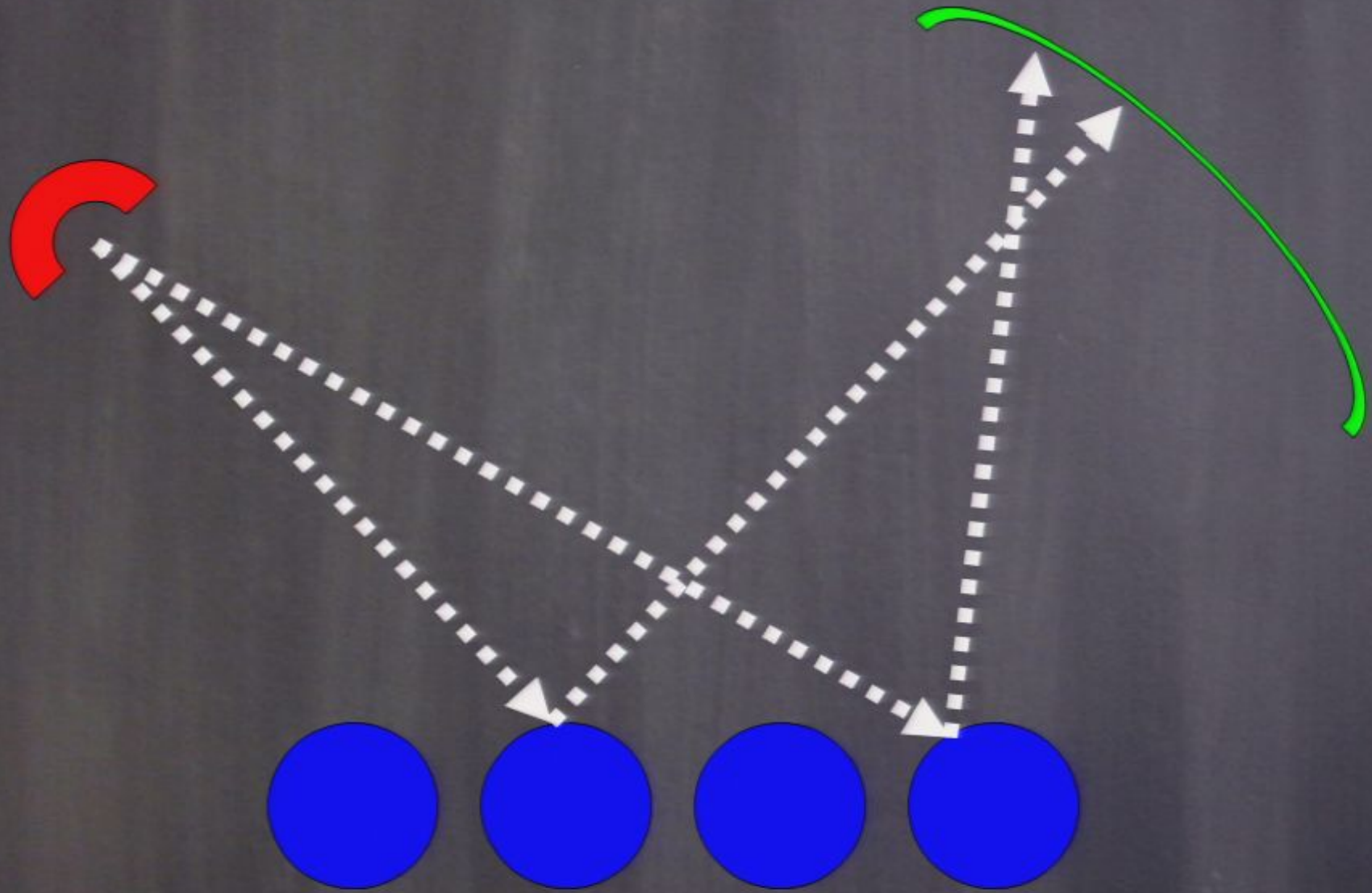

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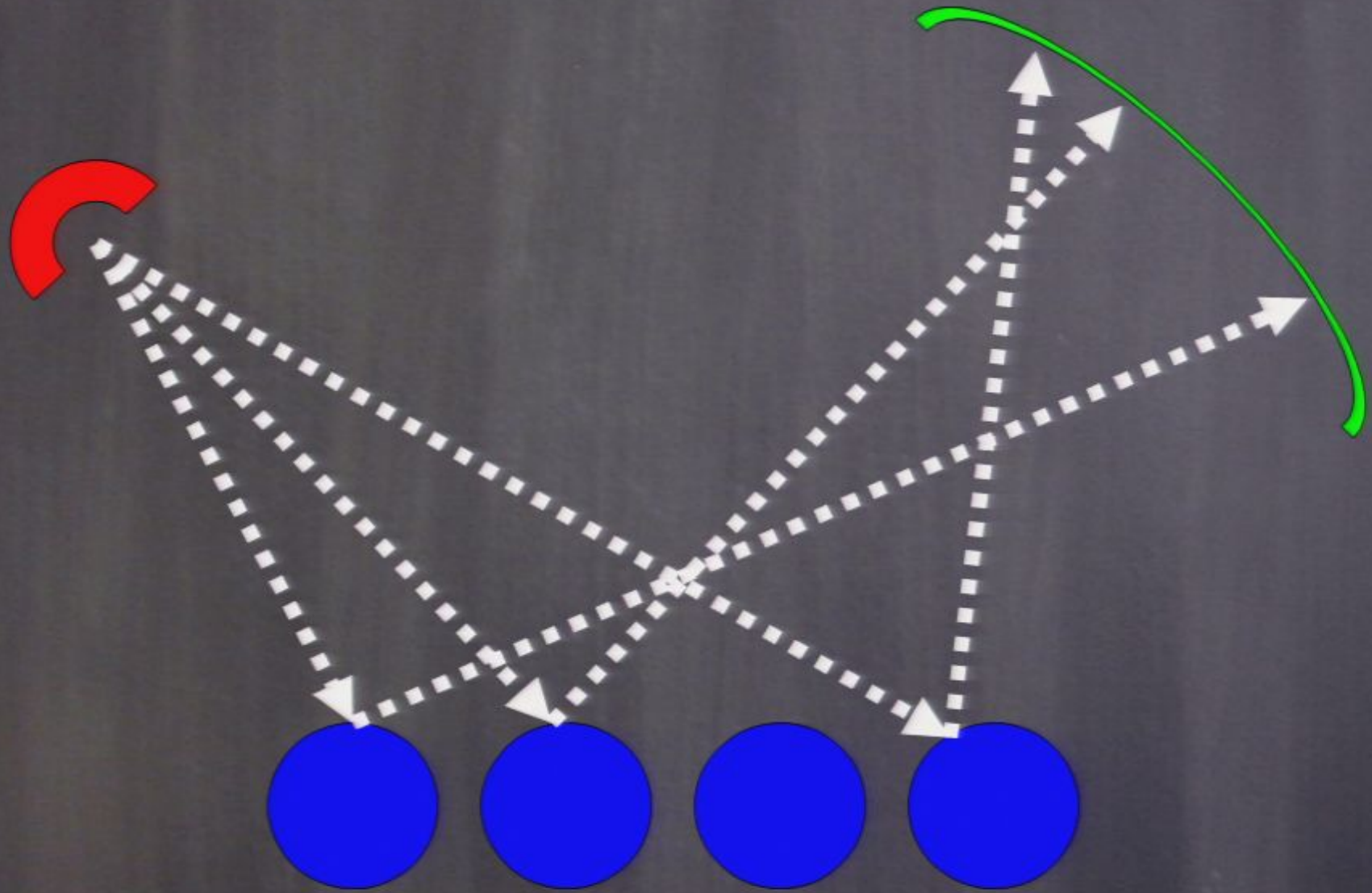
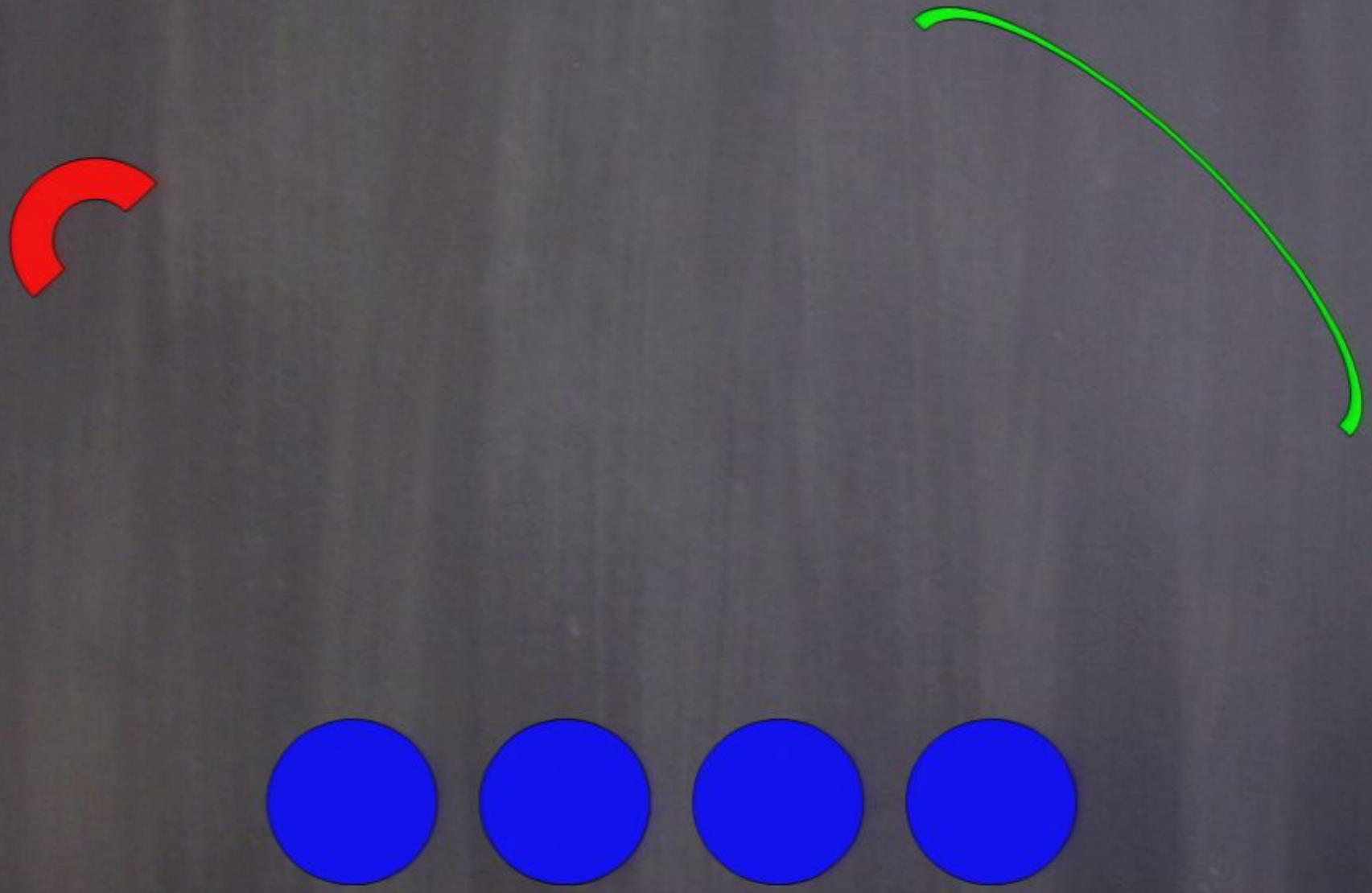


Simplify: Only ONE Atom



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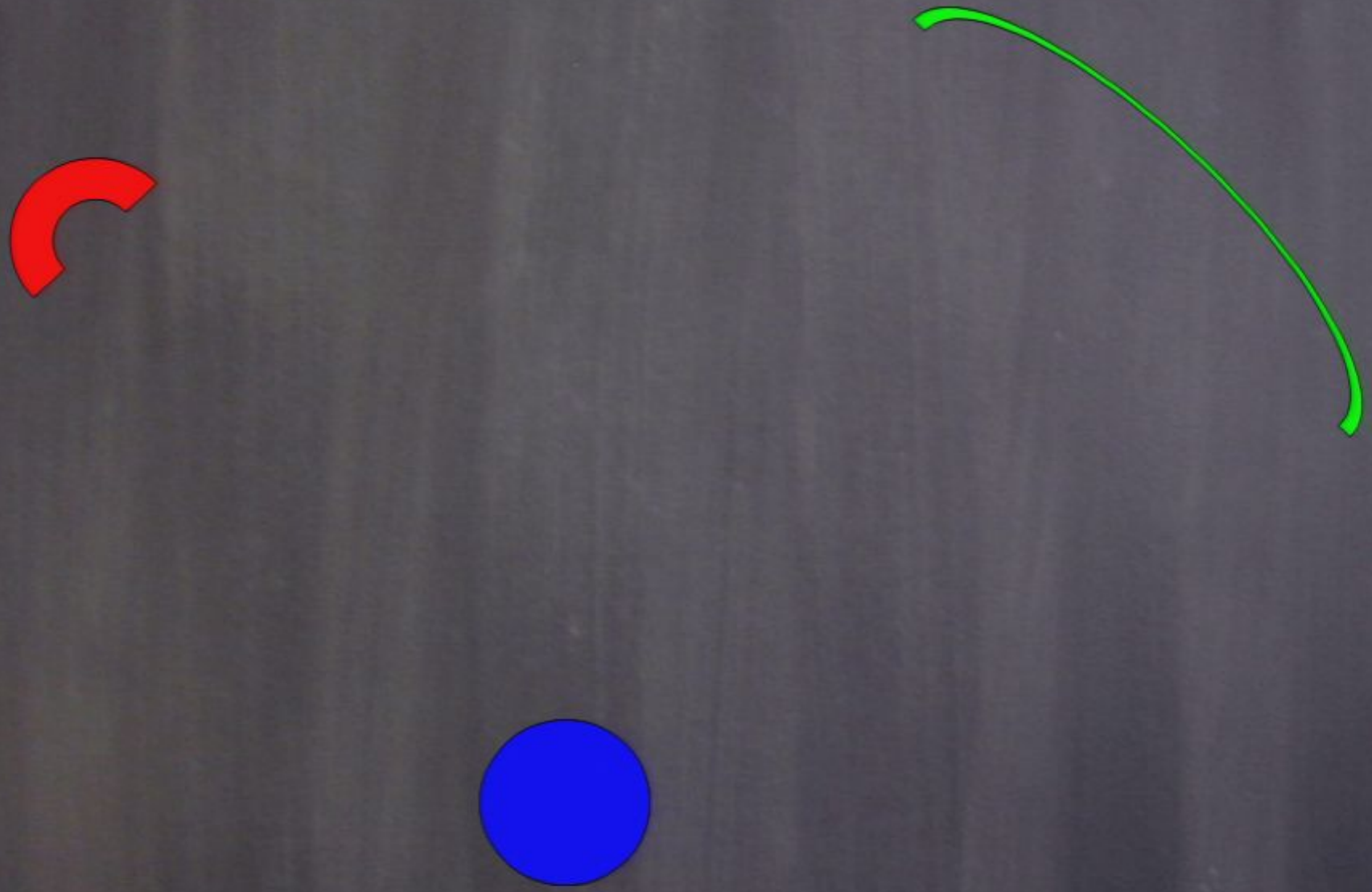

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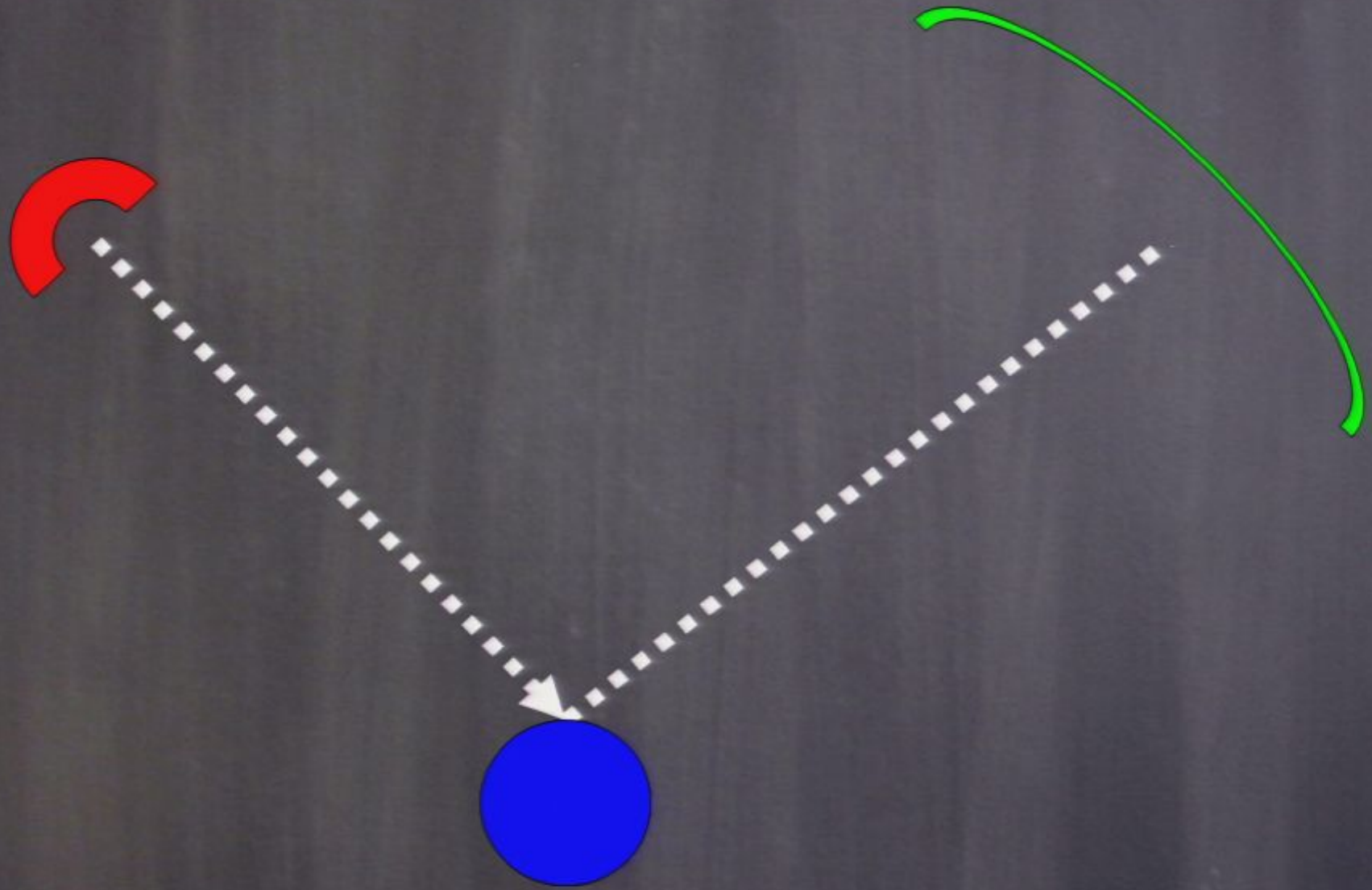

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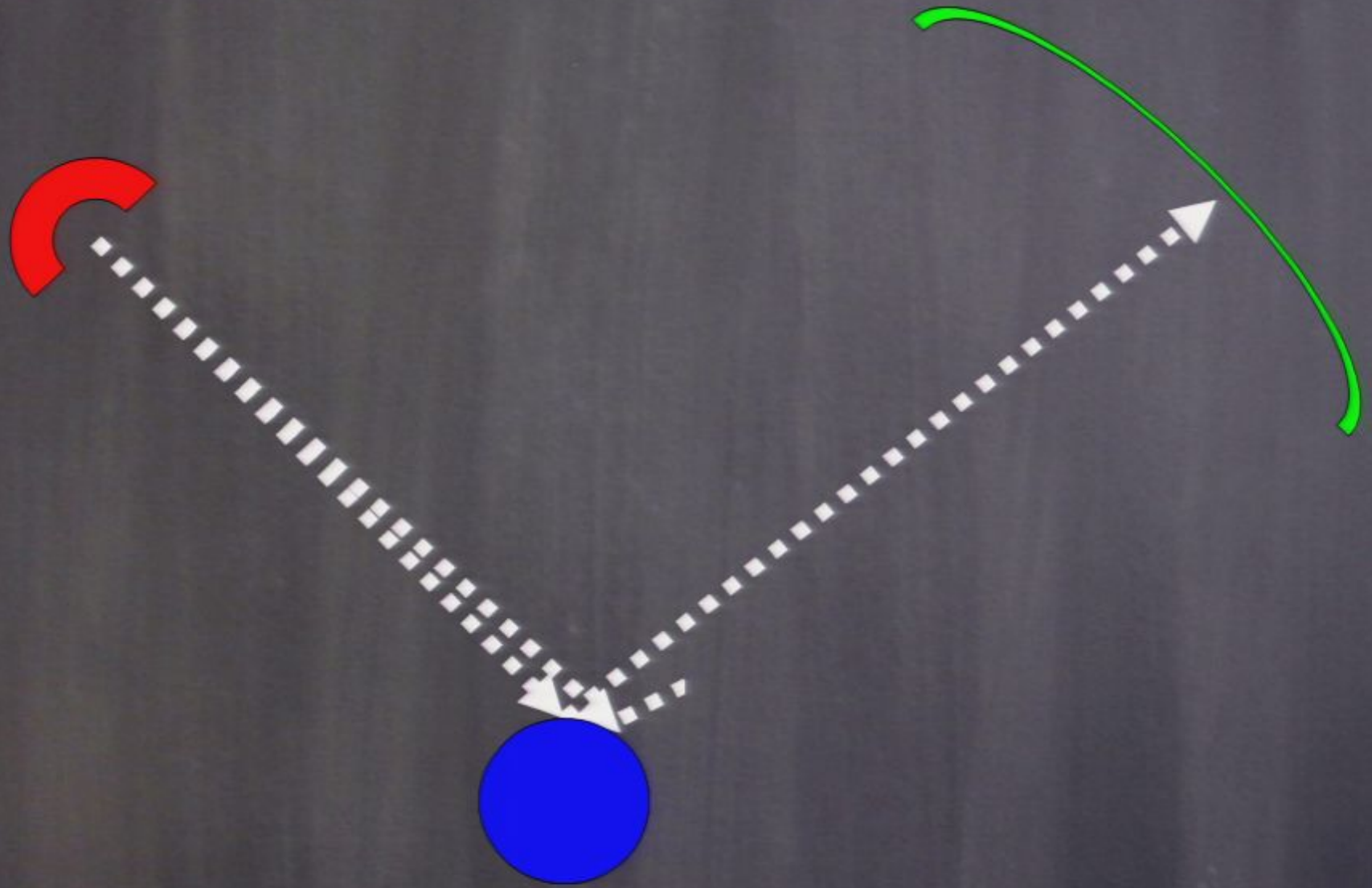

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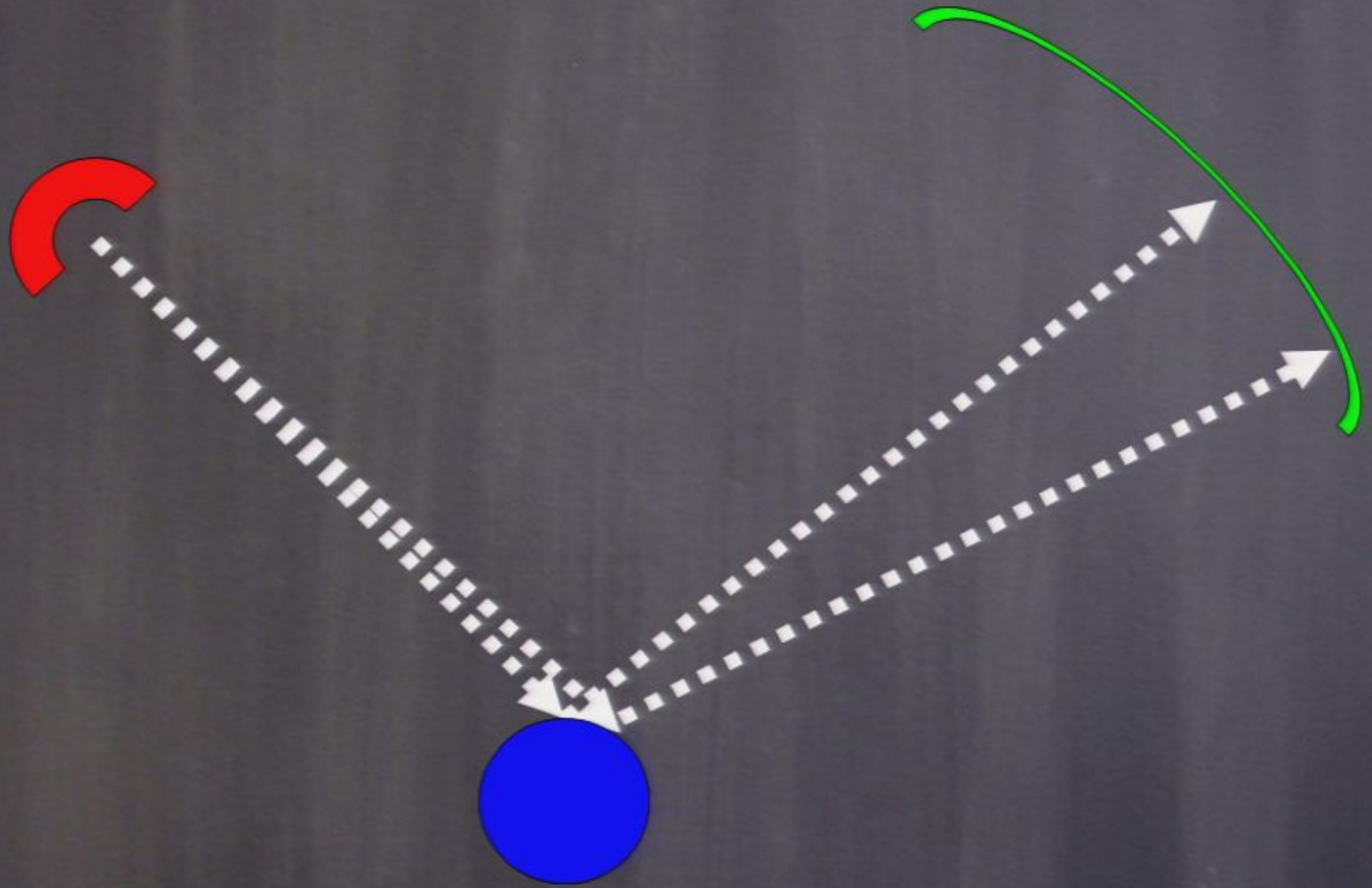

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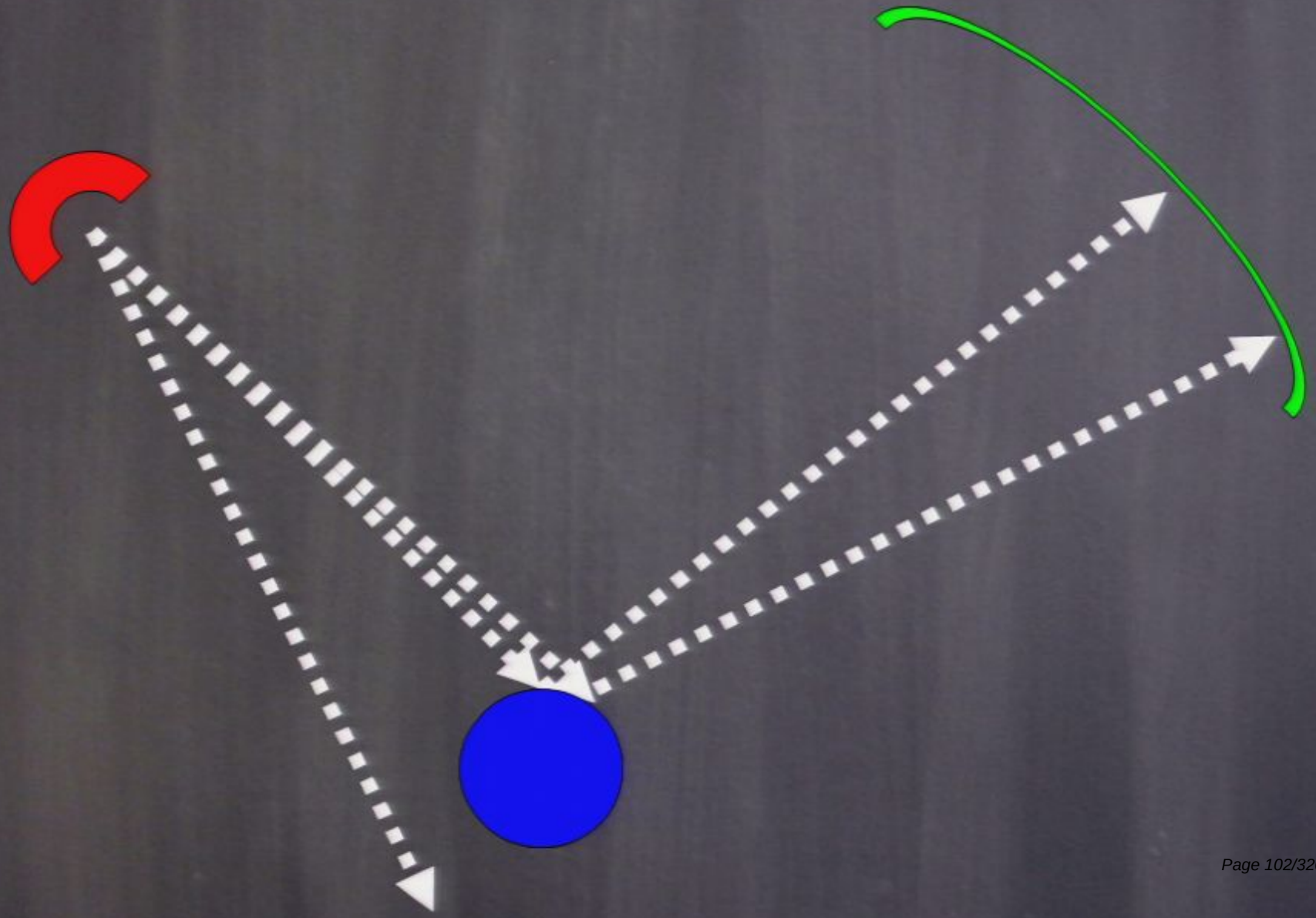

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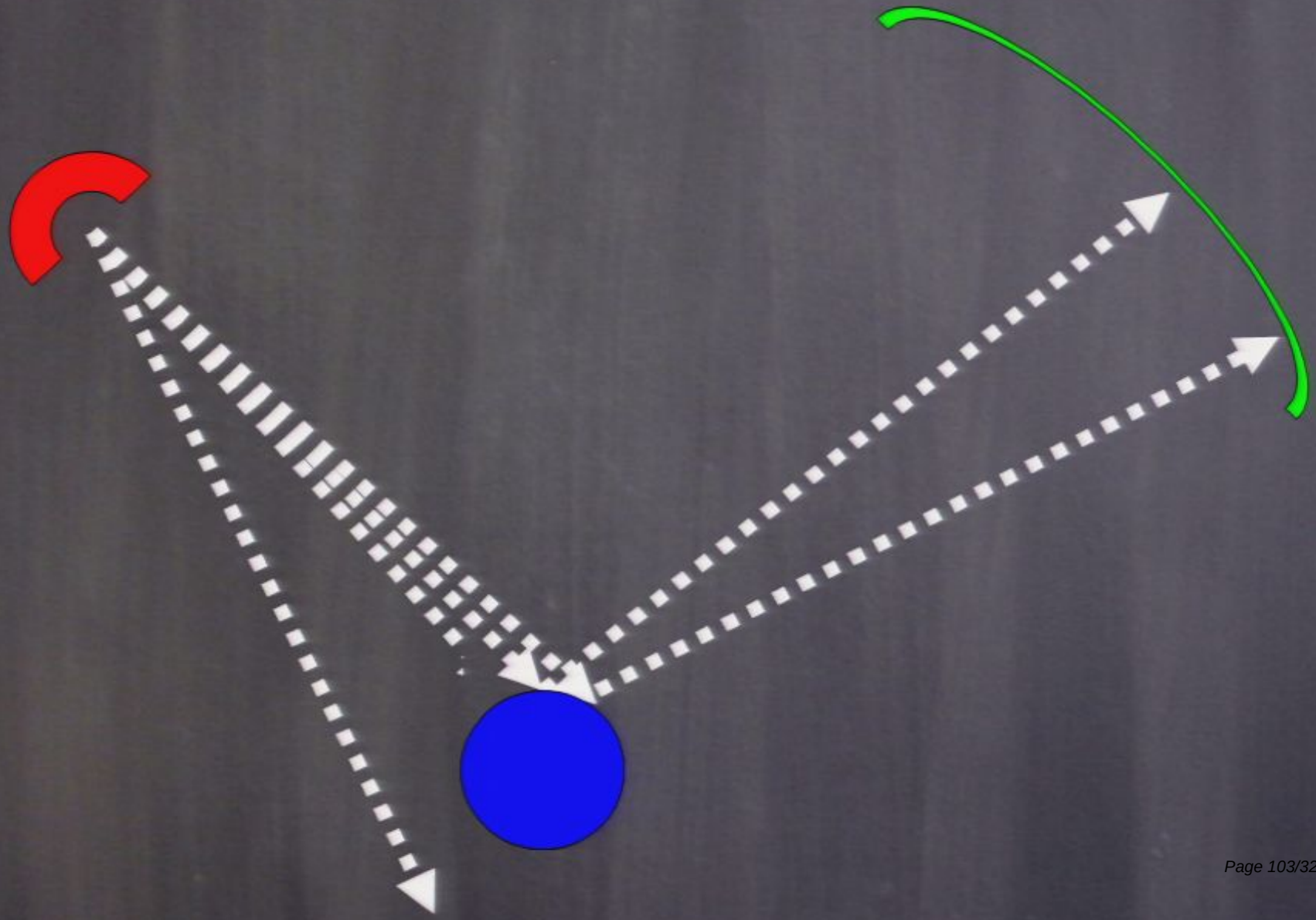

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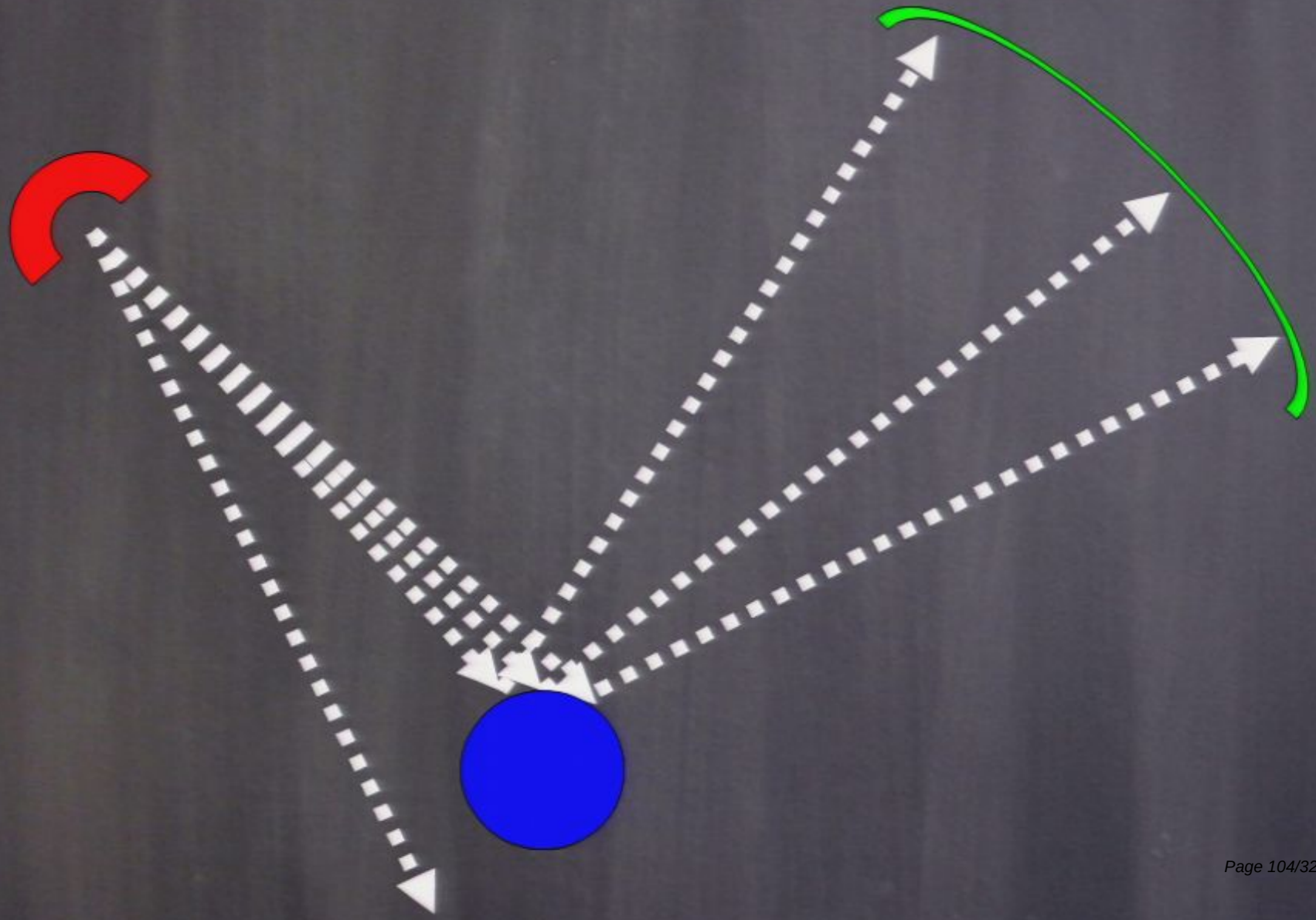
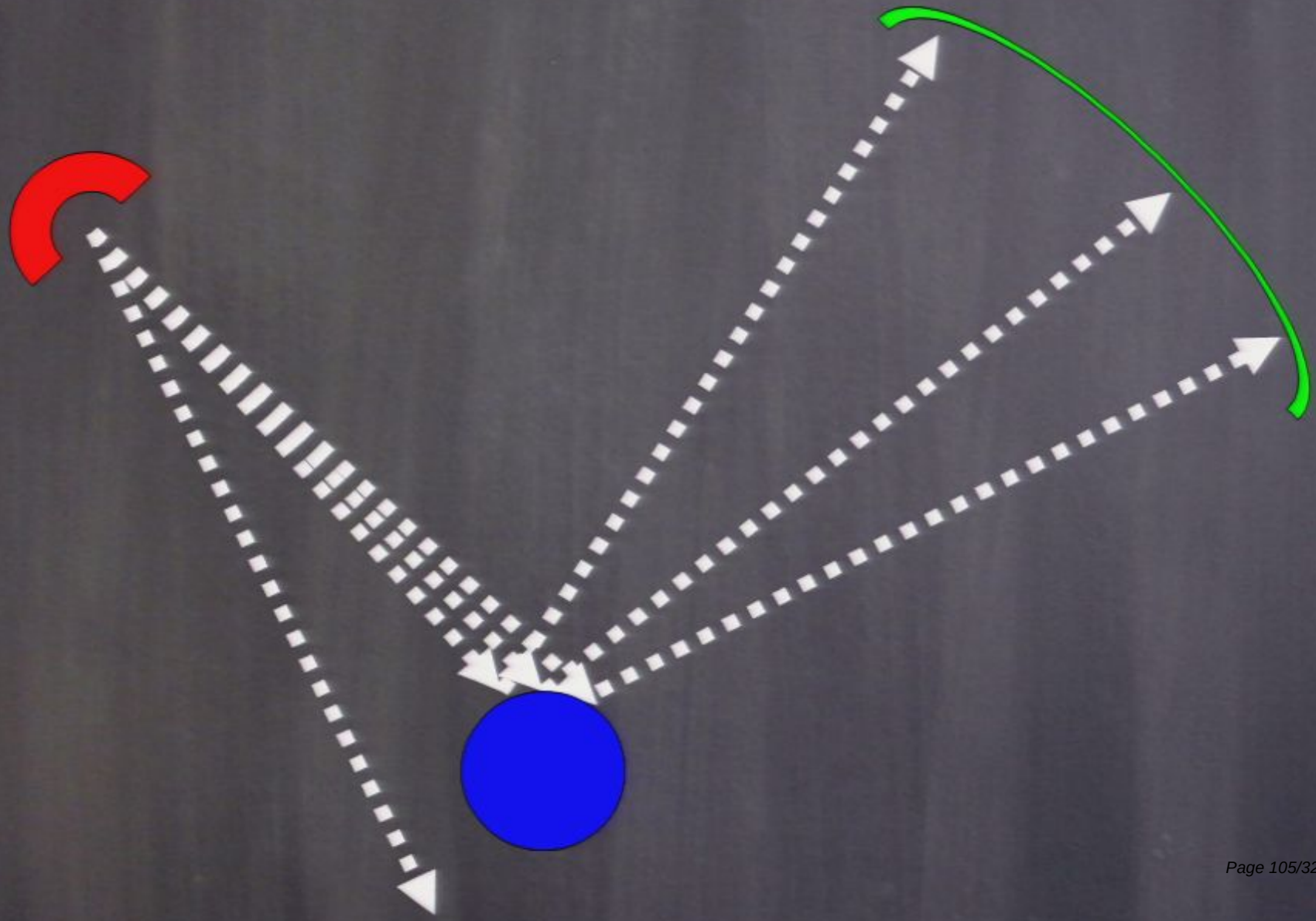
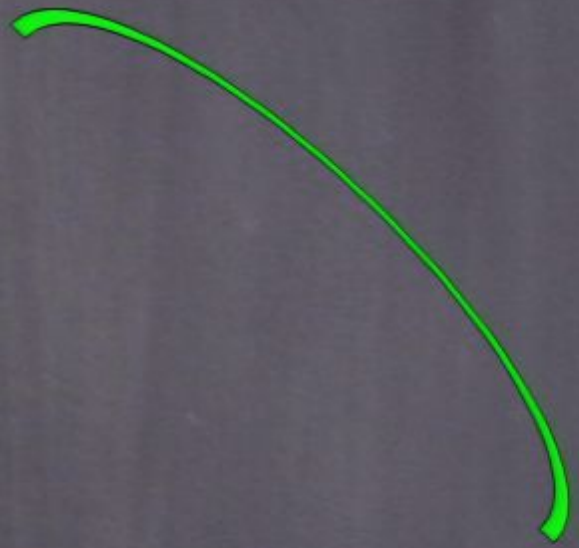


Expect?



Bring in a SECOND Atom



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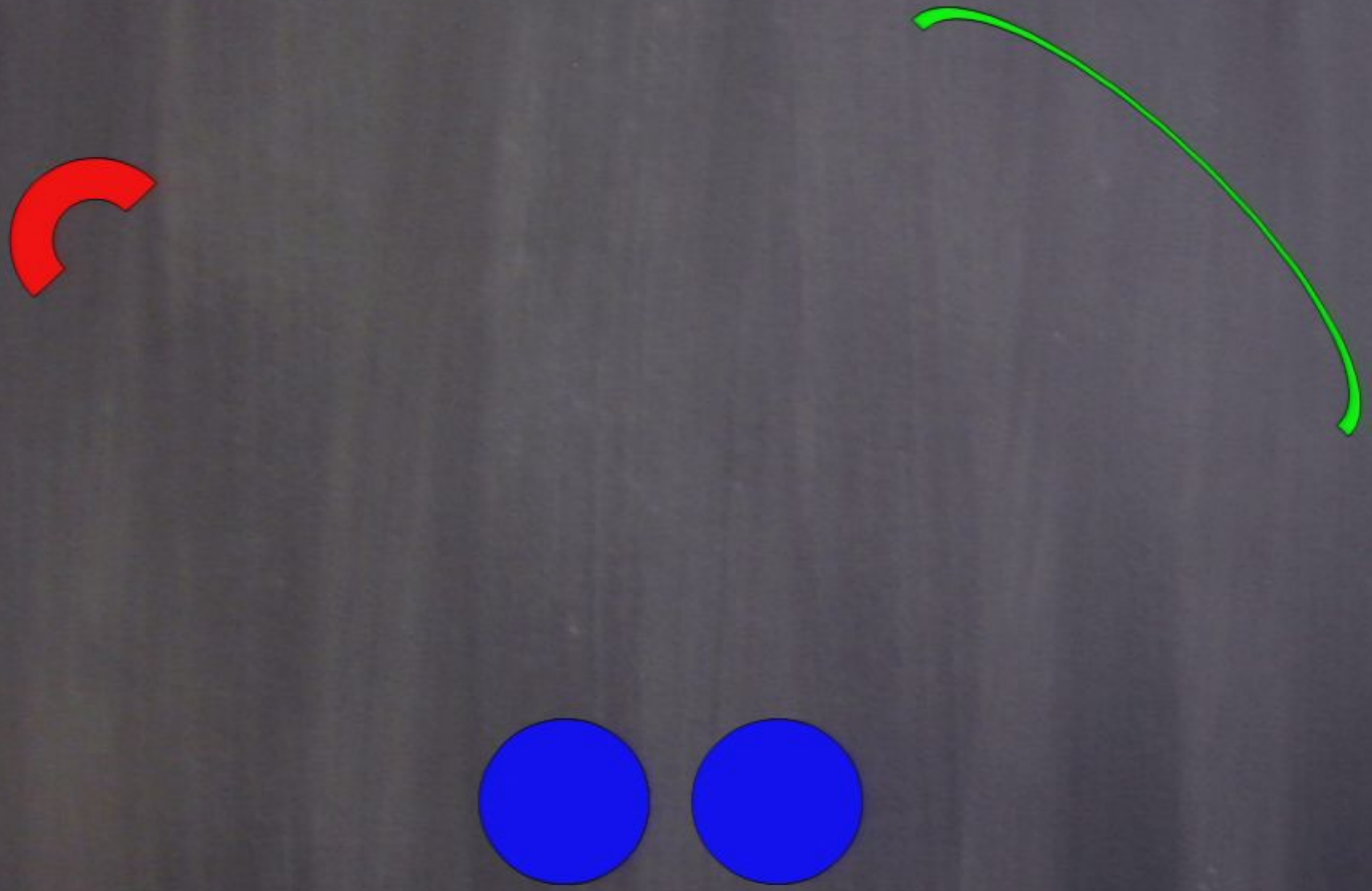

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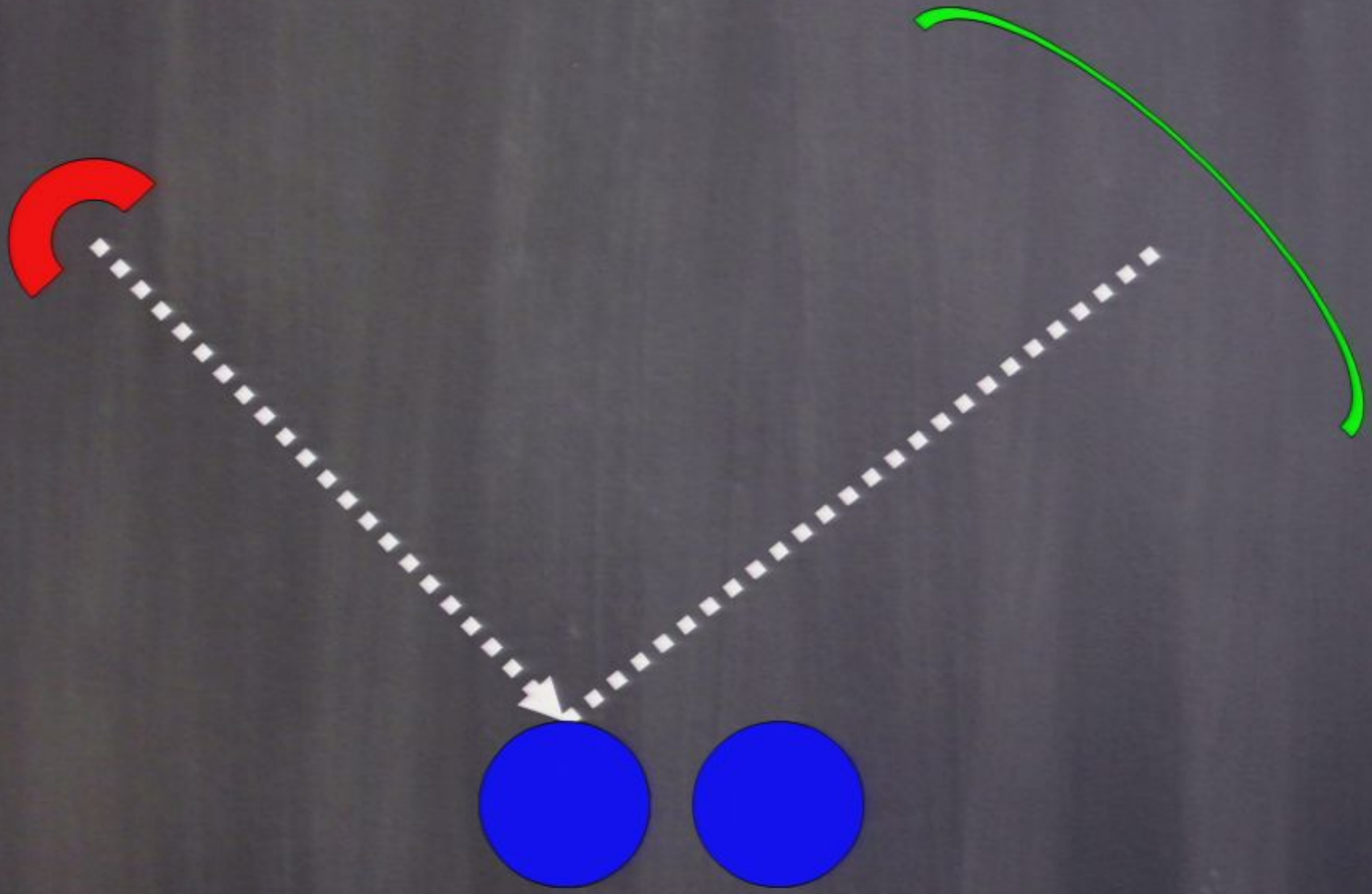

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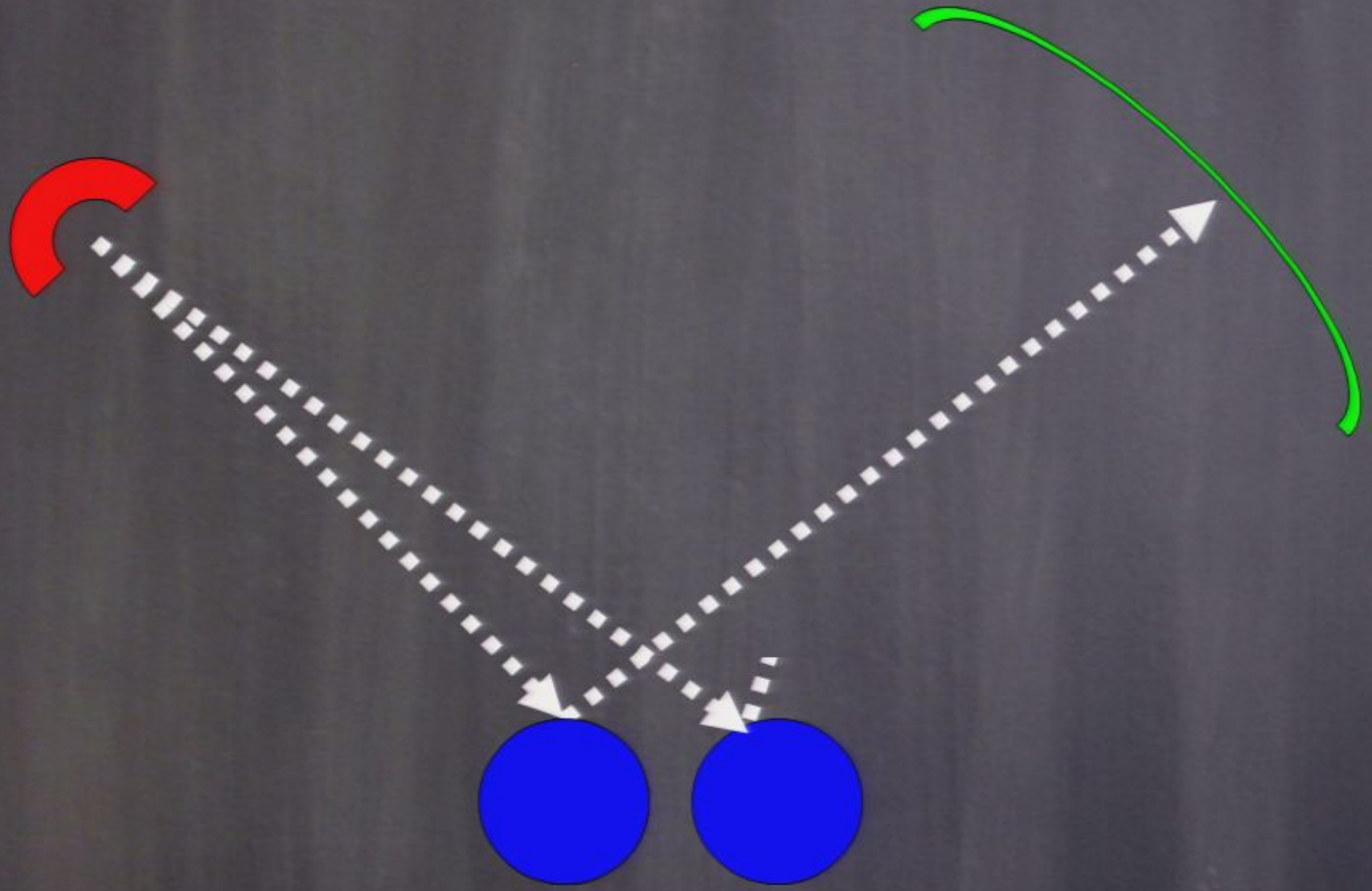

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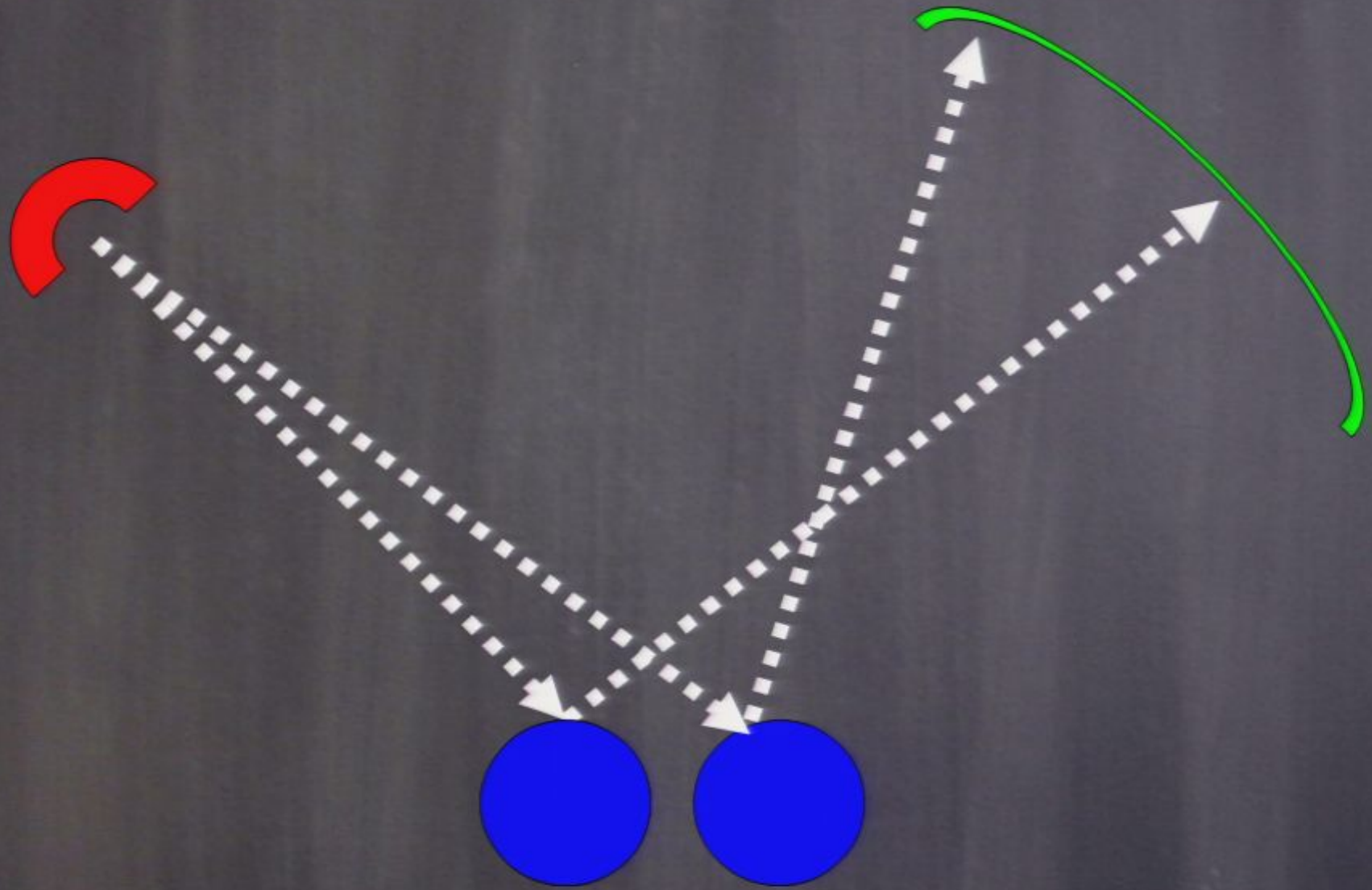

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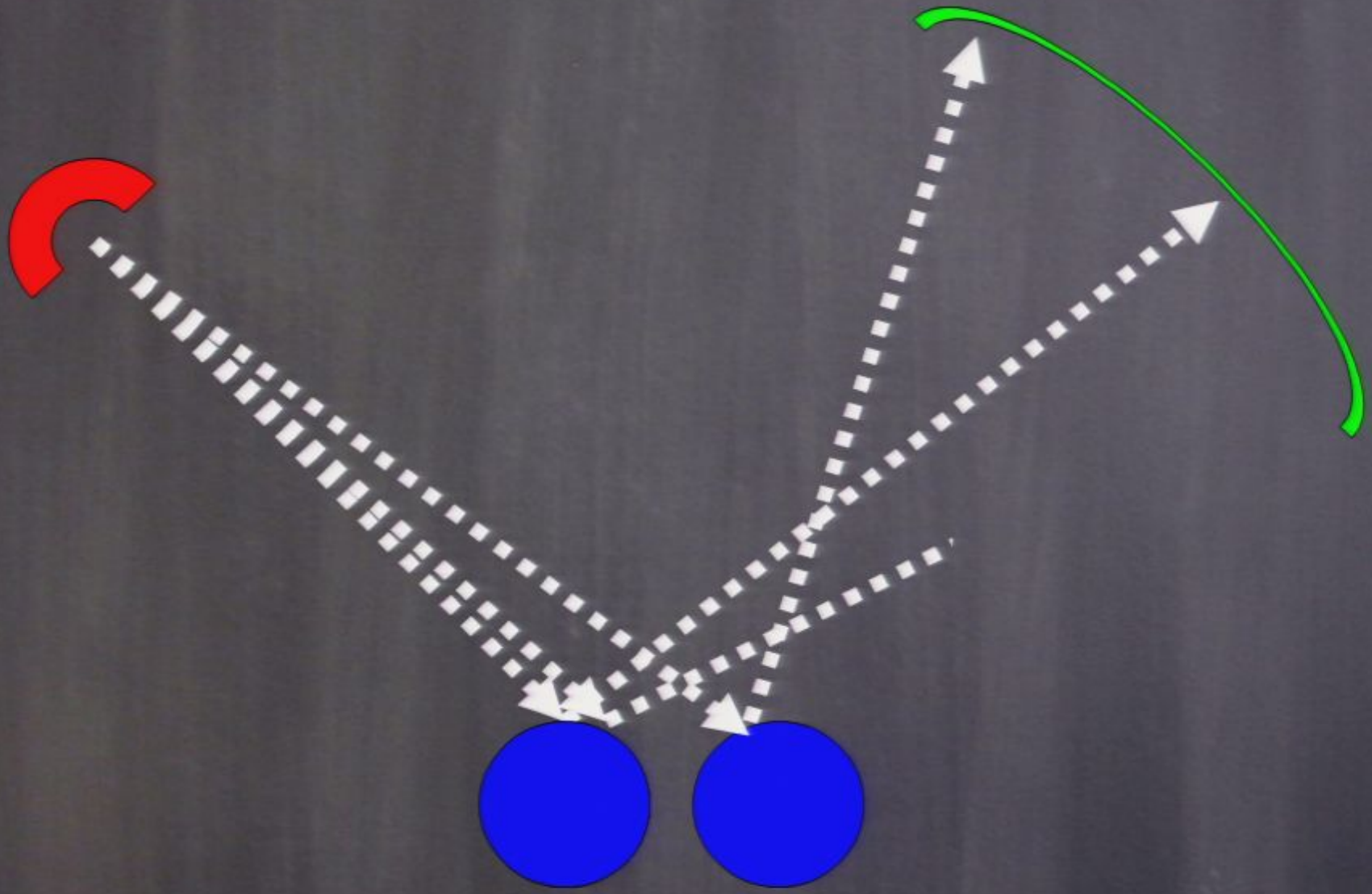

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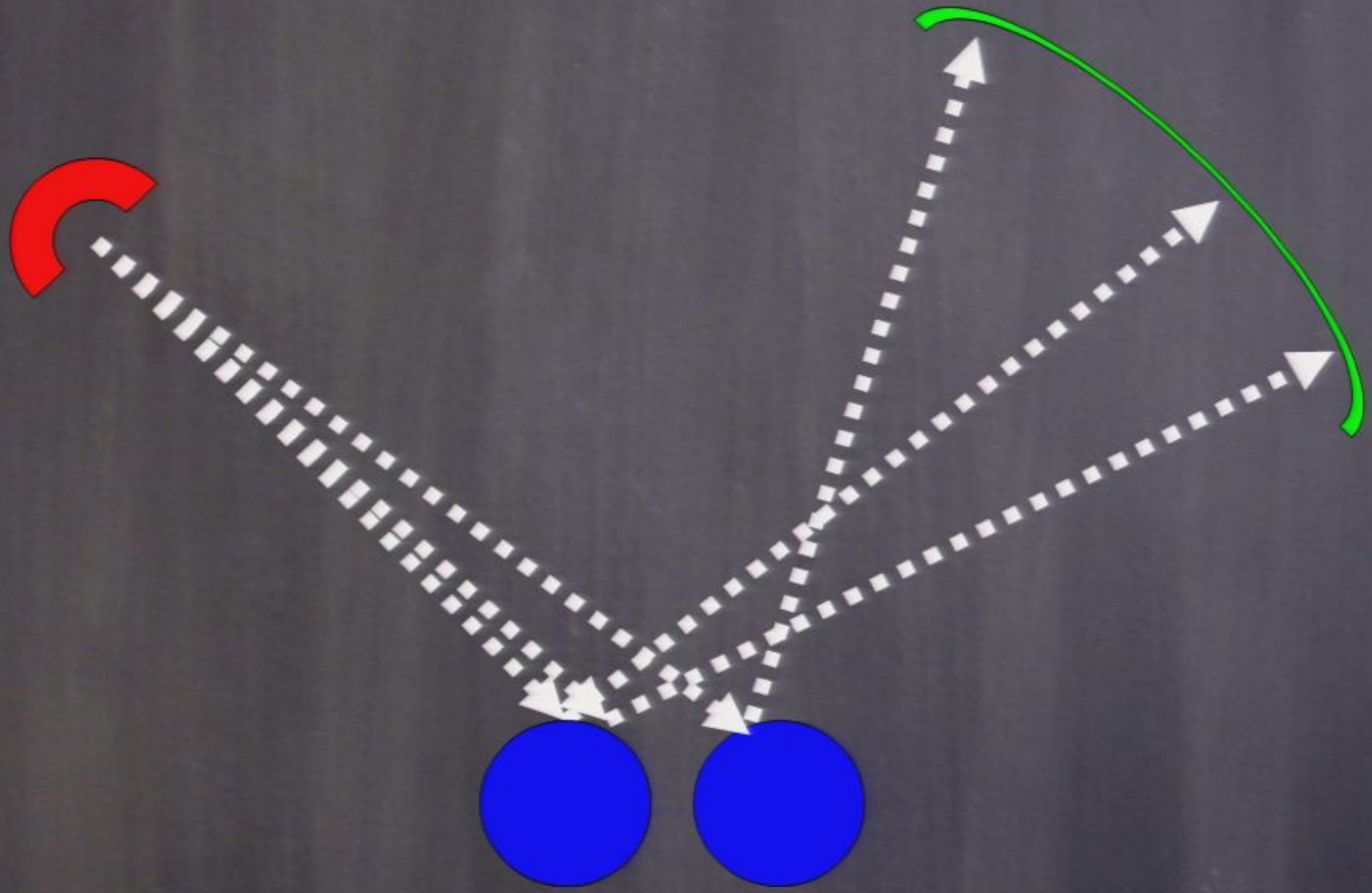

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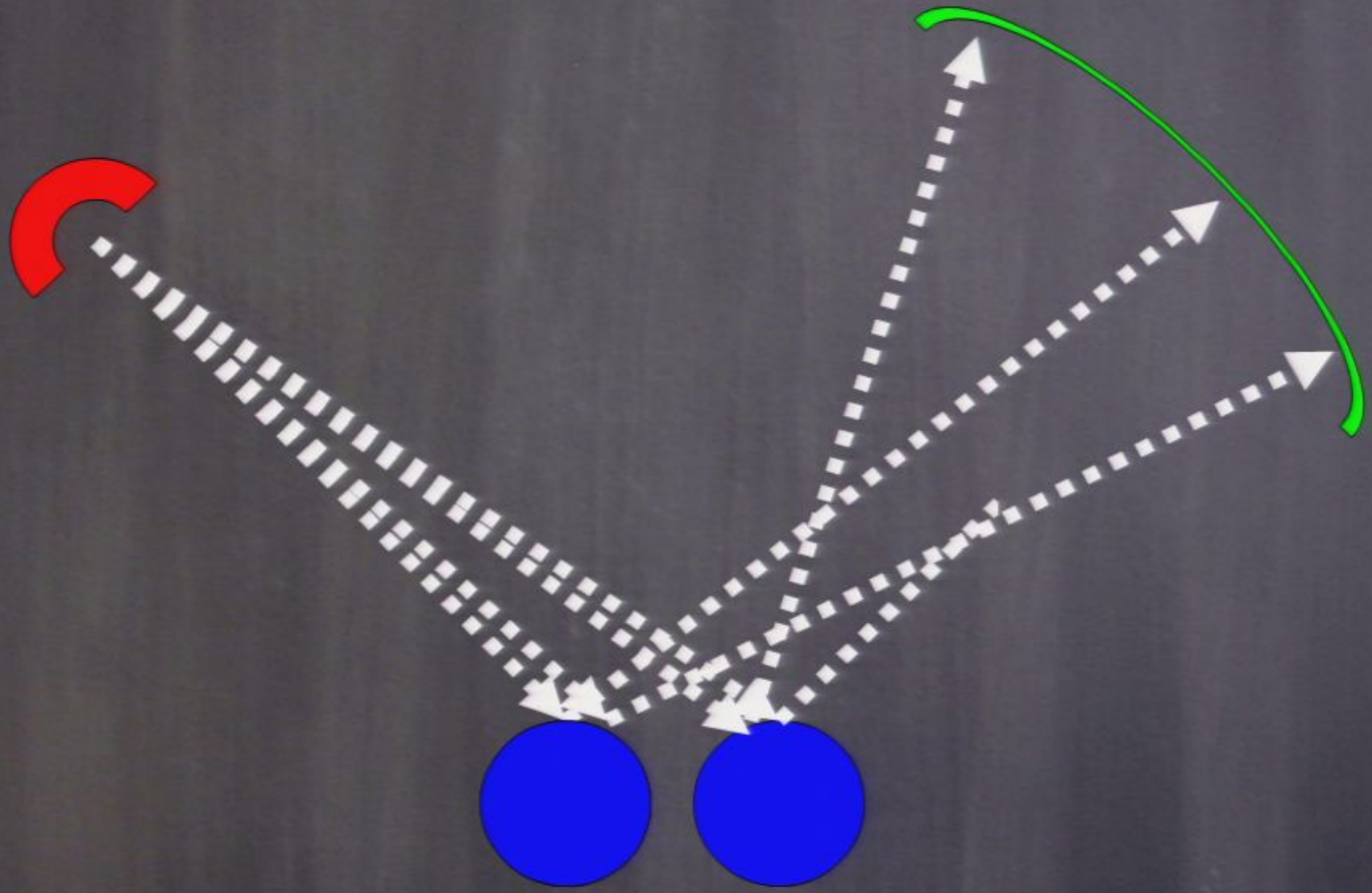

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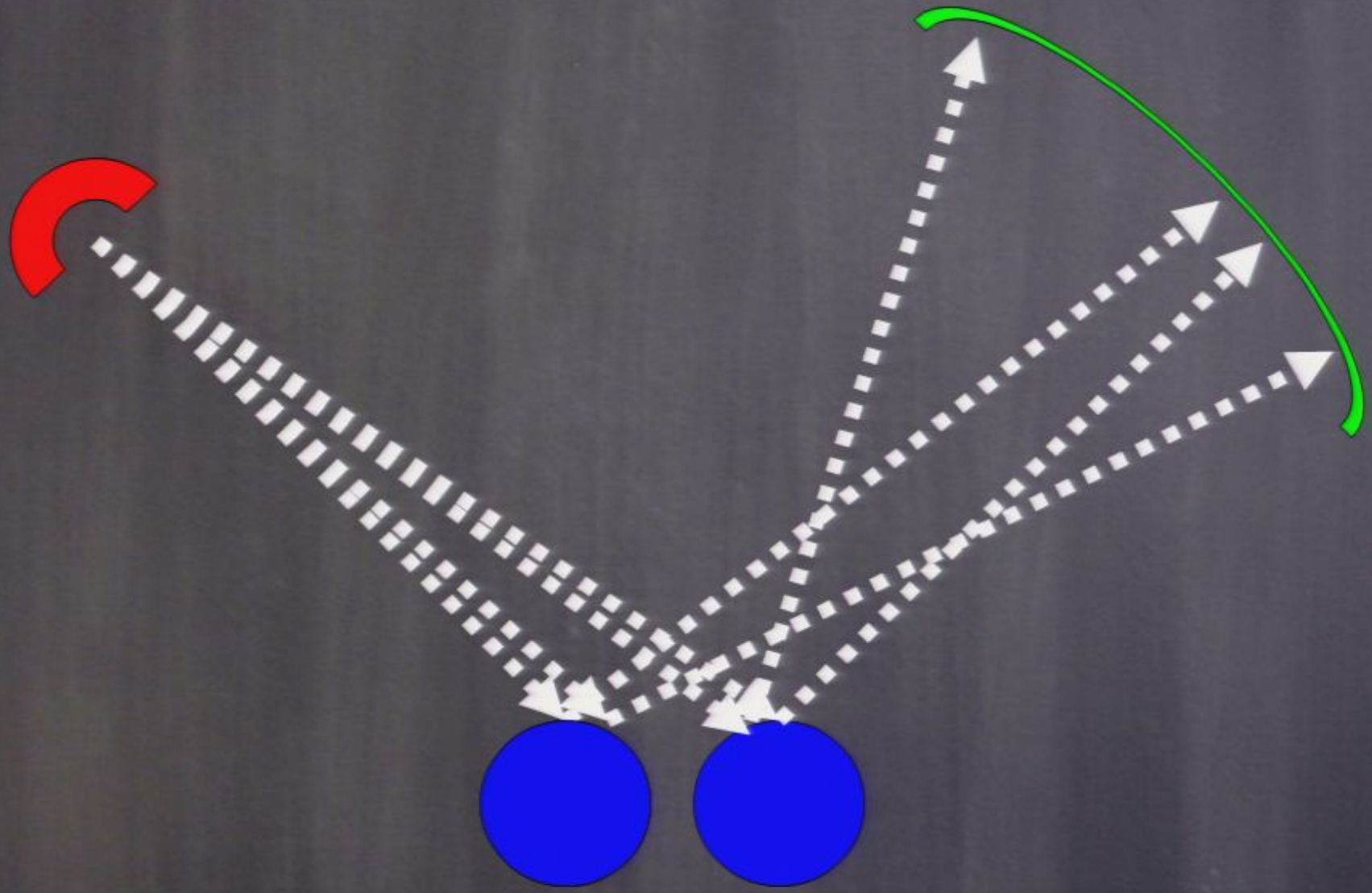
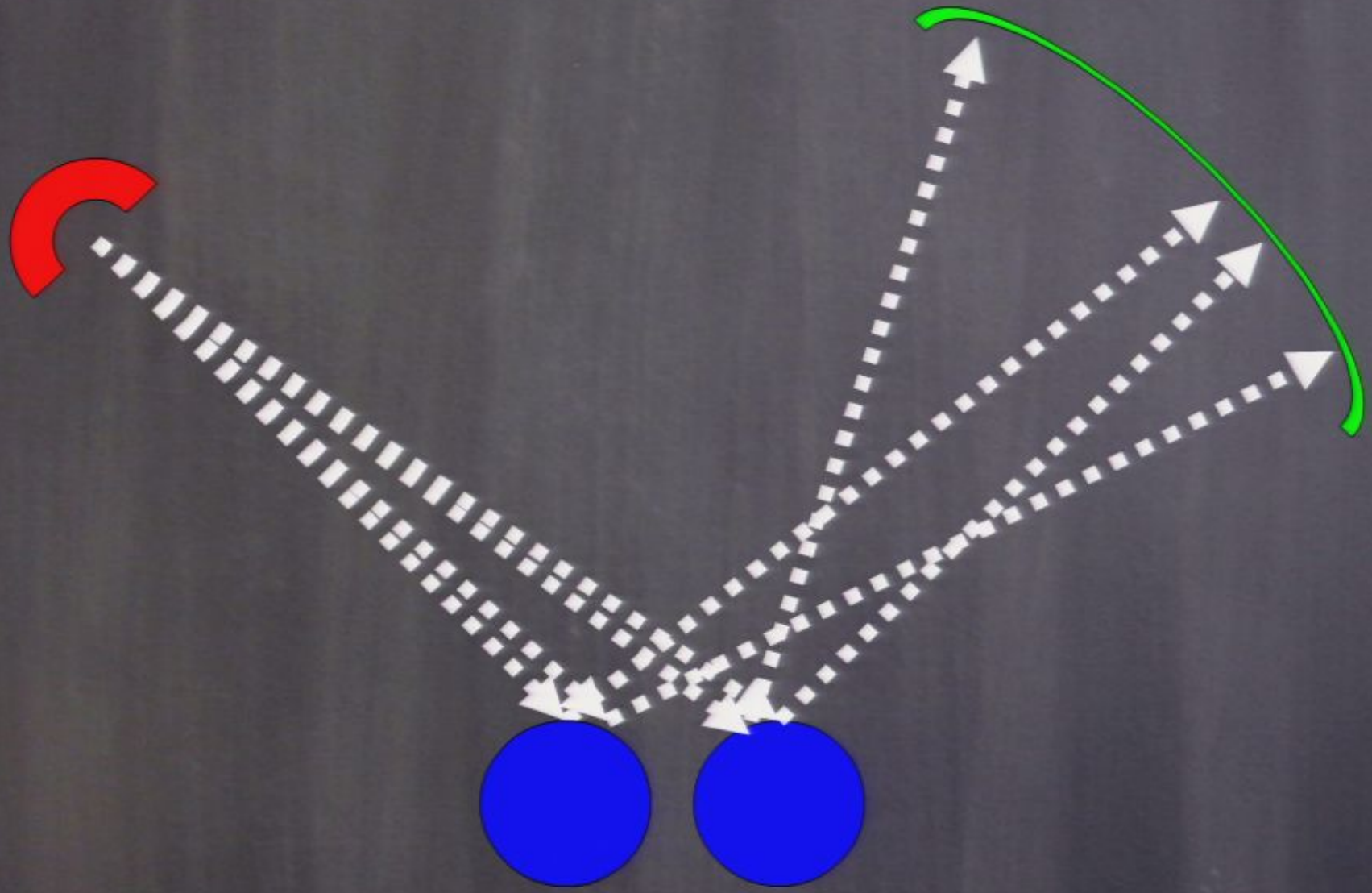


Actual: Pattern of Hits!



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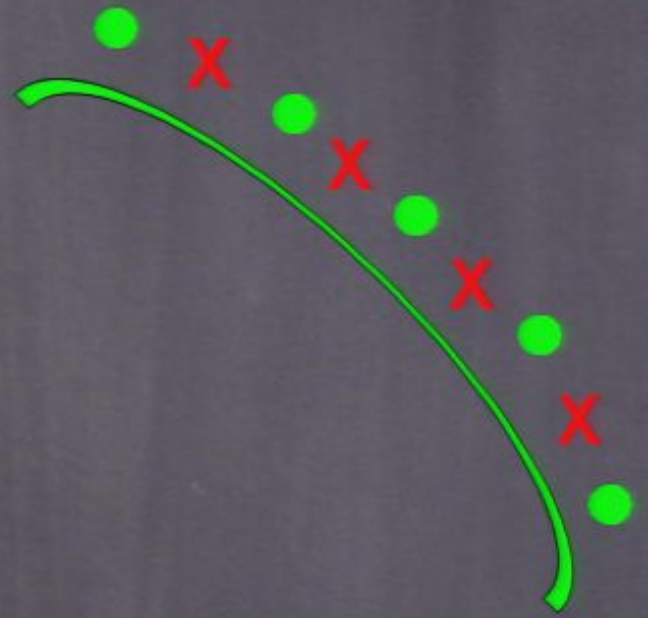

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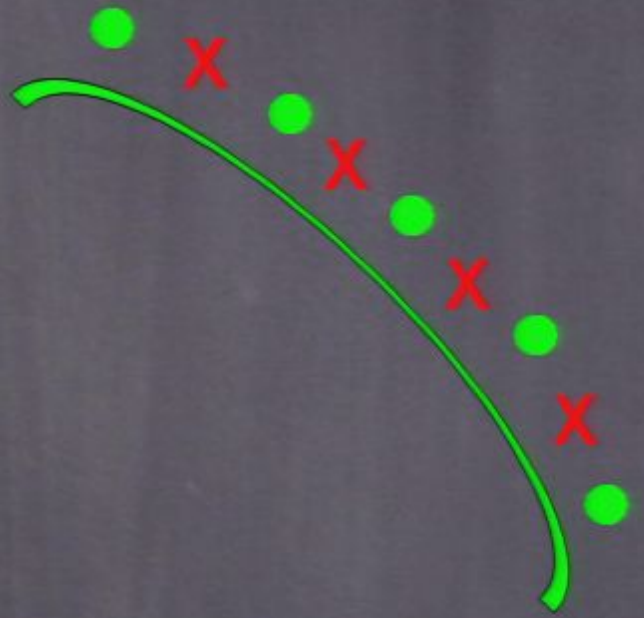

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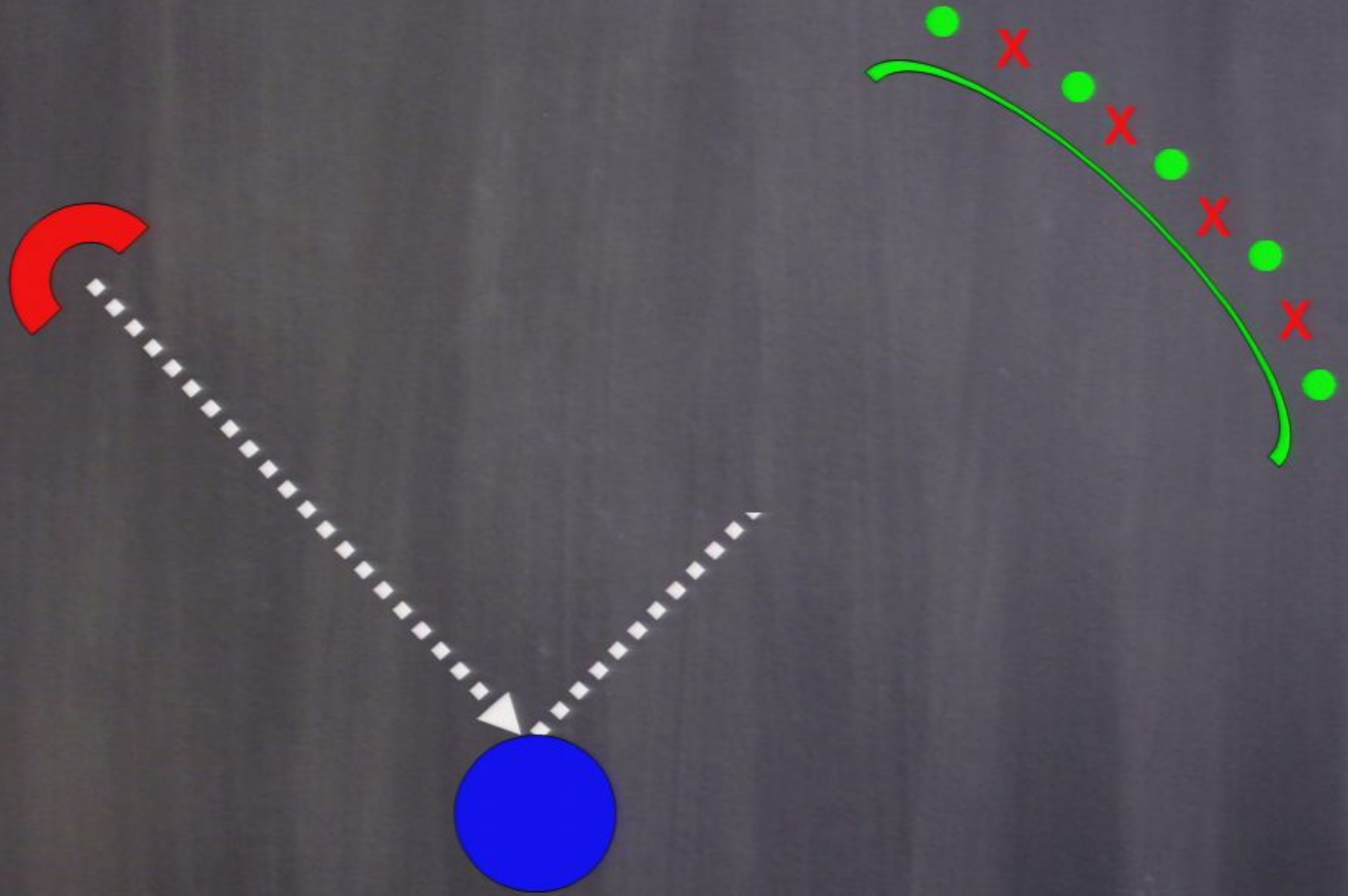

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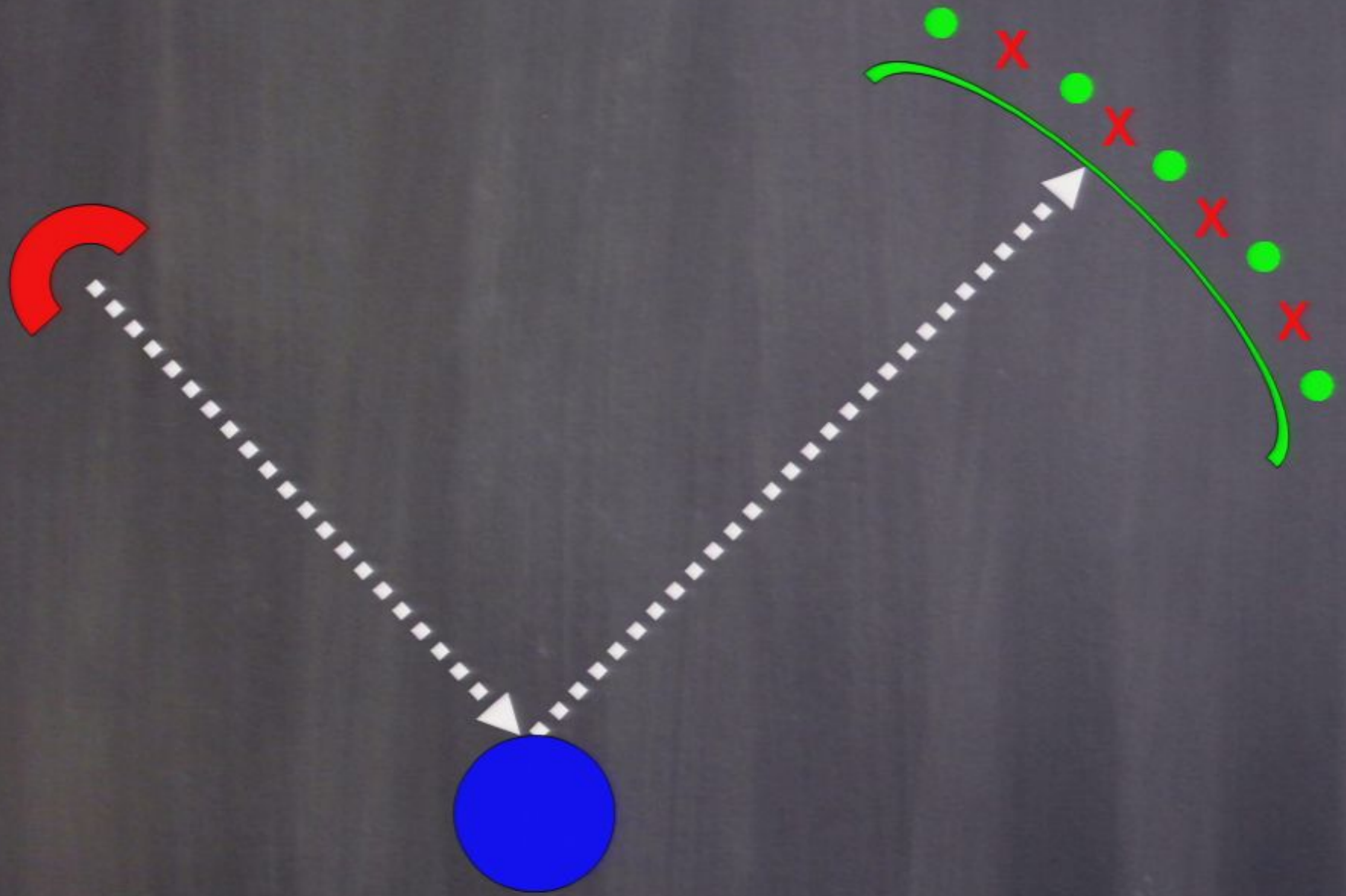

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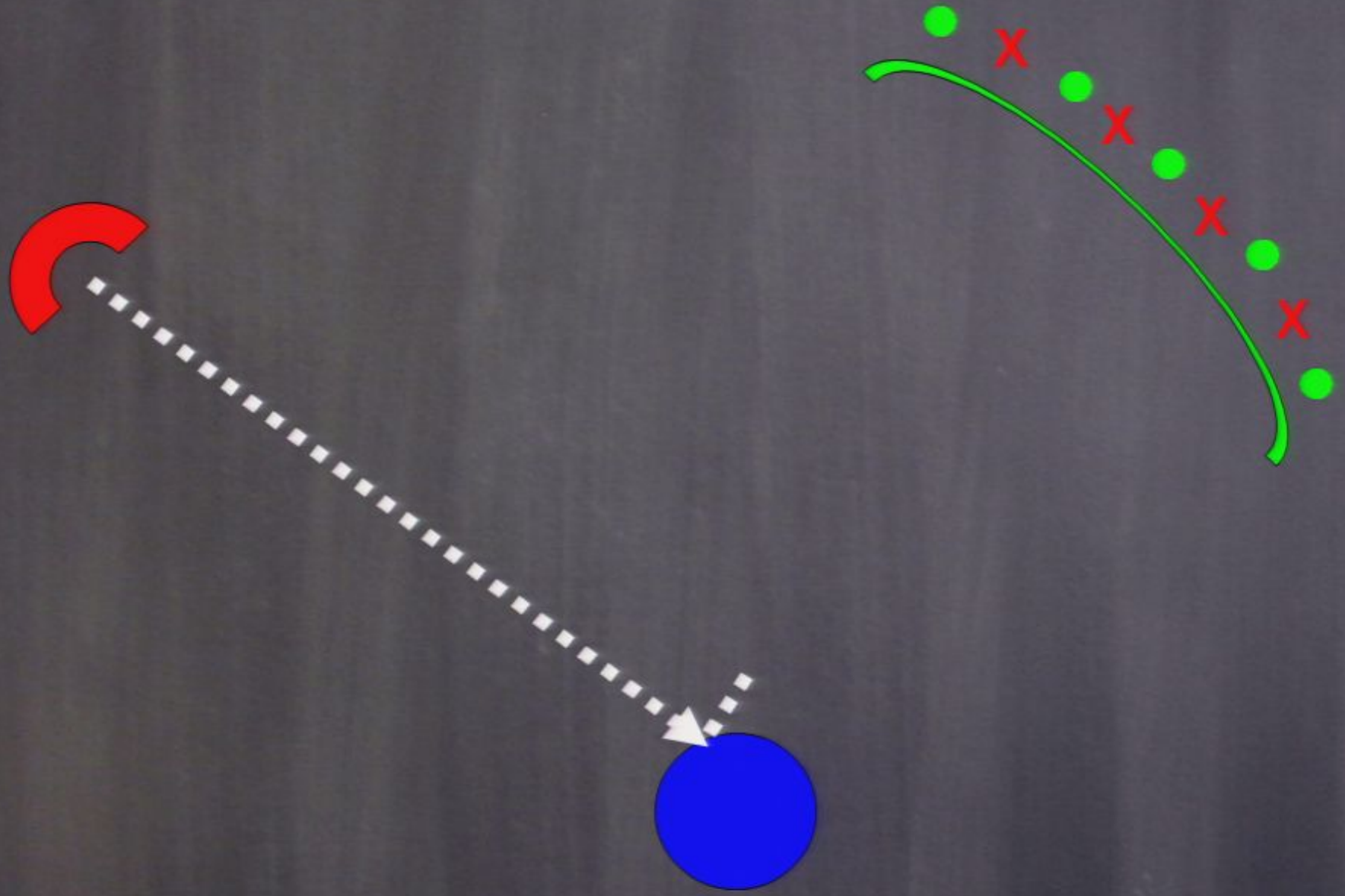

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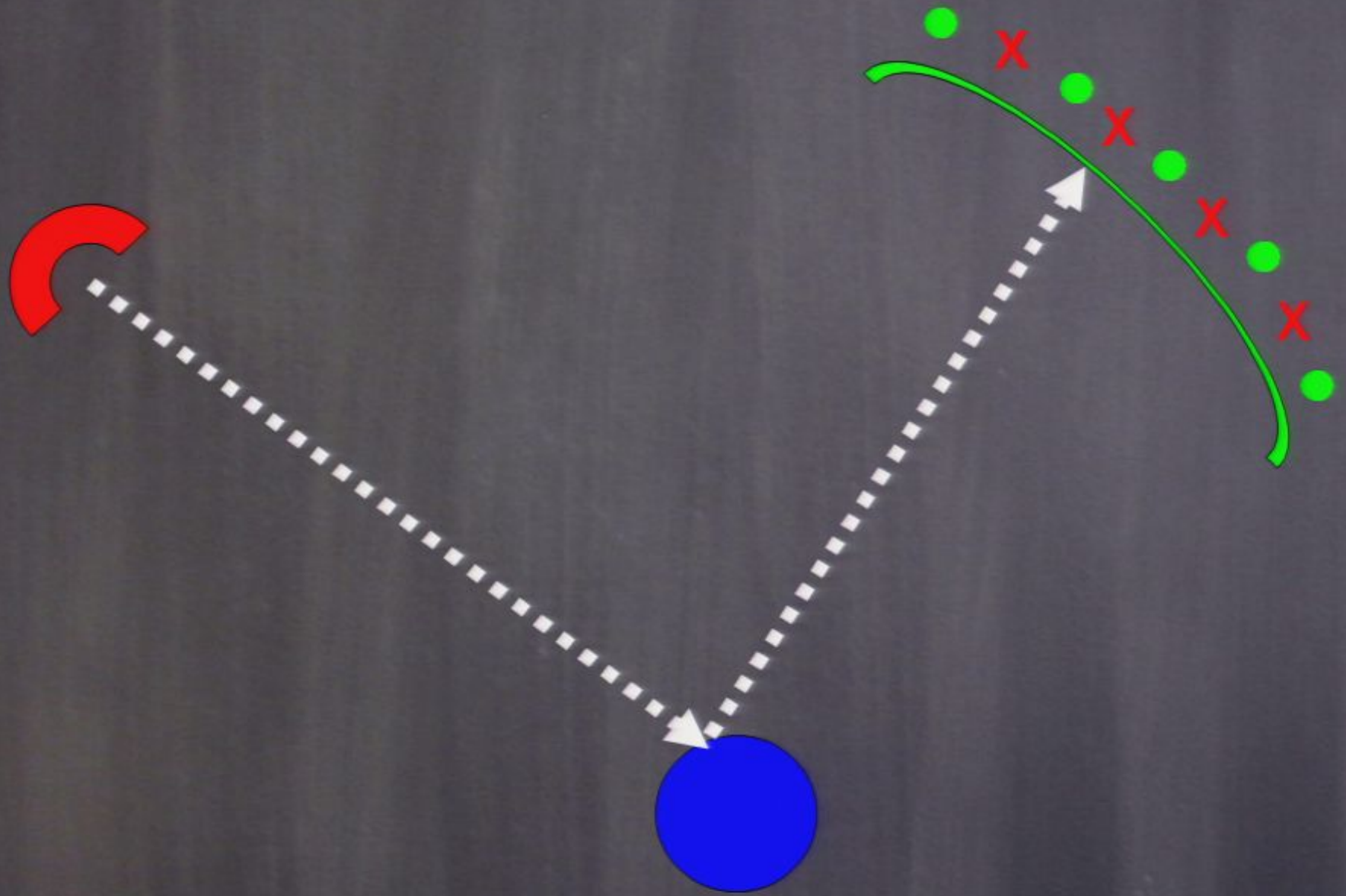

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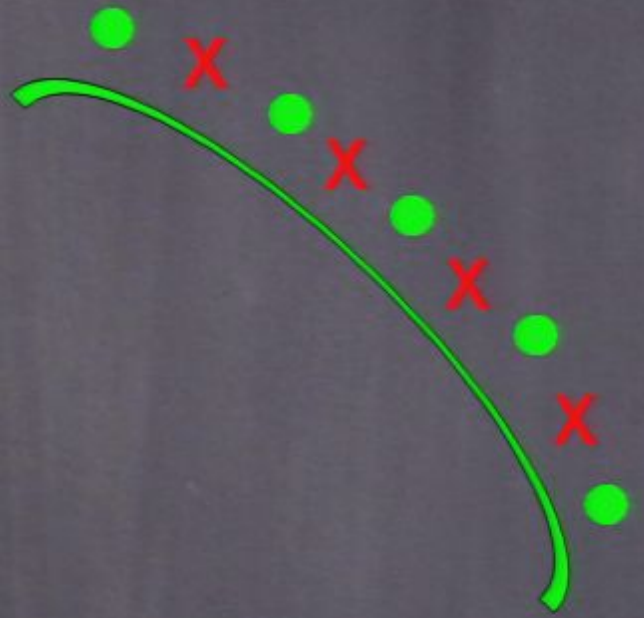

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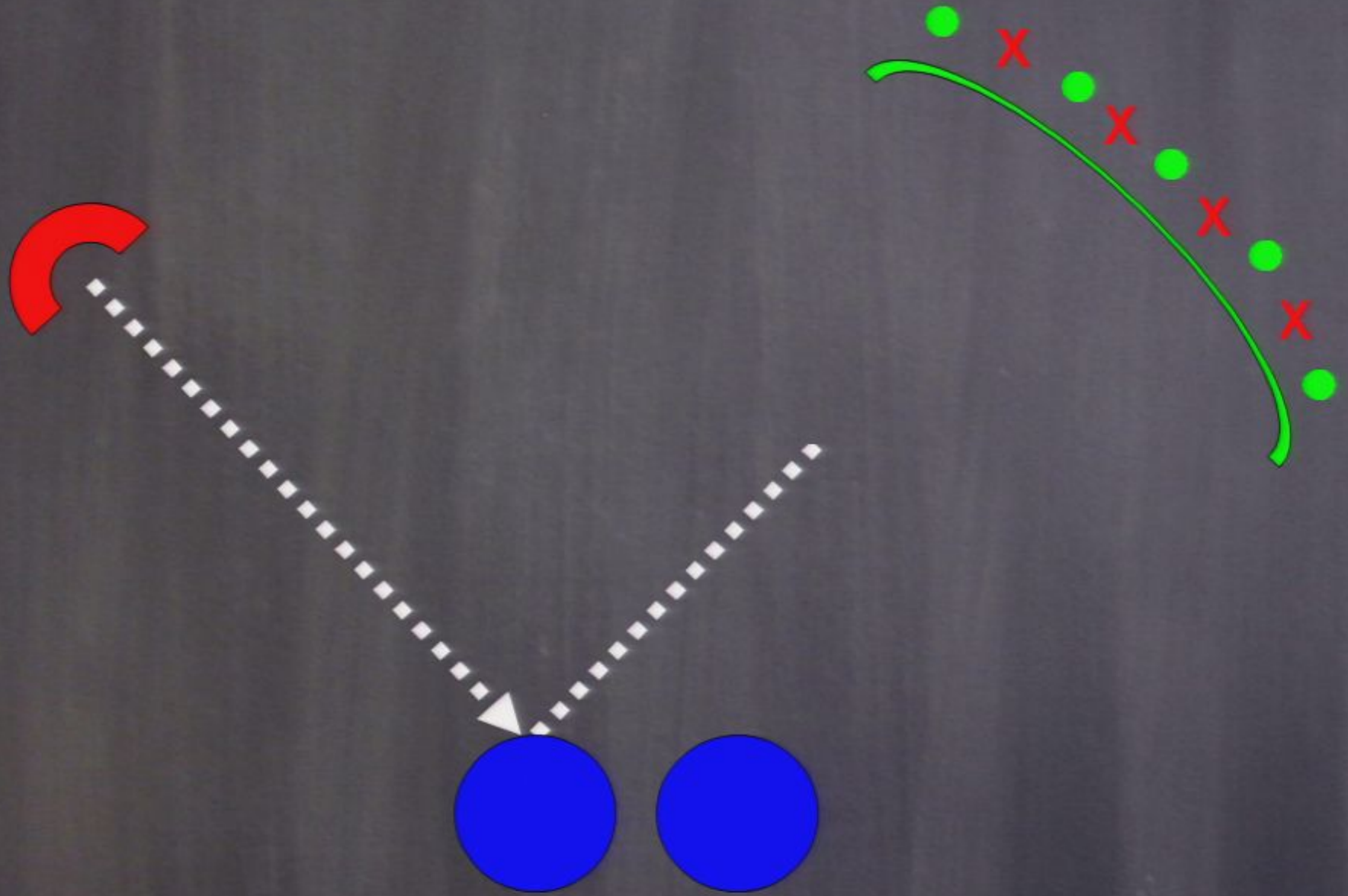

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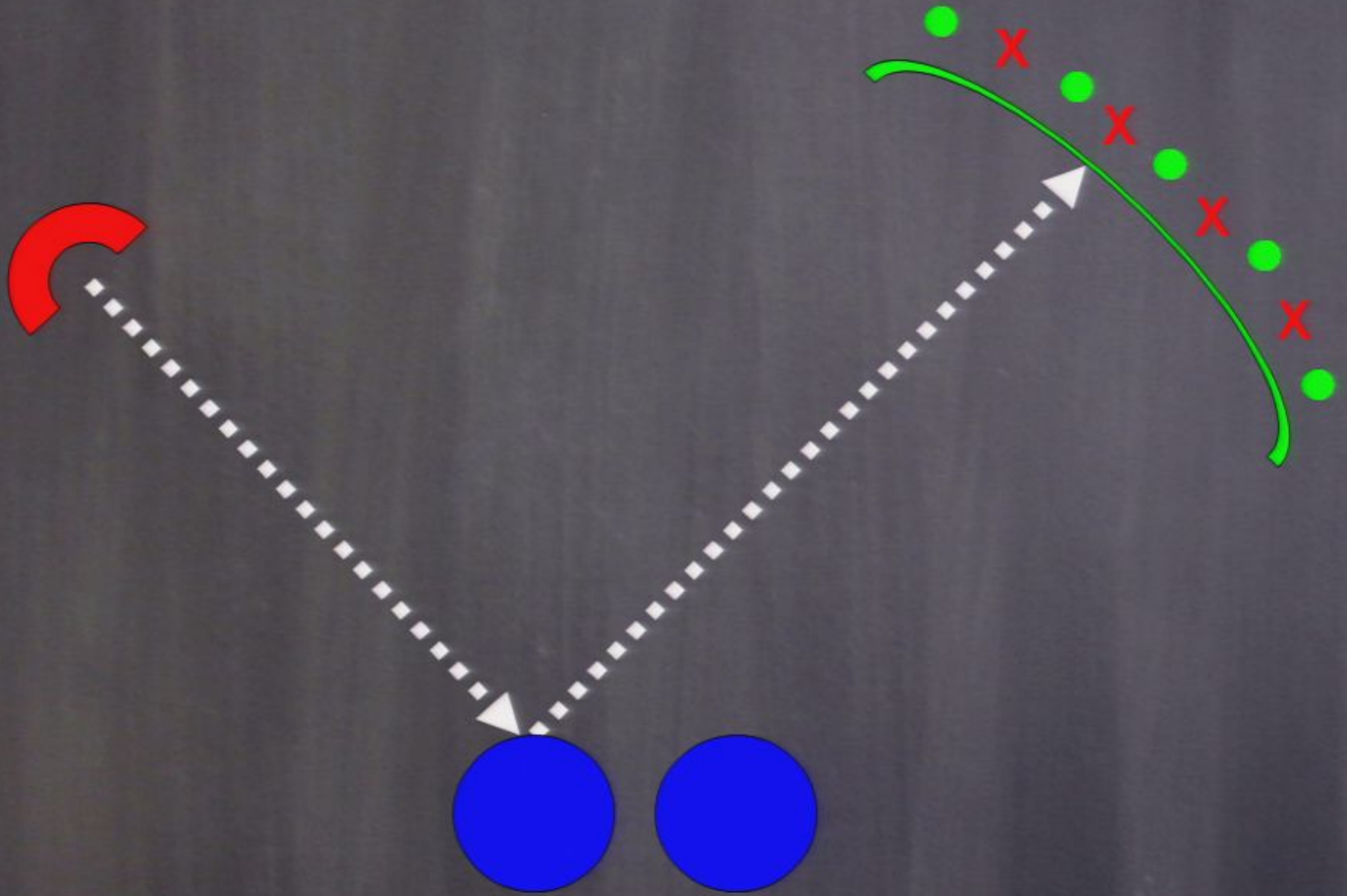
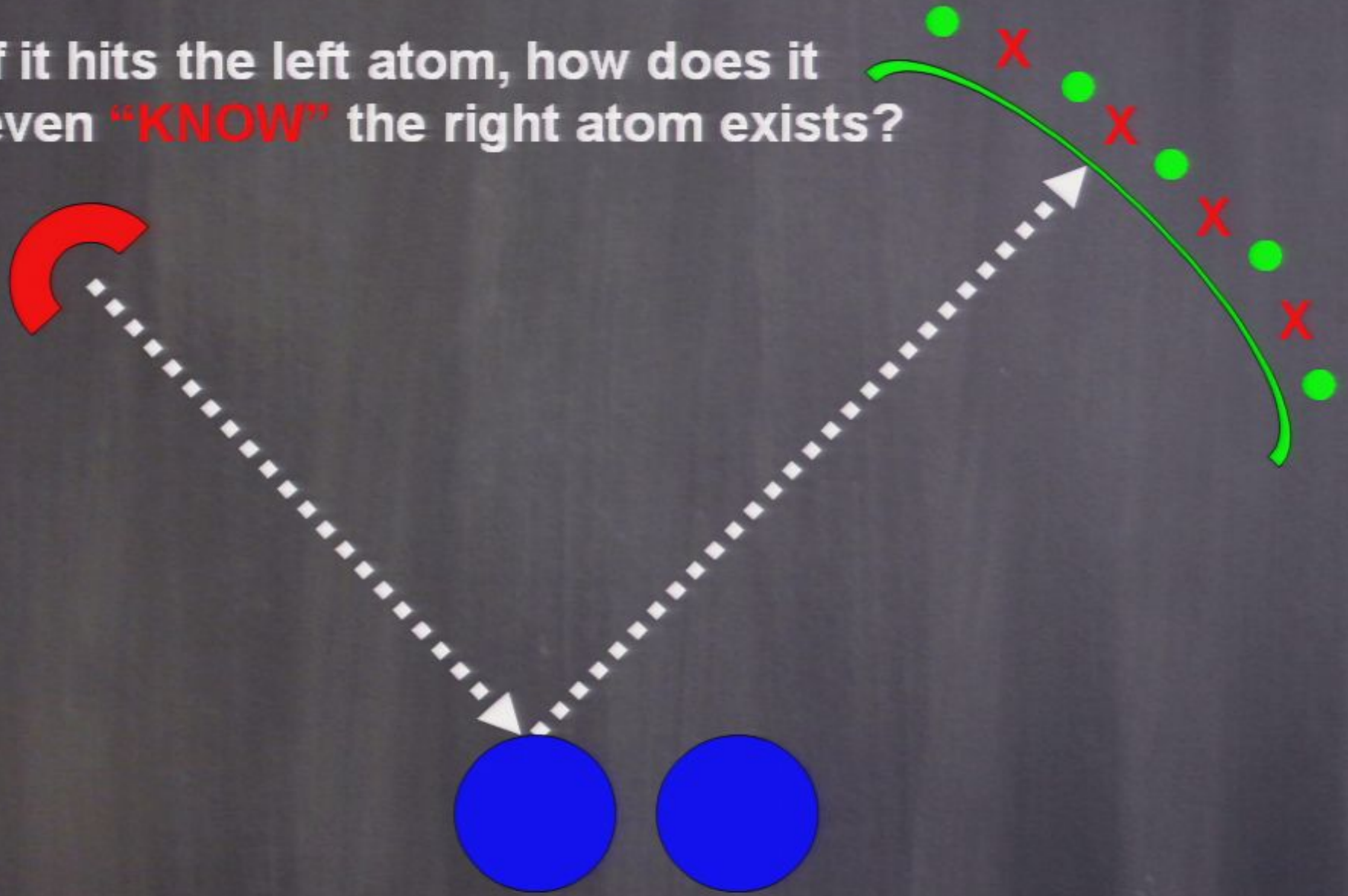


How is this POSSIBLE?

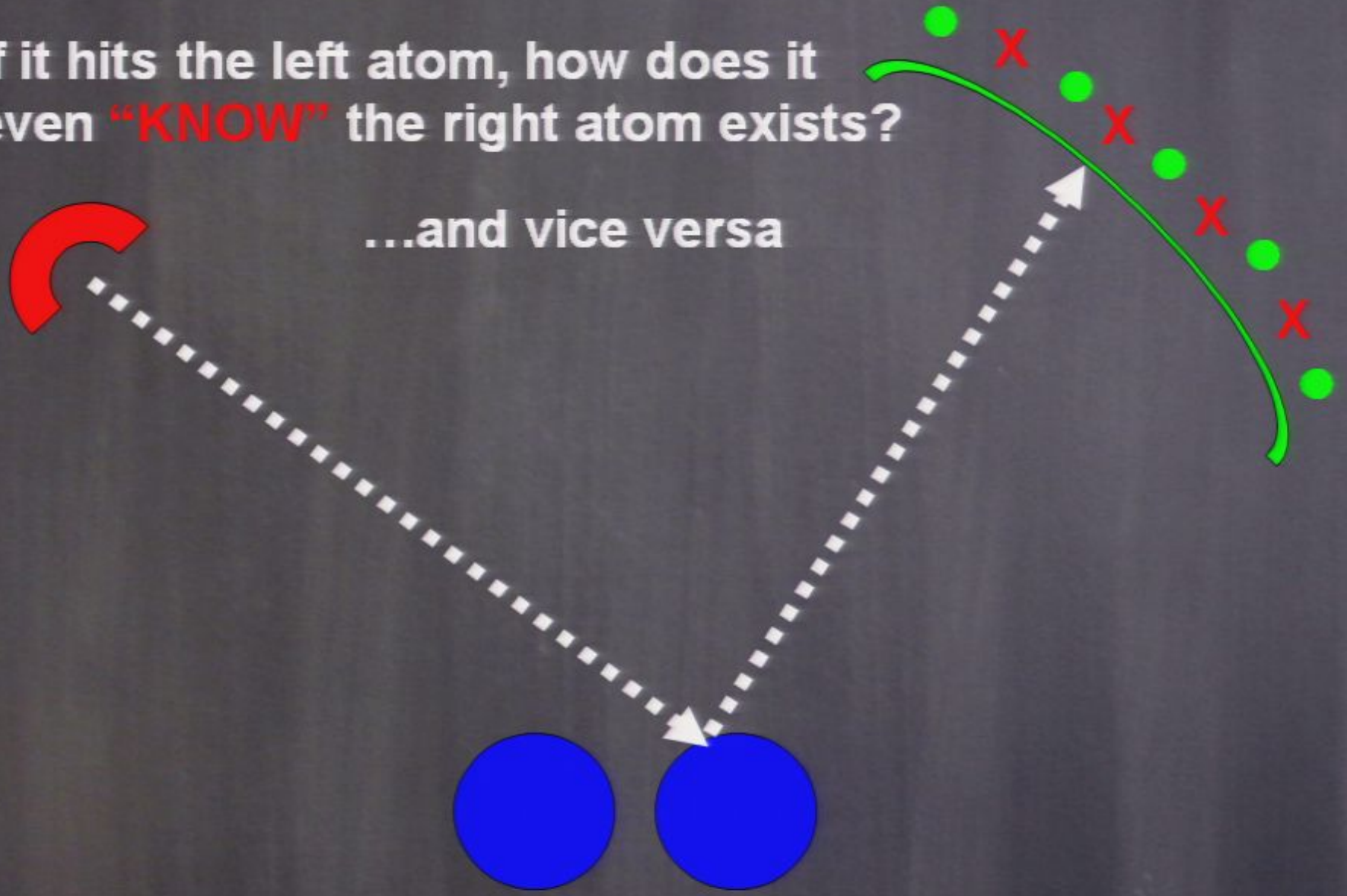
If it hits the left atom, how does it even "KNOW" the right atom exists?



How is this POSSIBLE?

If it hits the left atom, how does it even "KNOW" the right atom exists?

…and vice versa



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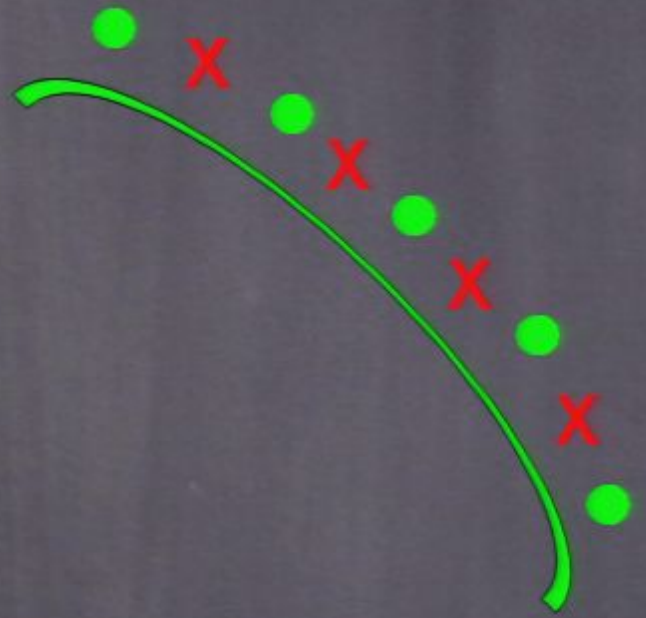
CLUE: Pattern depends on the difference in the two path lengths



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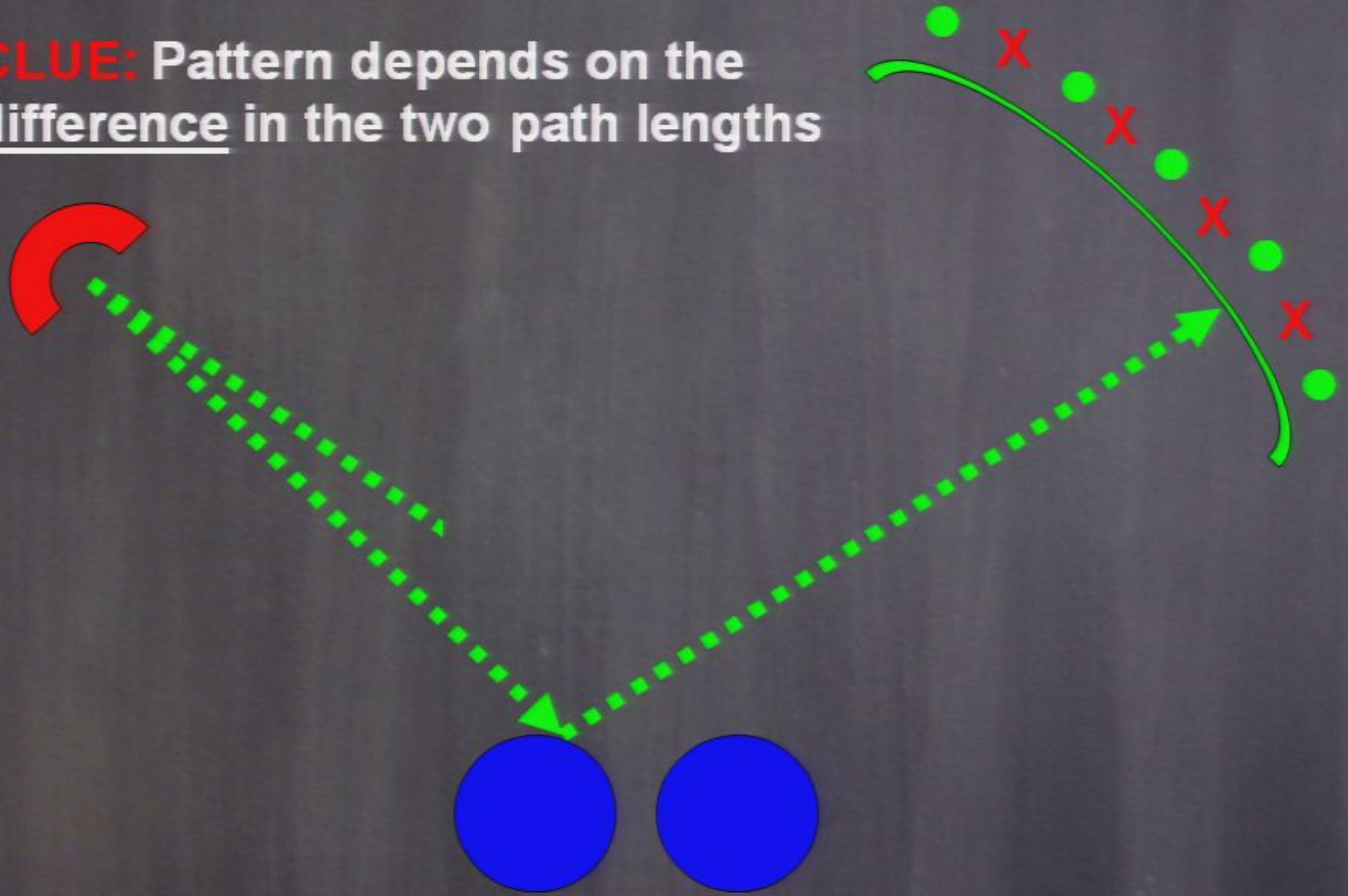

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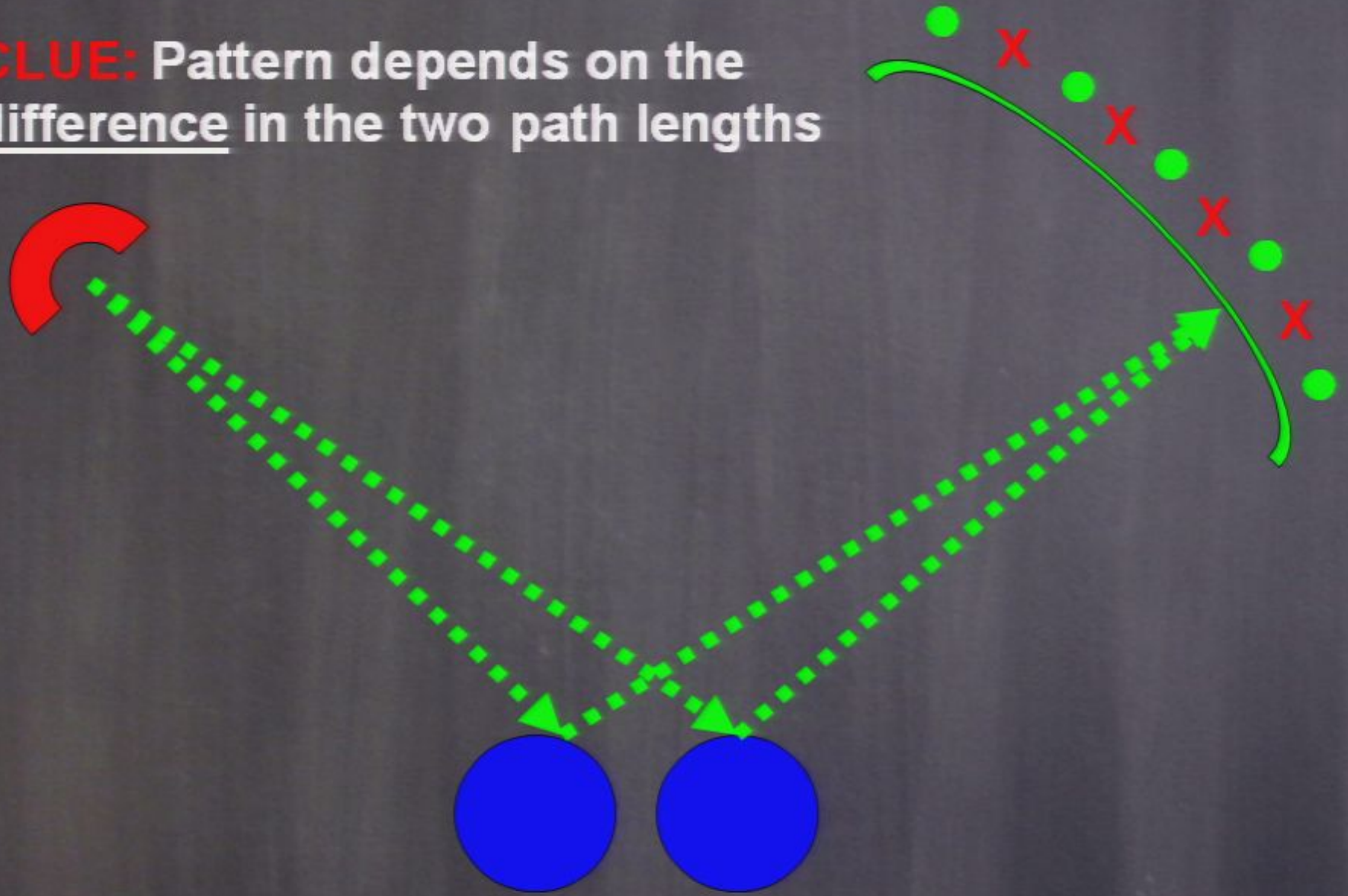
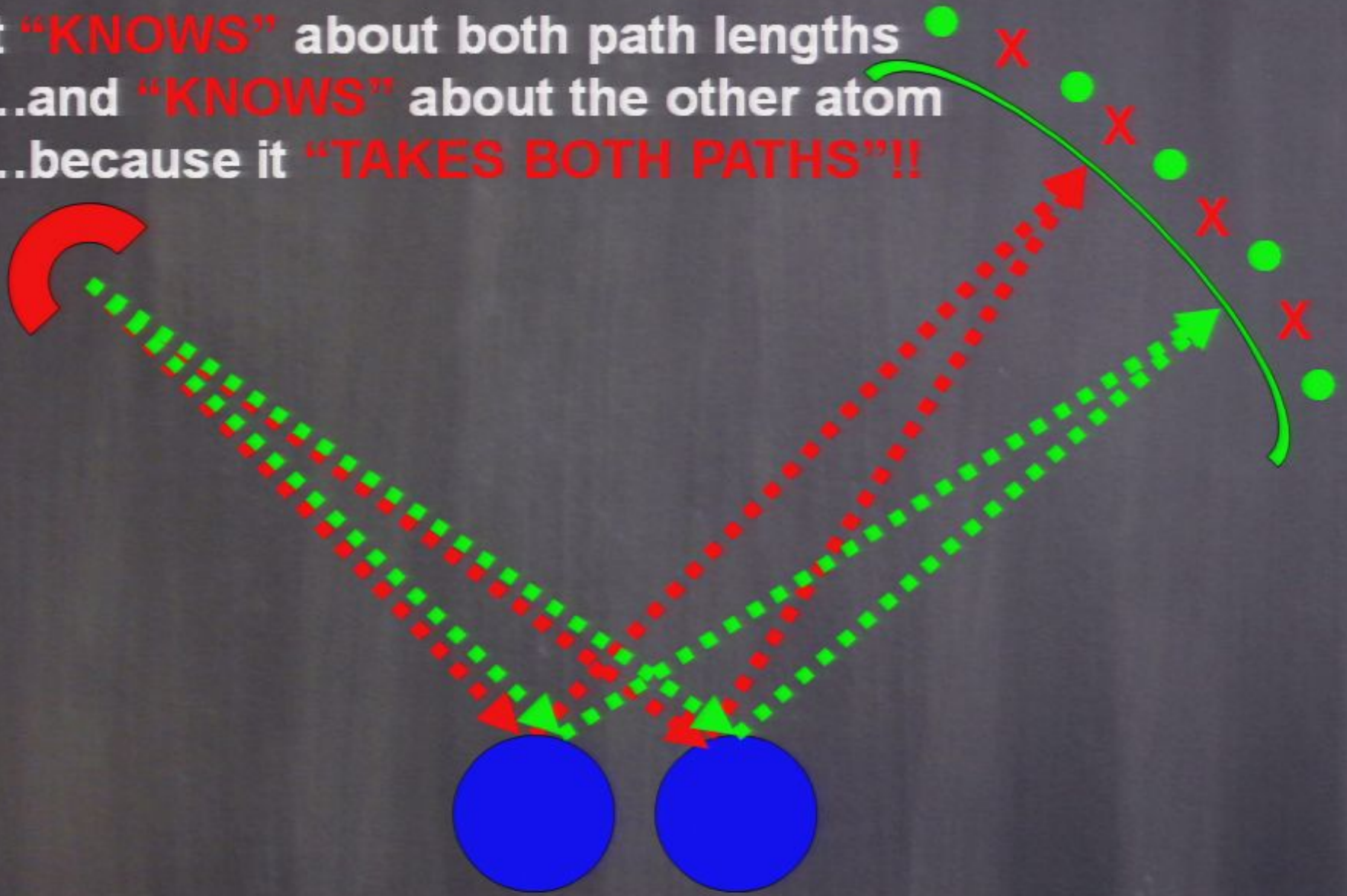


How is this POSSIBLE?

It "KNOWS" about both path lengths

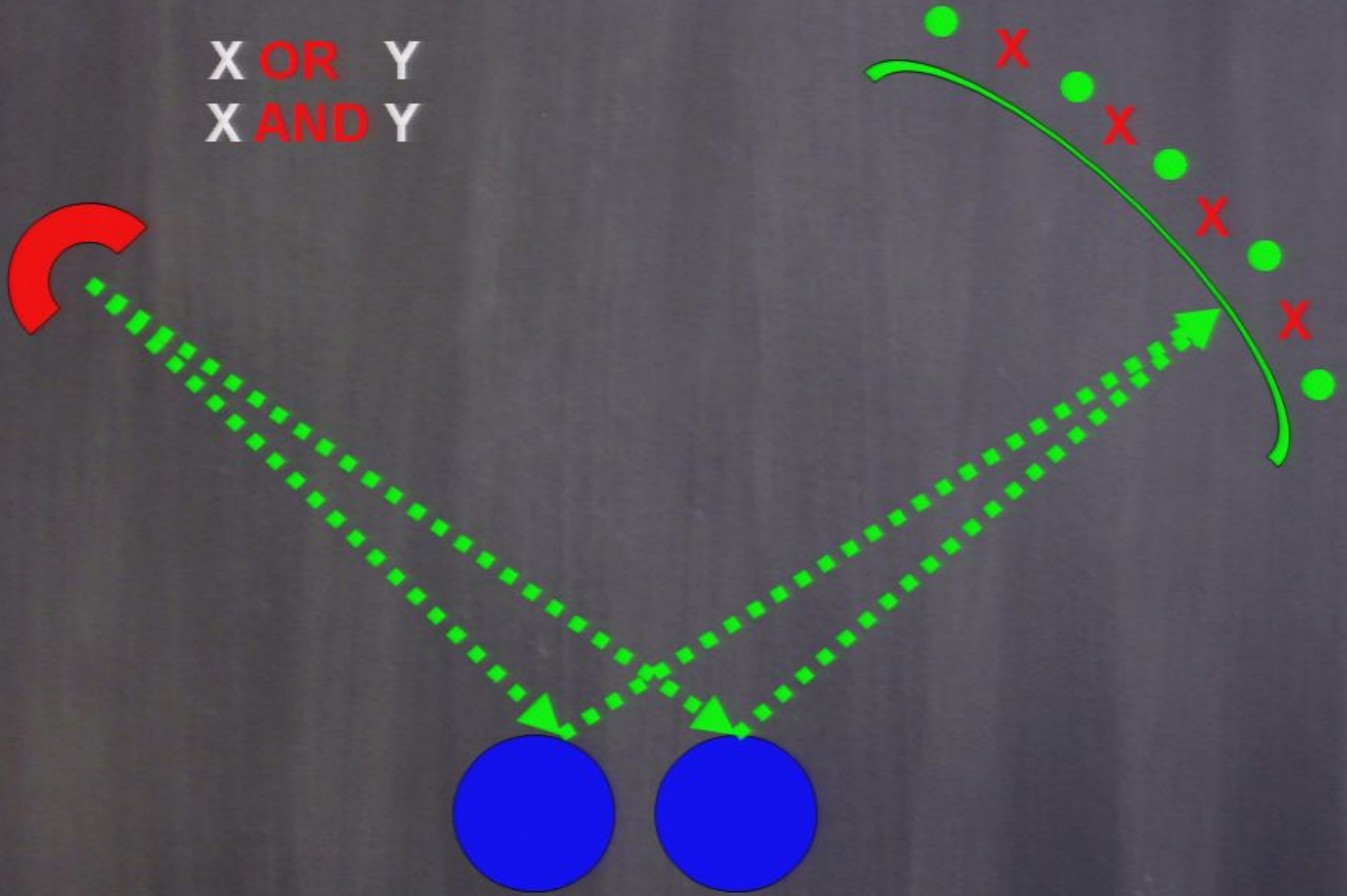
…and "KNOWS" about the other atom

…because it "TAKES BOTH PATHS"!!



How is this POSSIBLE?

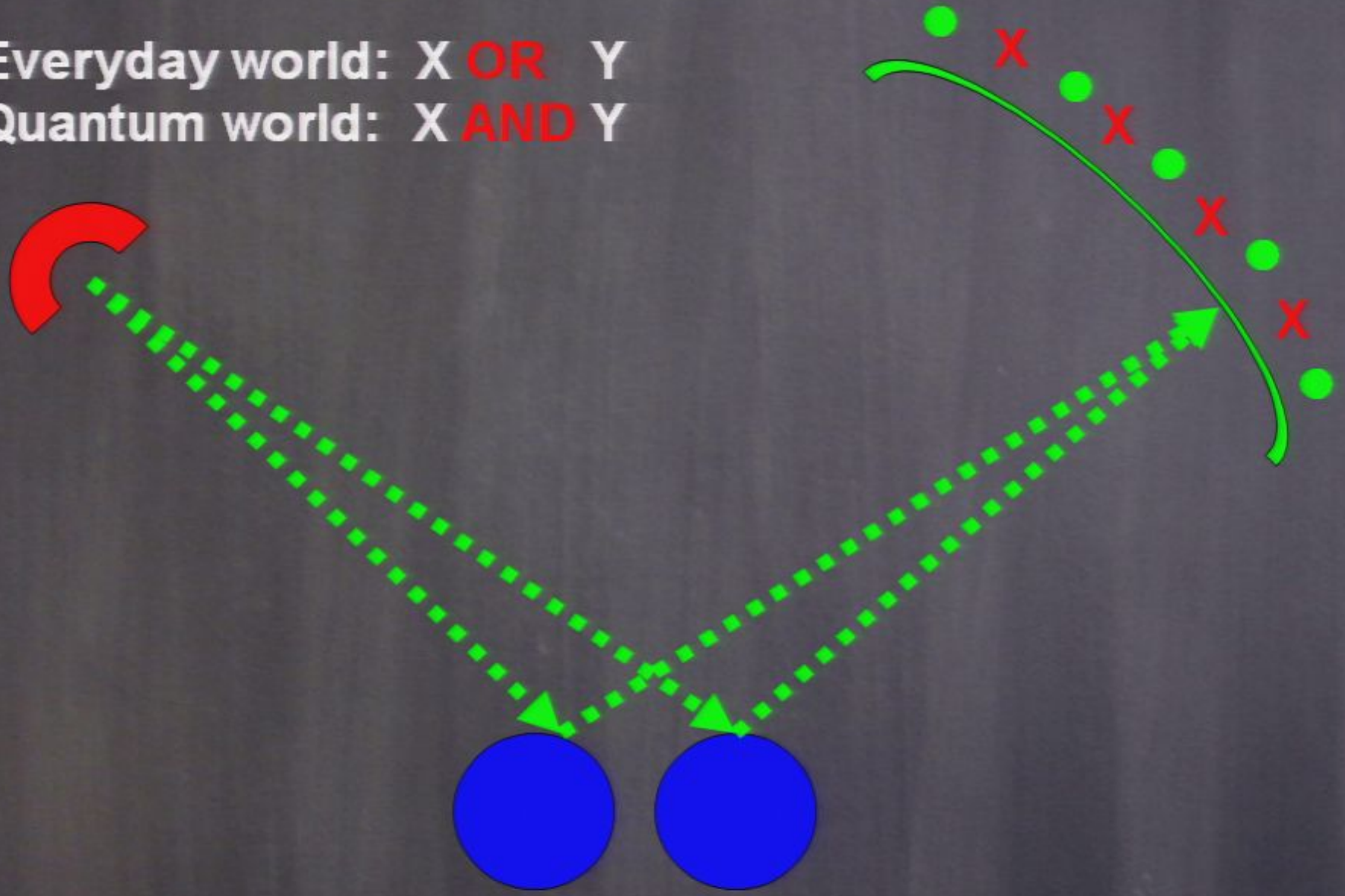
X OR Y
X AND Y



How is this POSSIBLE?

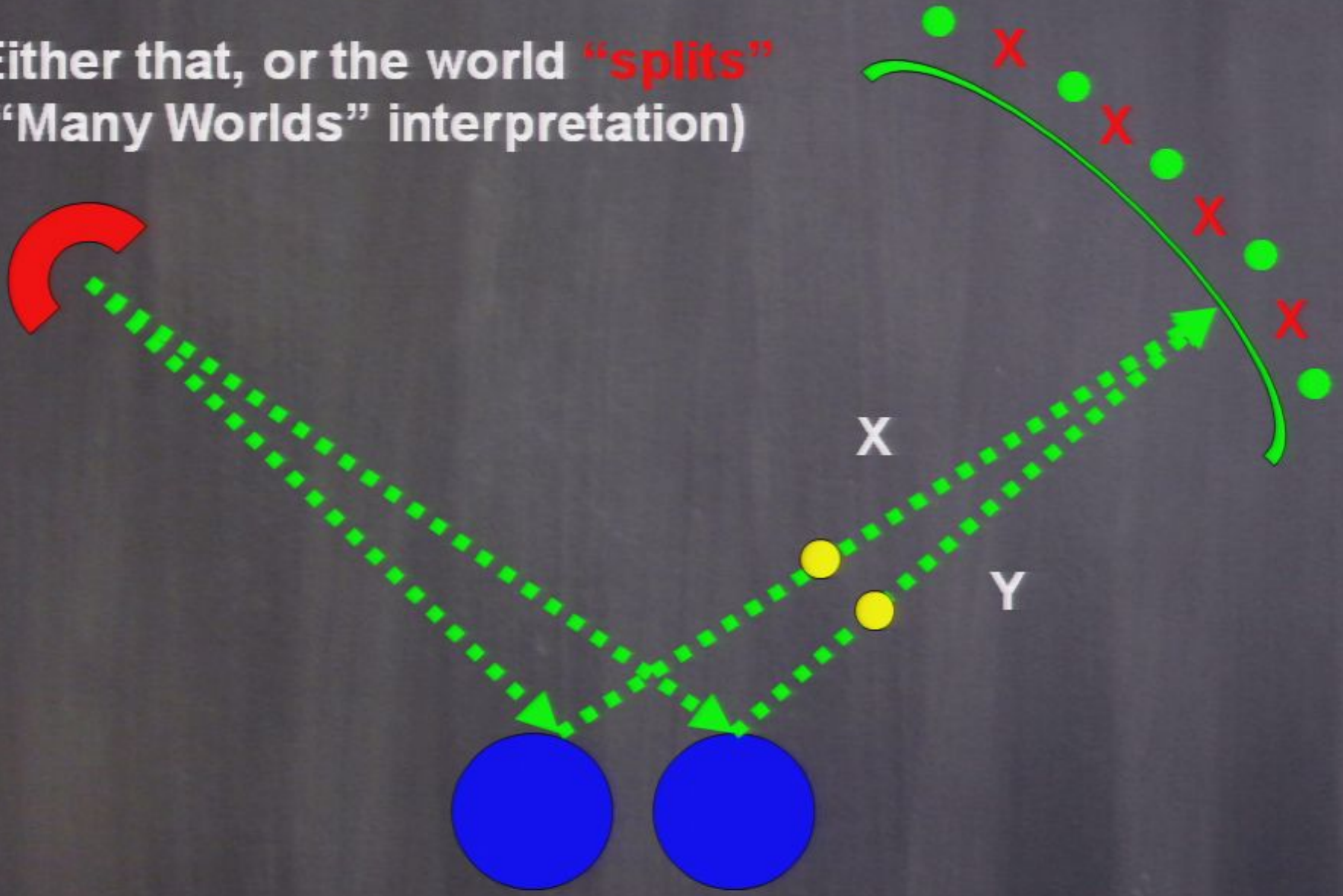
Everyday world: X OR Y

Quantum world: X AND Y

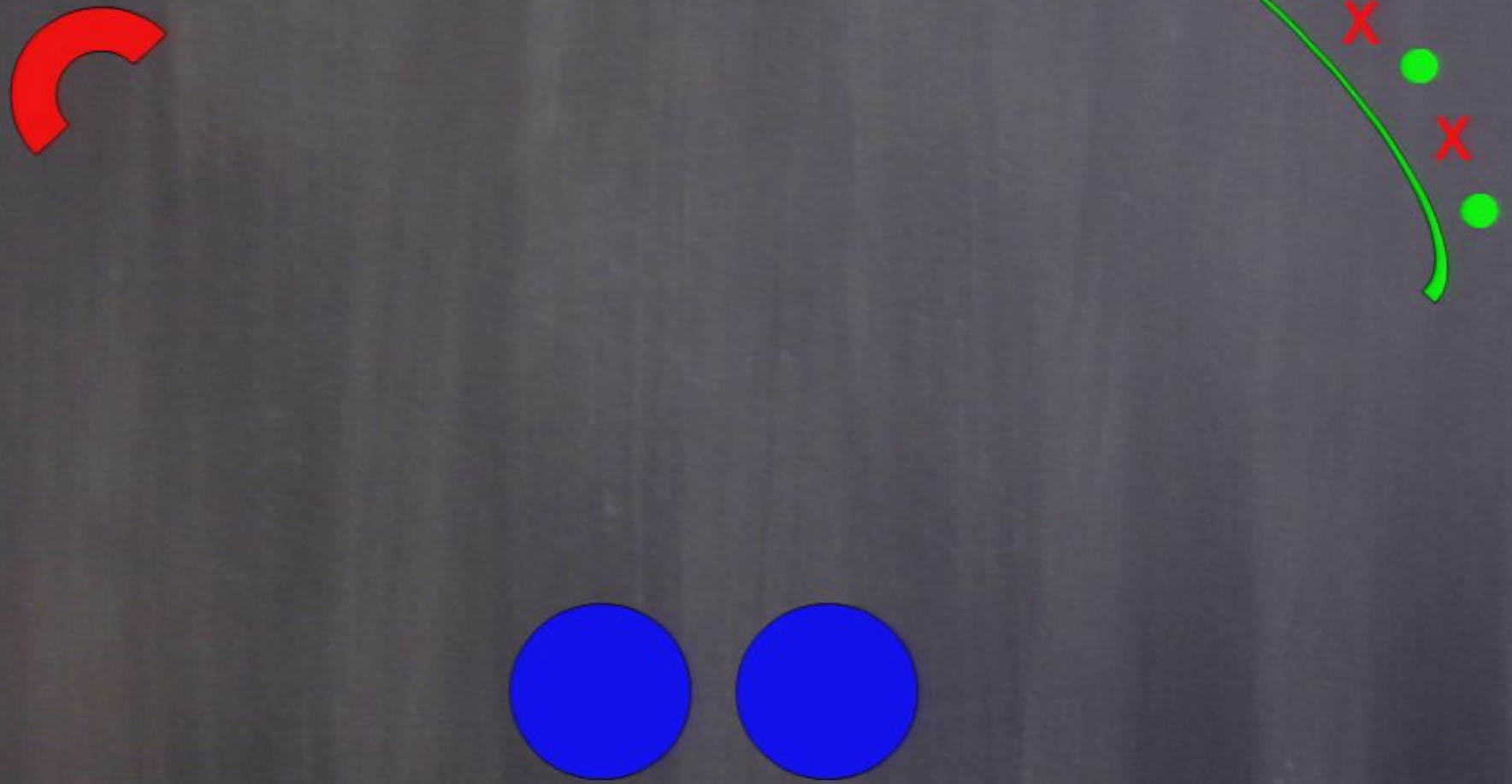


How is this POSSIBLE?

Either that, or the world "splits"
("Many Worlds" interpretation)



Consider ALL the Atoms



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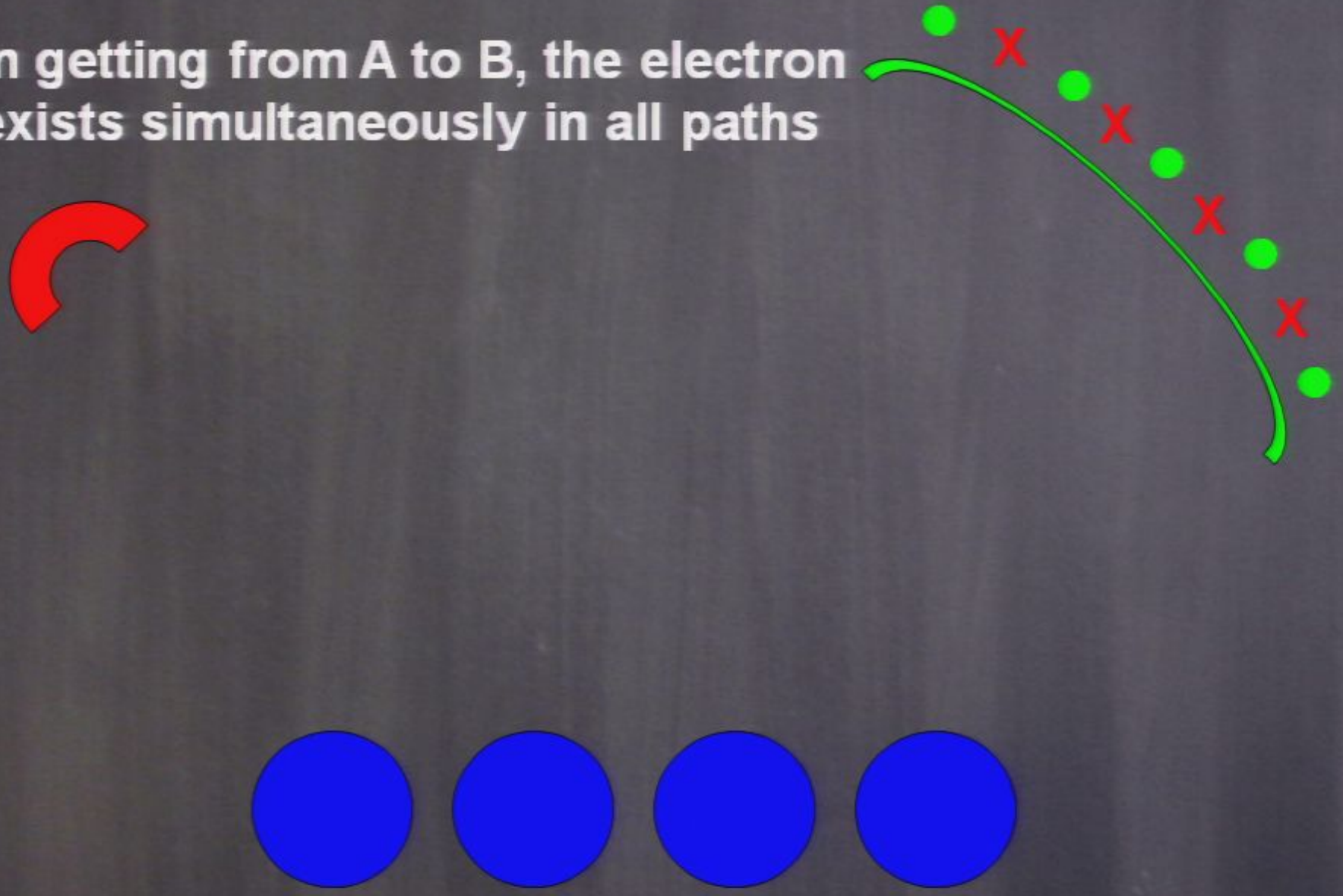
In getting from A to B, the electron exists simultaneously in all paths



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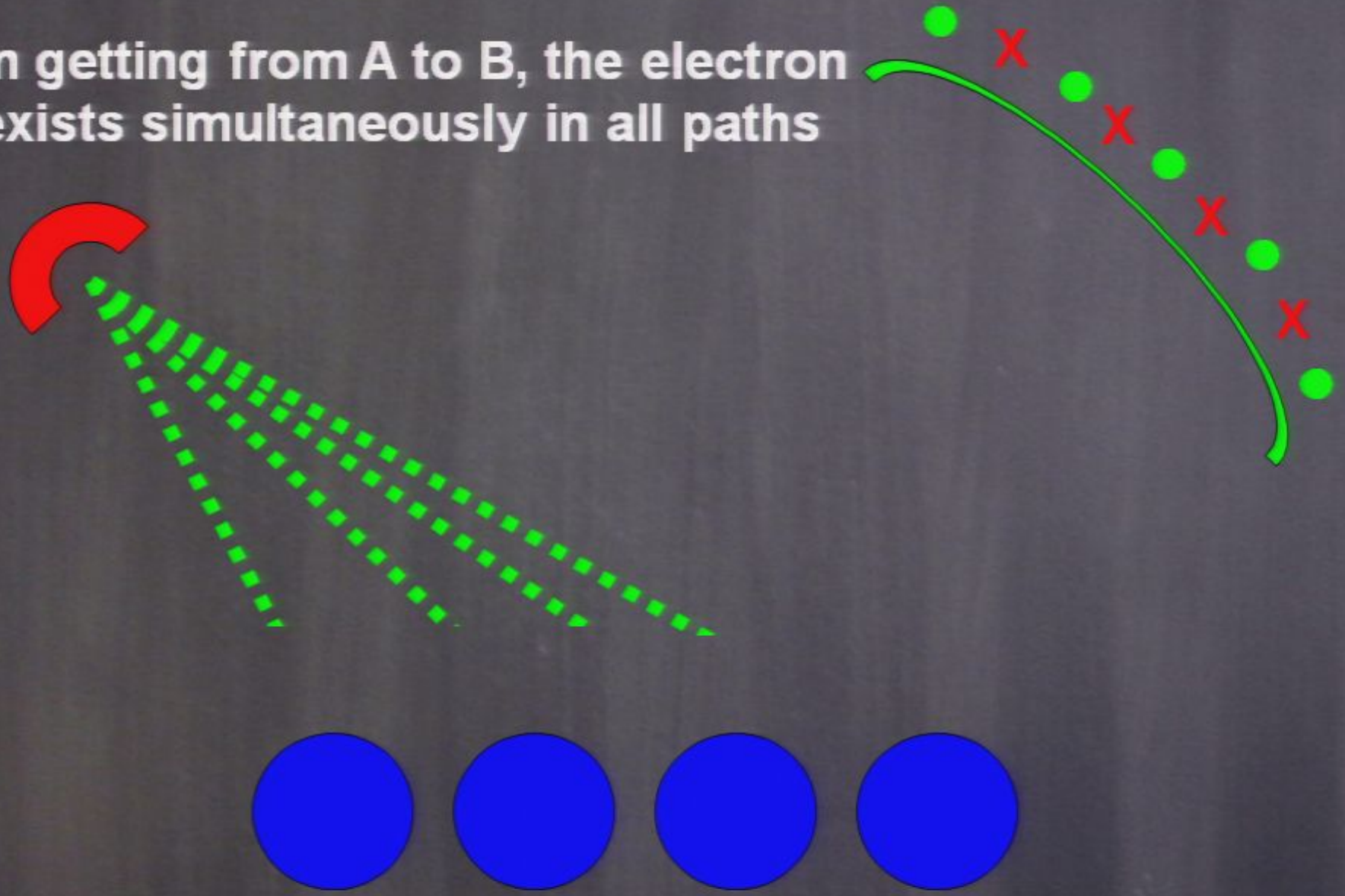
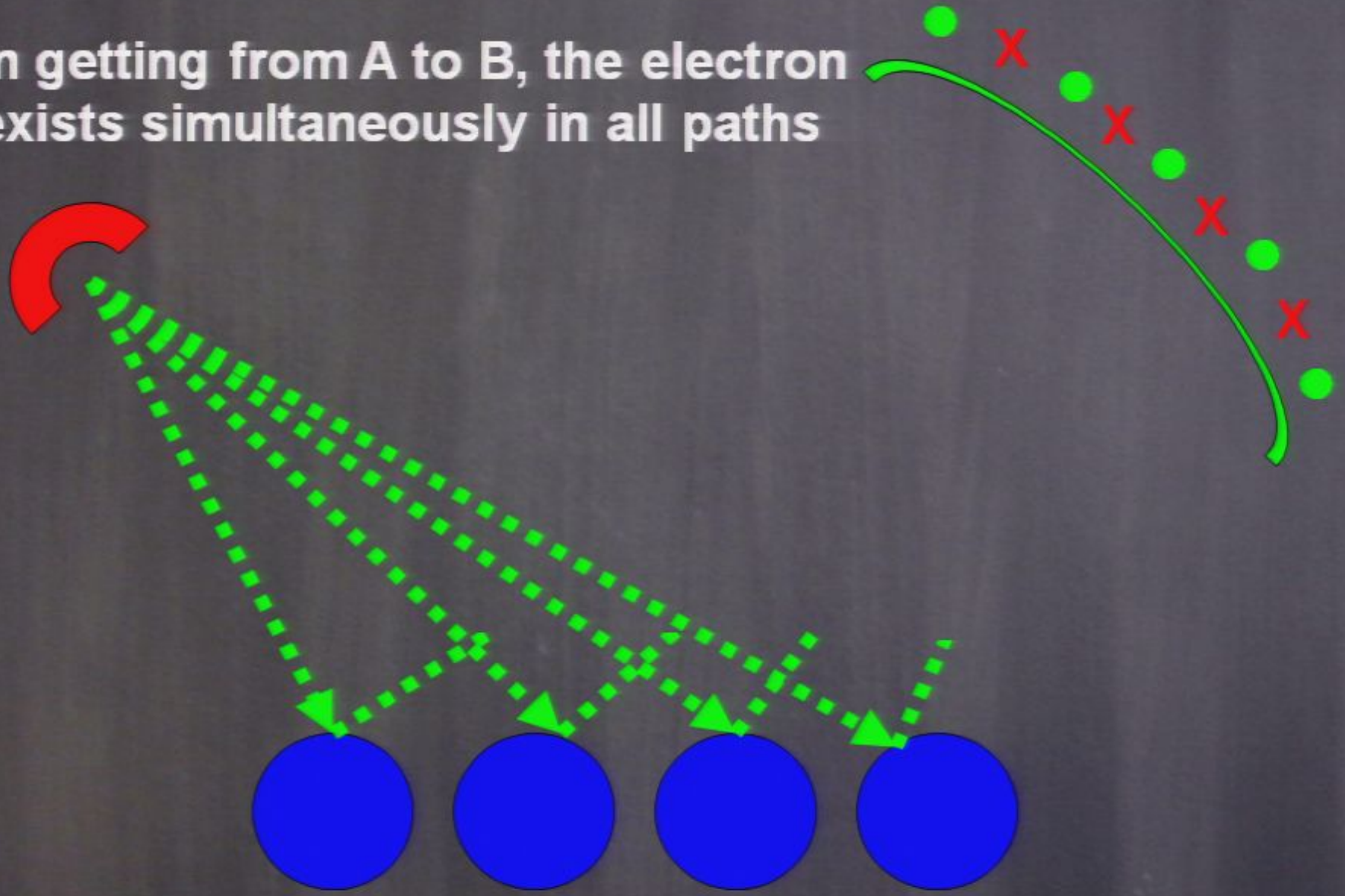


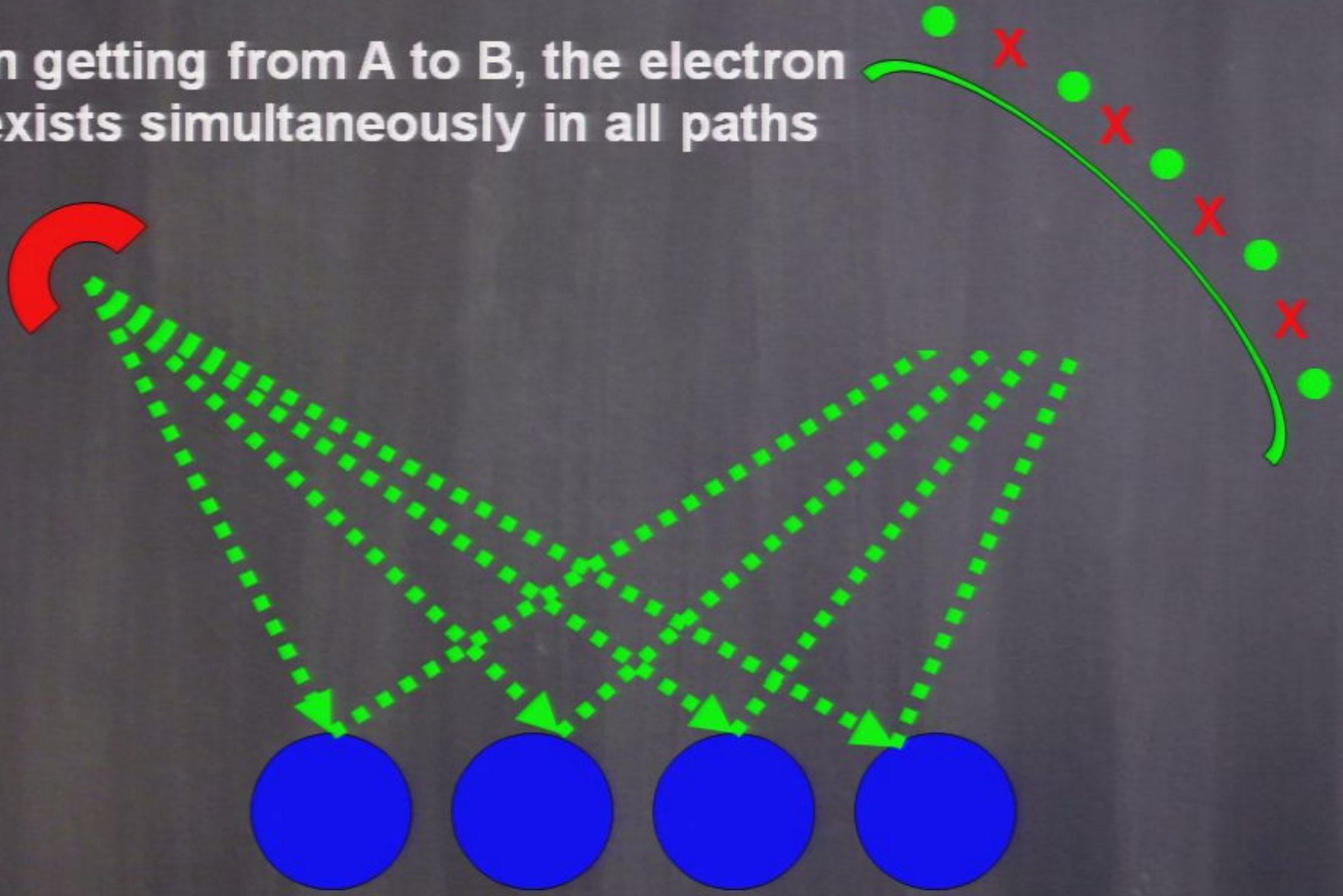
Consider ALL the Atoms

In getting from A to B, the electron exists simultaneously in all paths



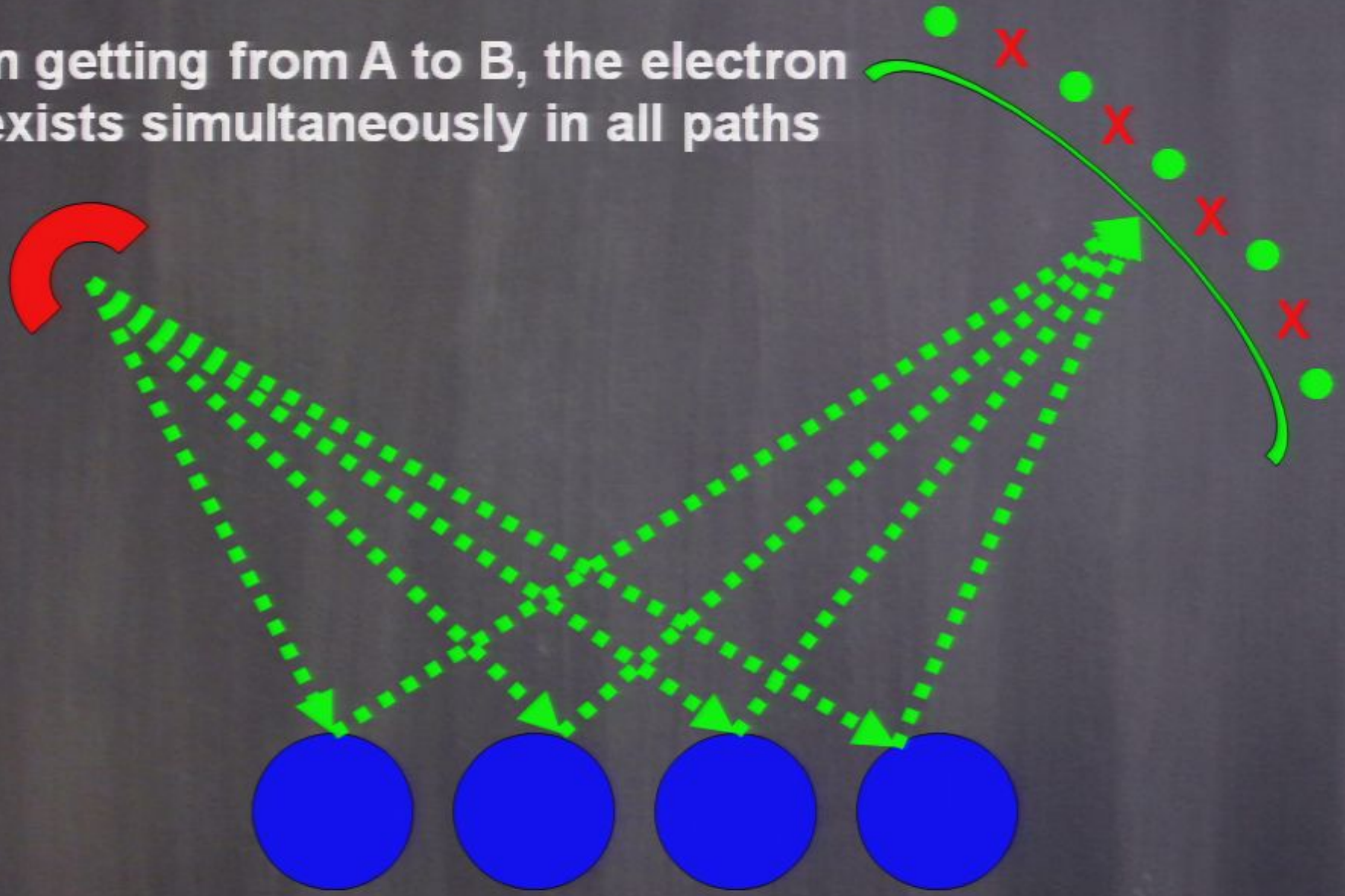
Consider ALL the Atoms

In getting from A to B, the electron exists simultaneously in all paths

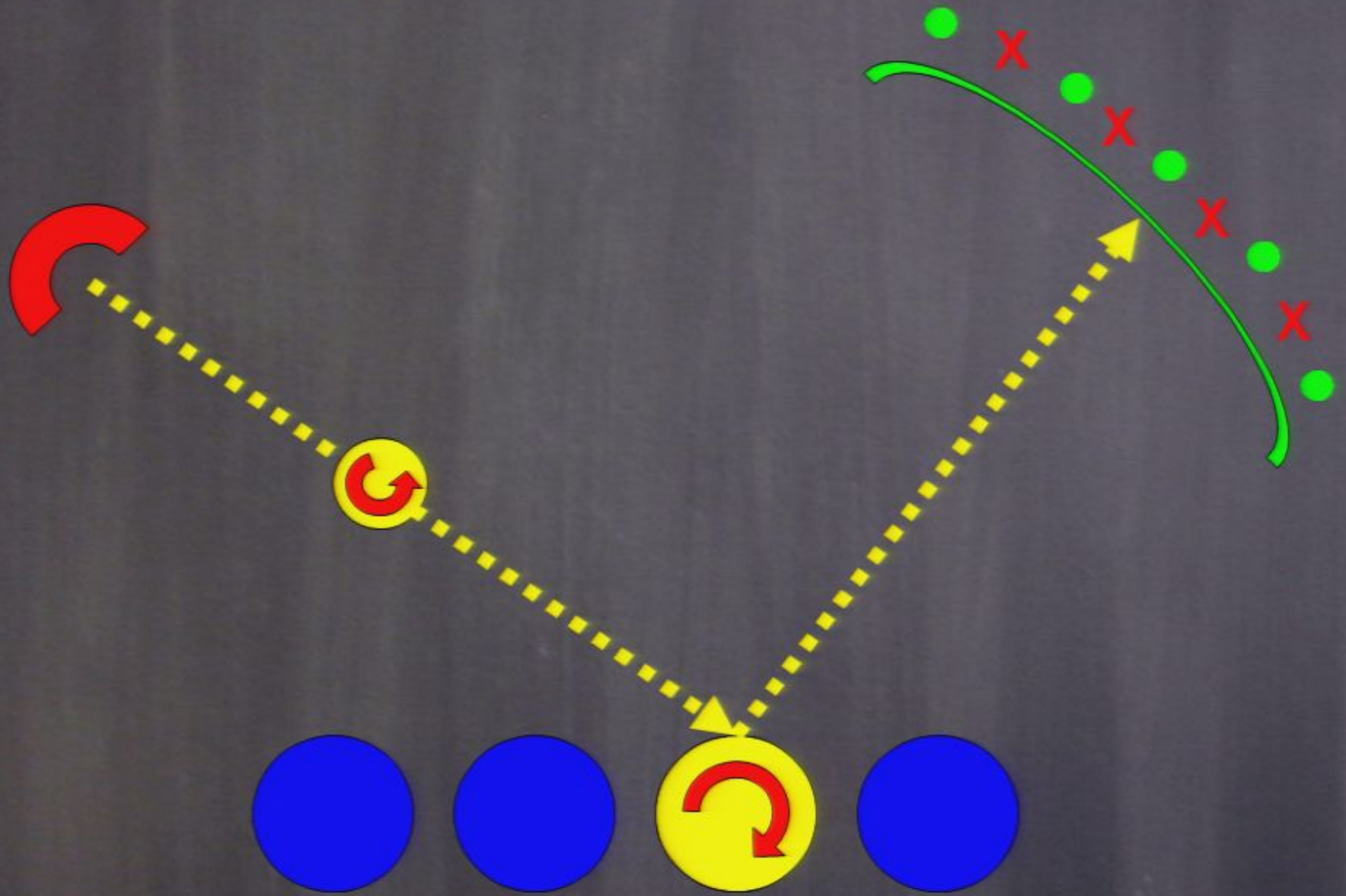


Consider ALL the Atoms

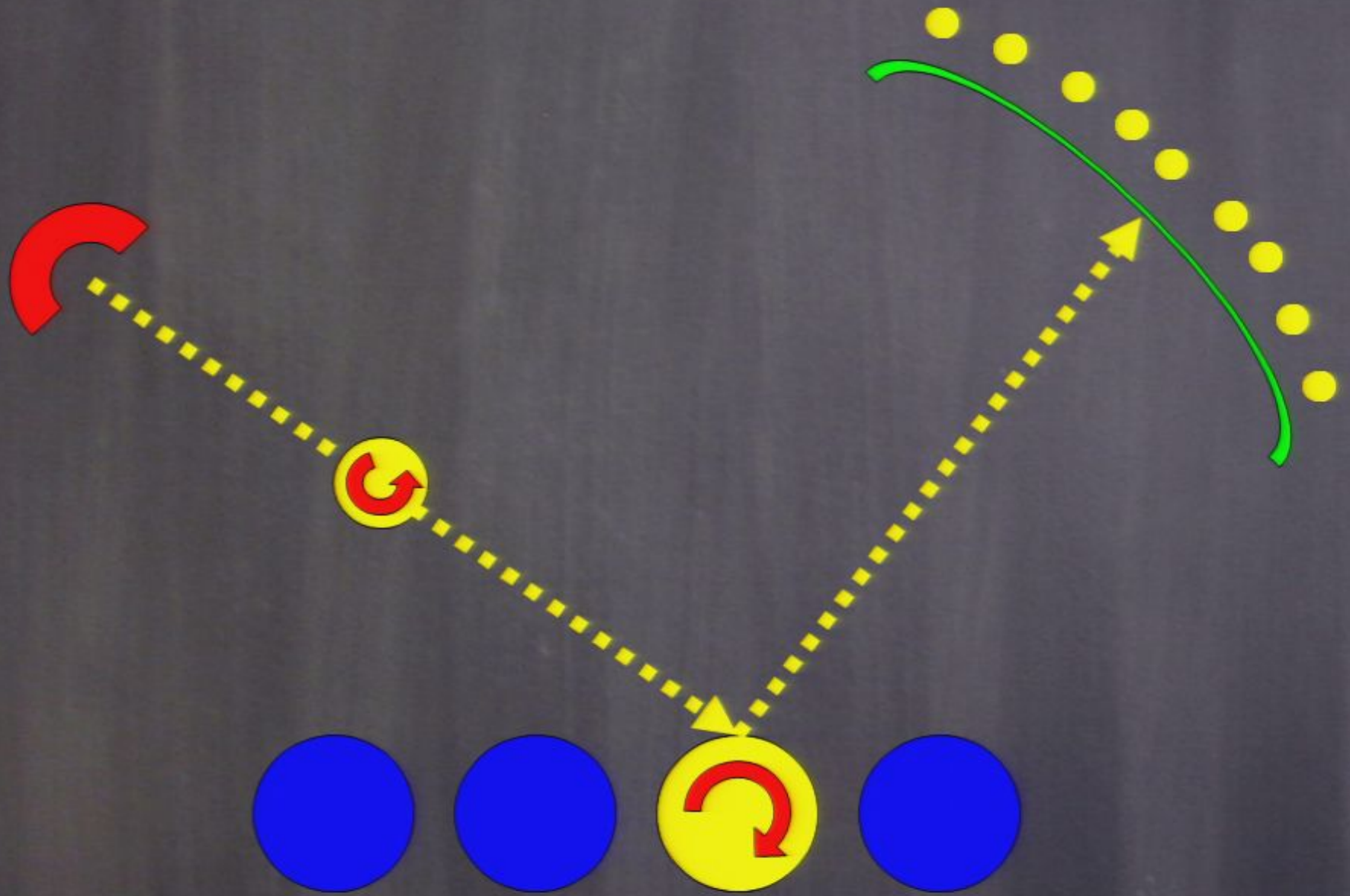
In getting from A to B, the electron exists simultaneously in all paths

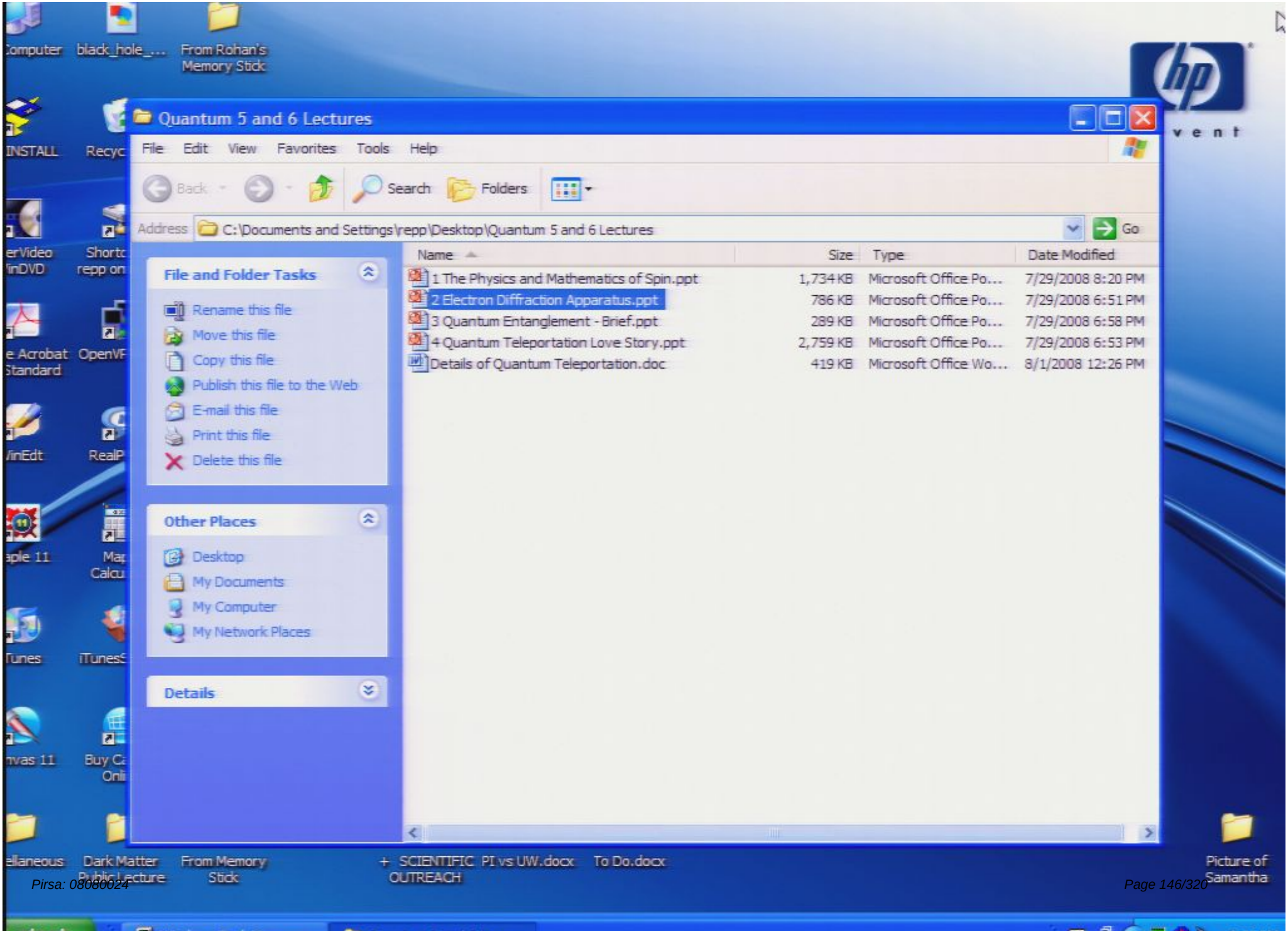


Give the Electron a "SPIN"



Give the Electron a "SPIN"

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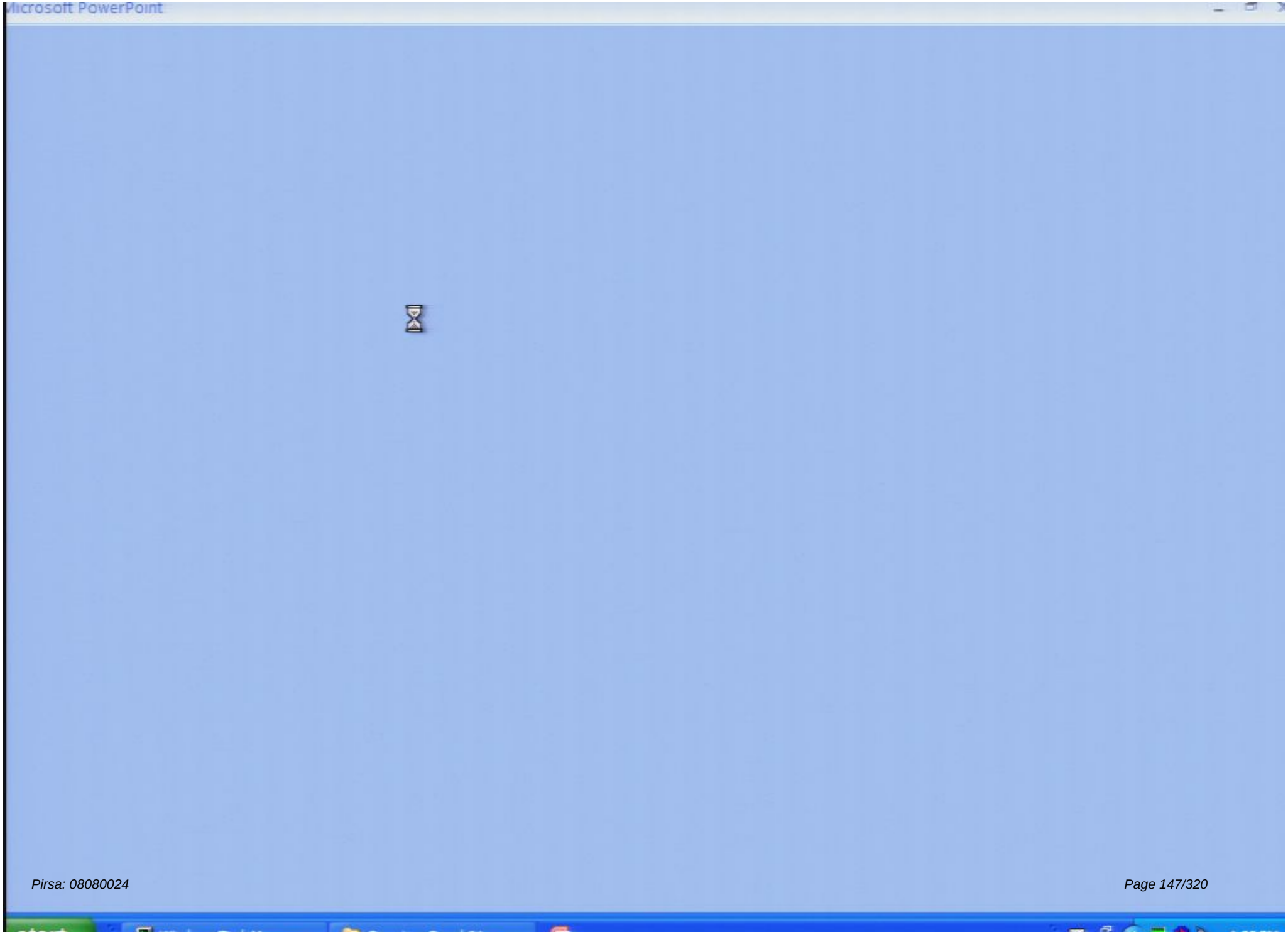
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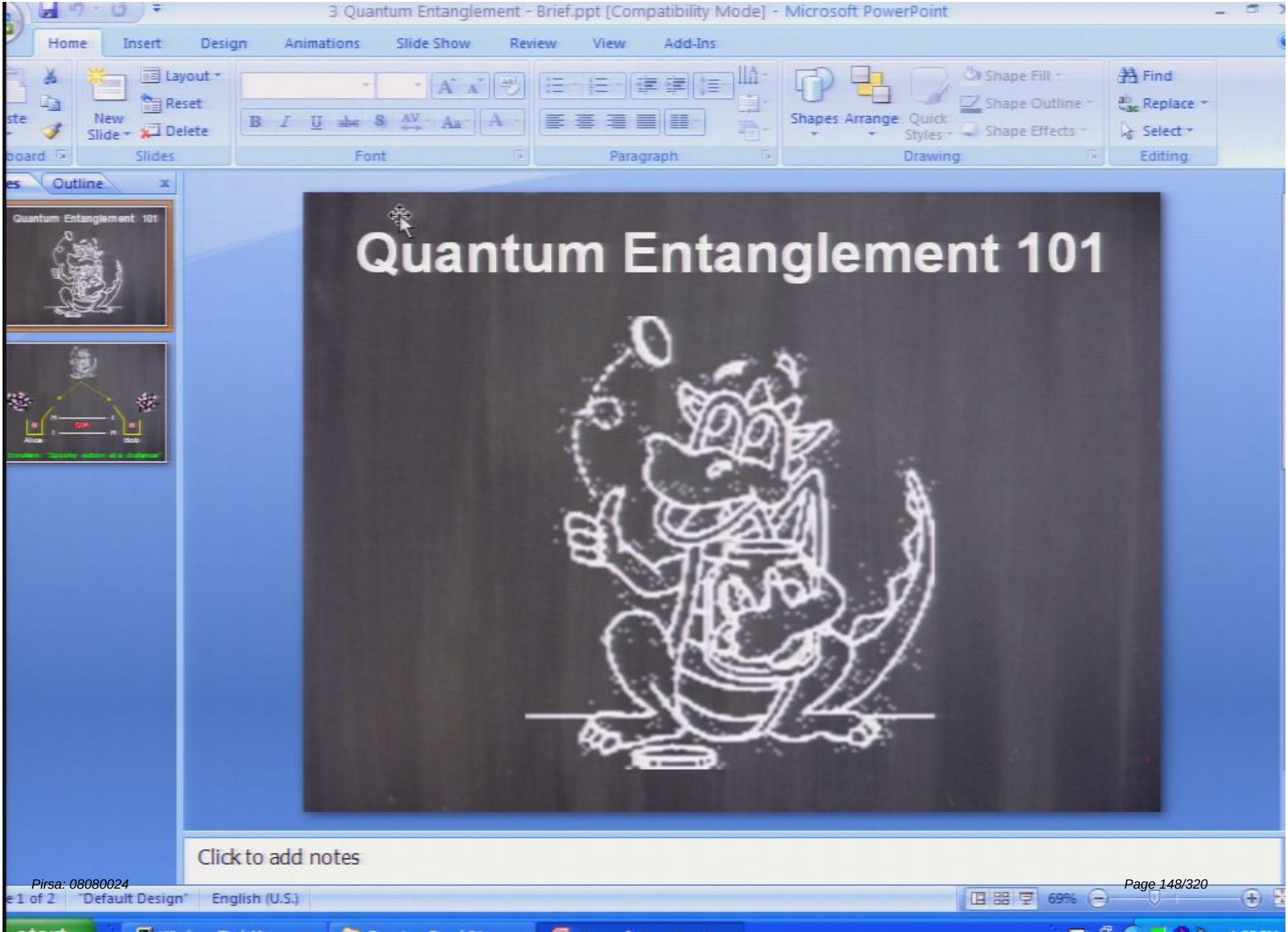
3 Quantum Entanglement - Brief.ppt [Compatibility Mode] - Microsoft PowerPoint
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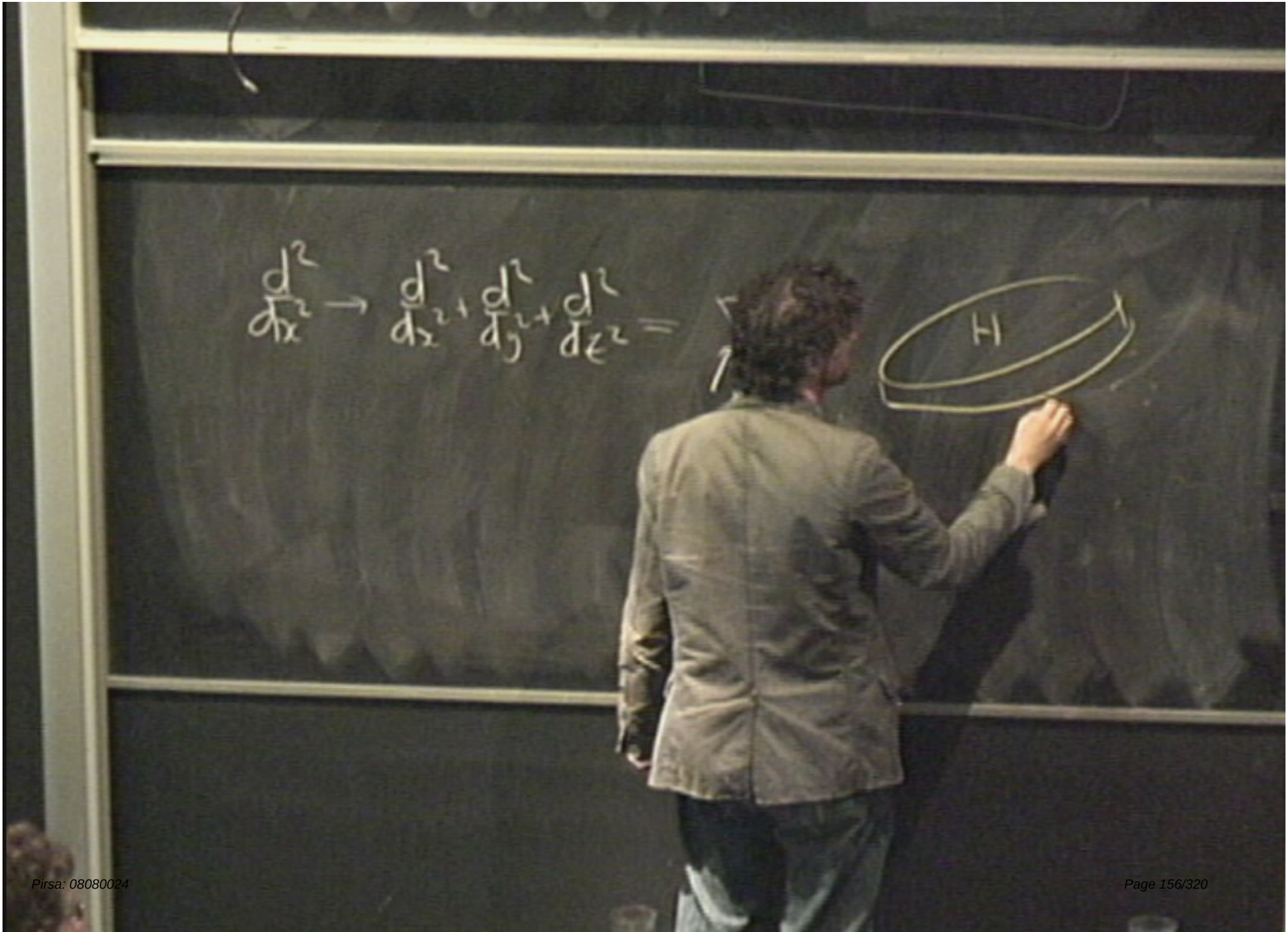
Quantum Entanglement 101

Quantum Entanglement 101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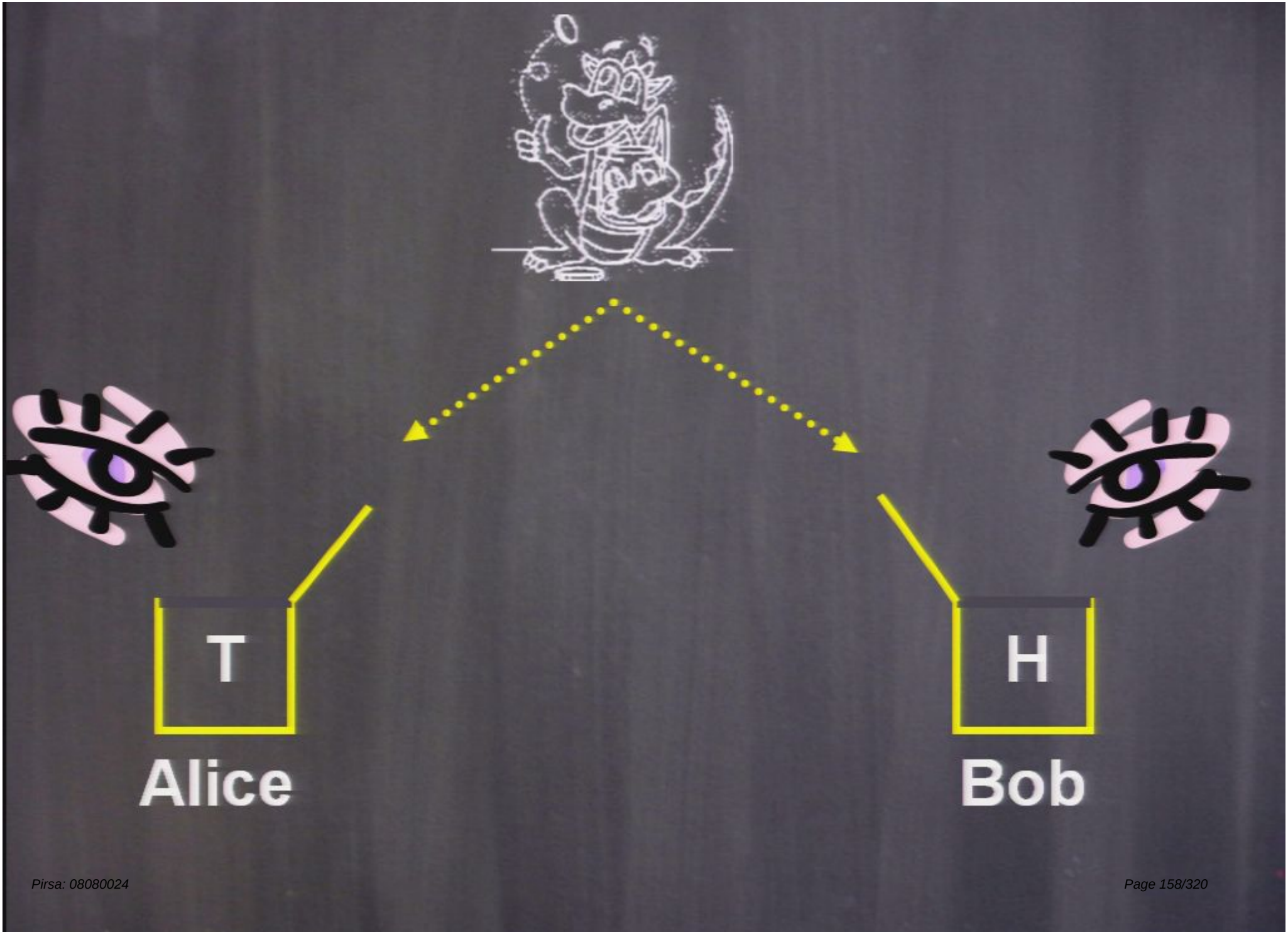
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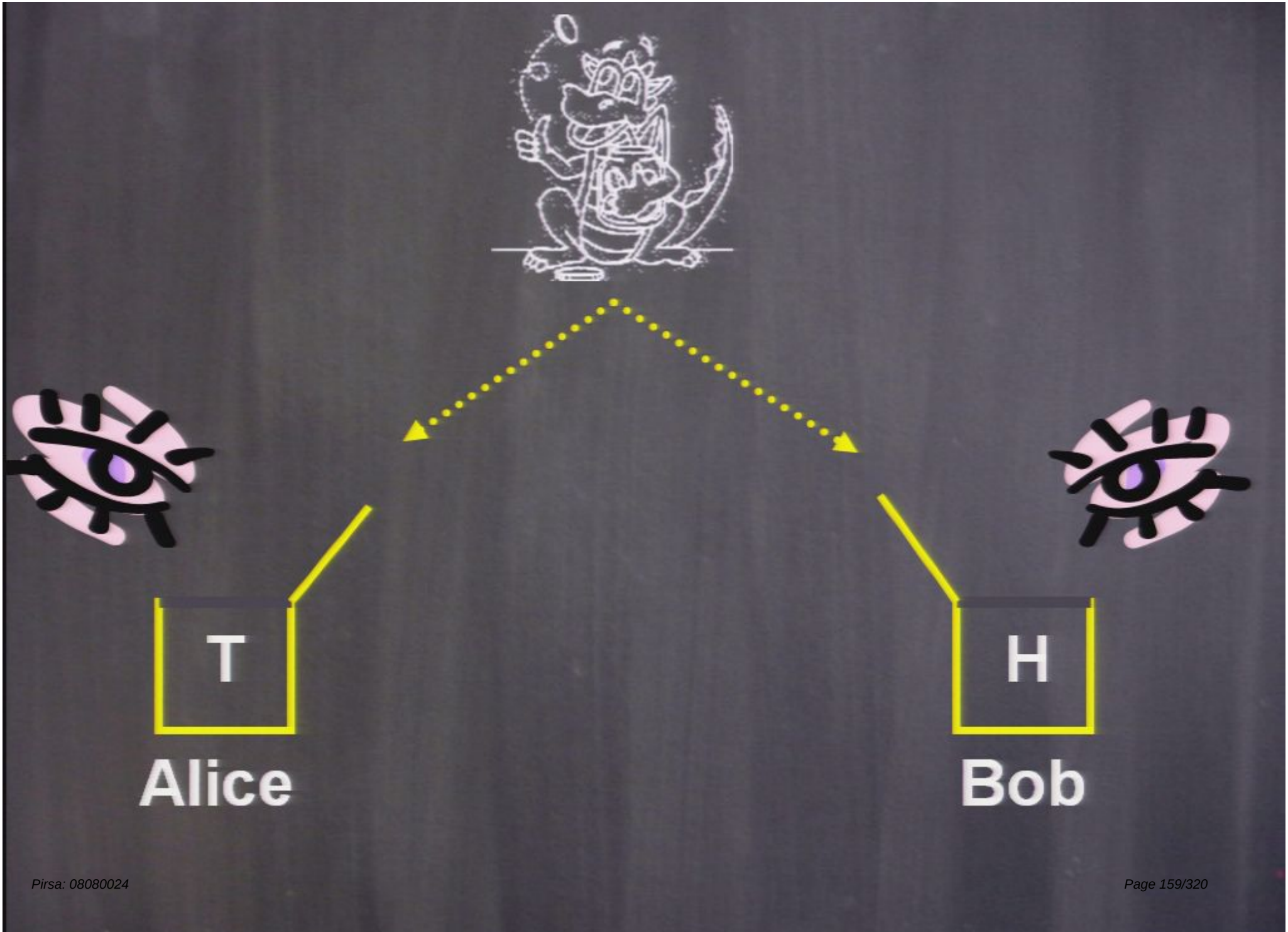
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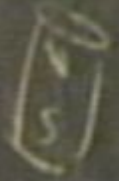

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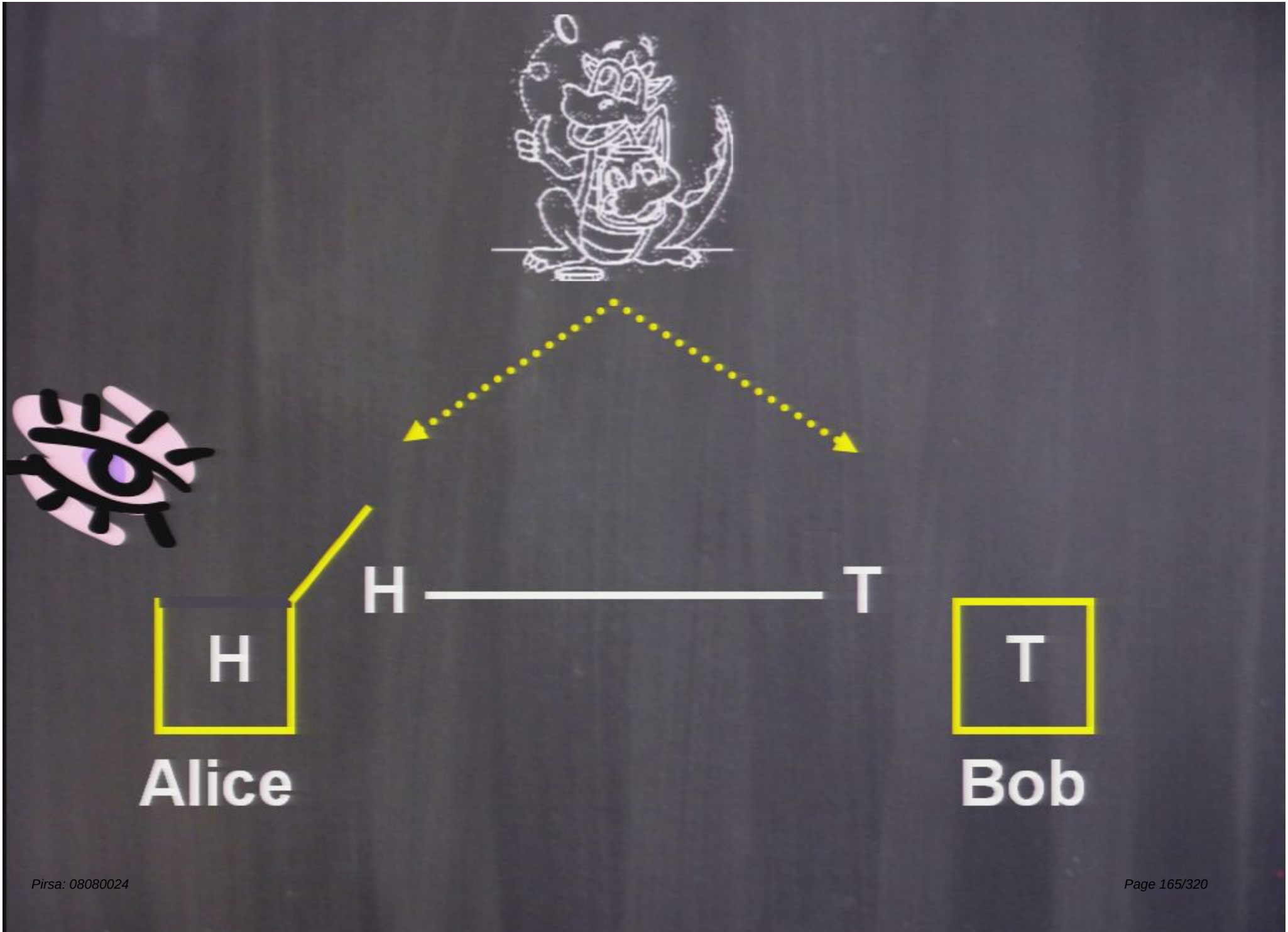
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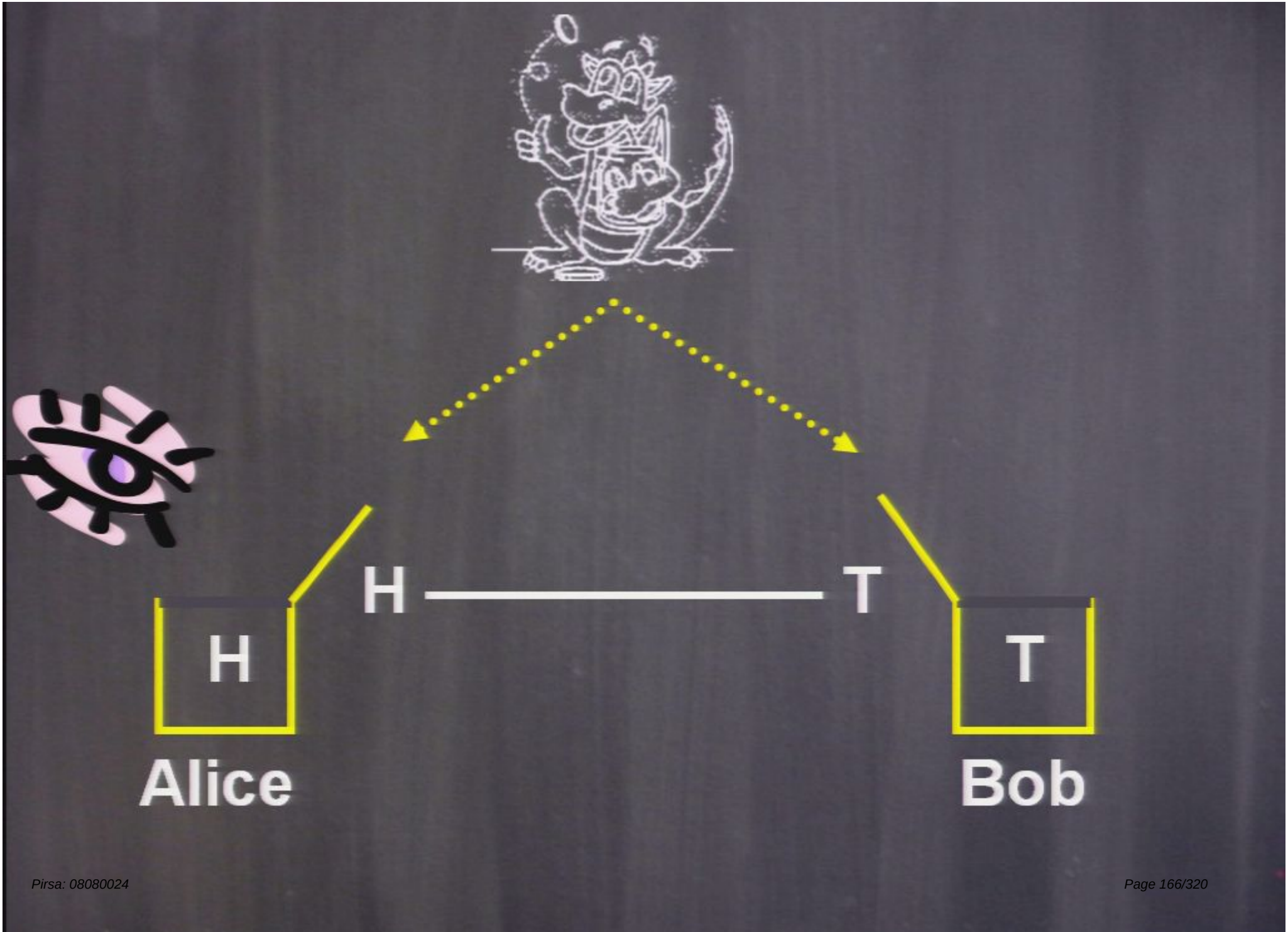
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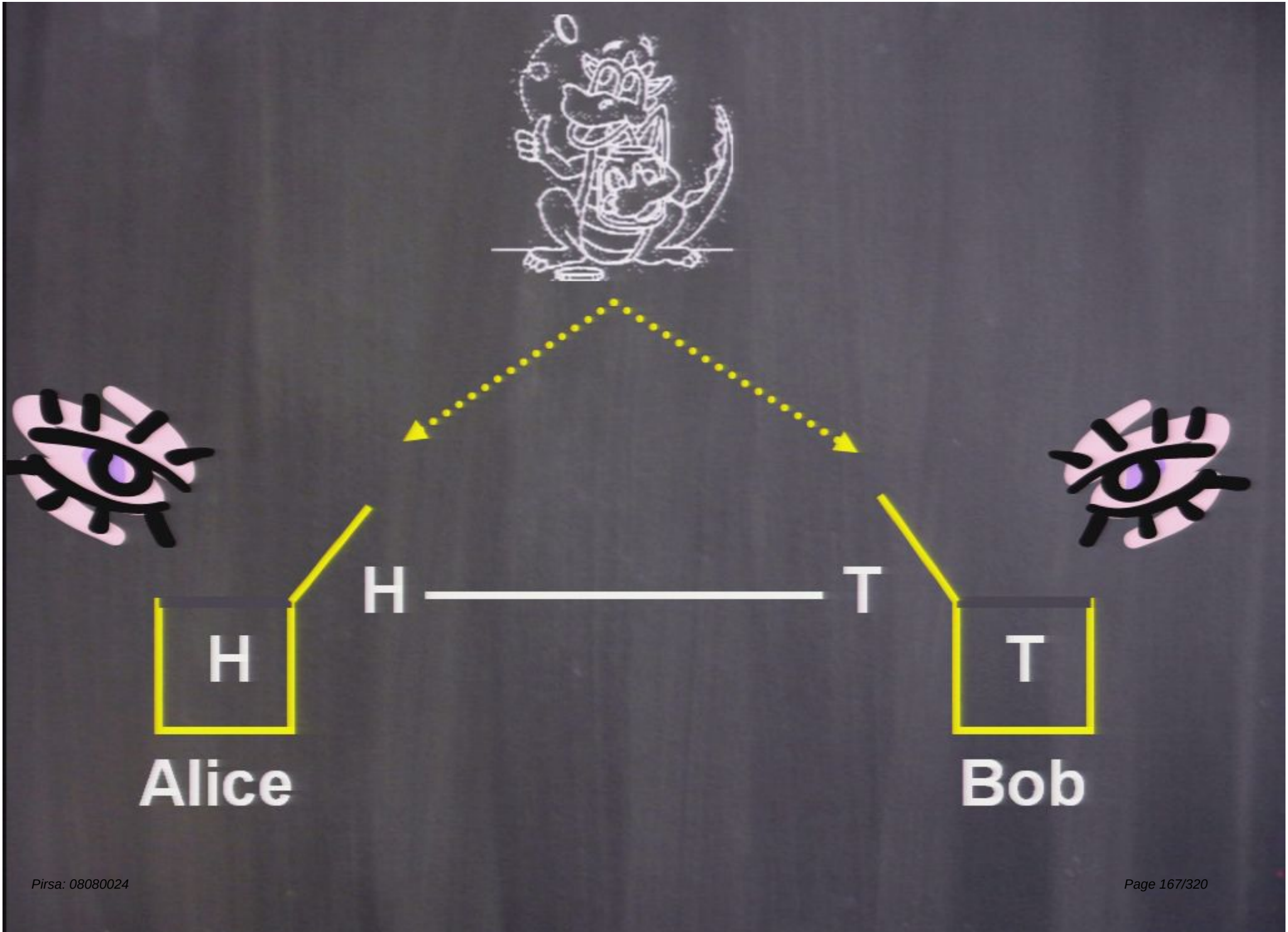
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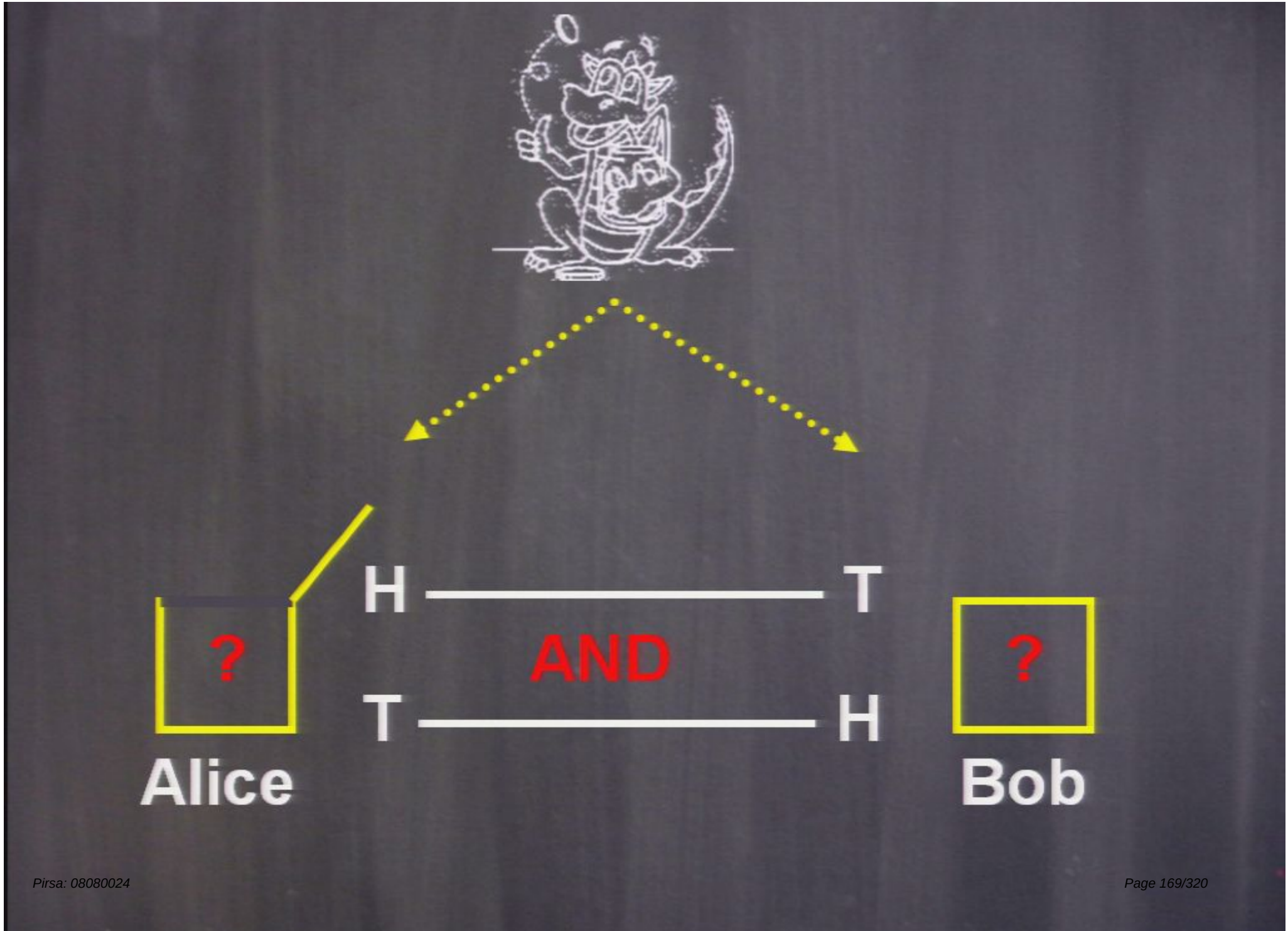
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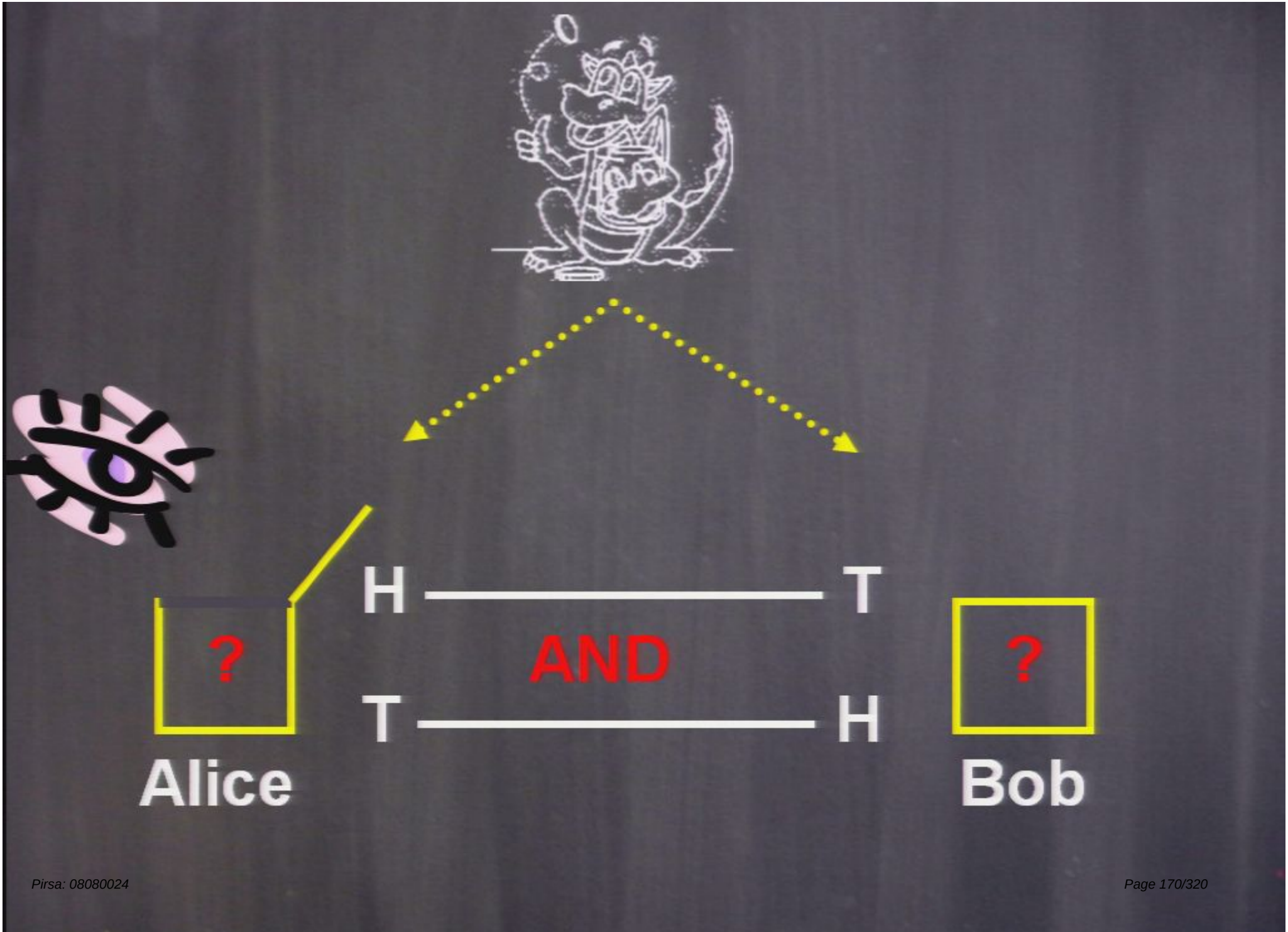
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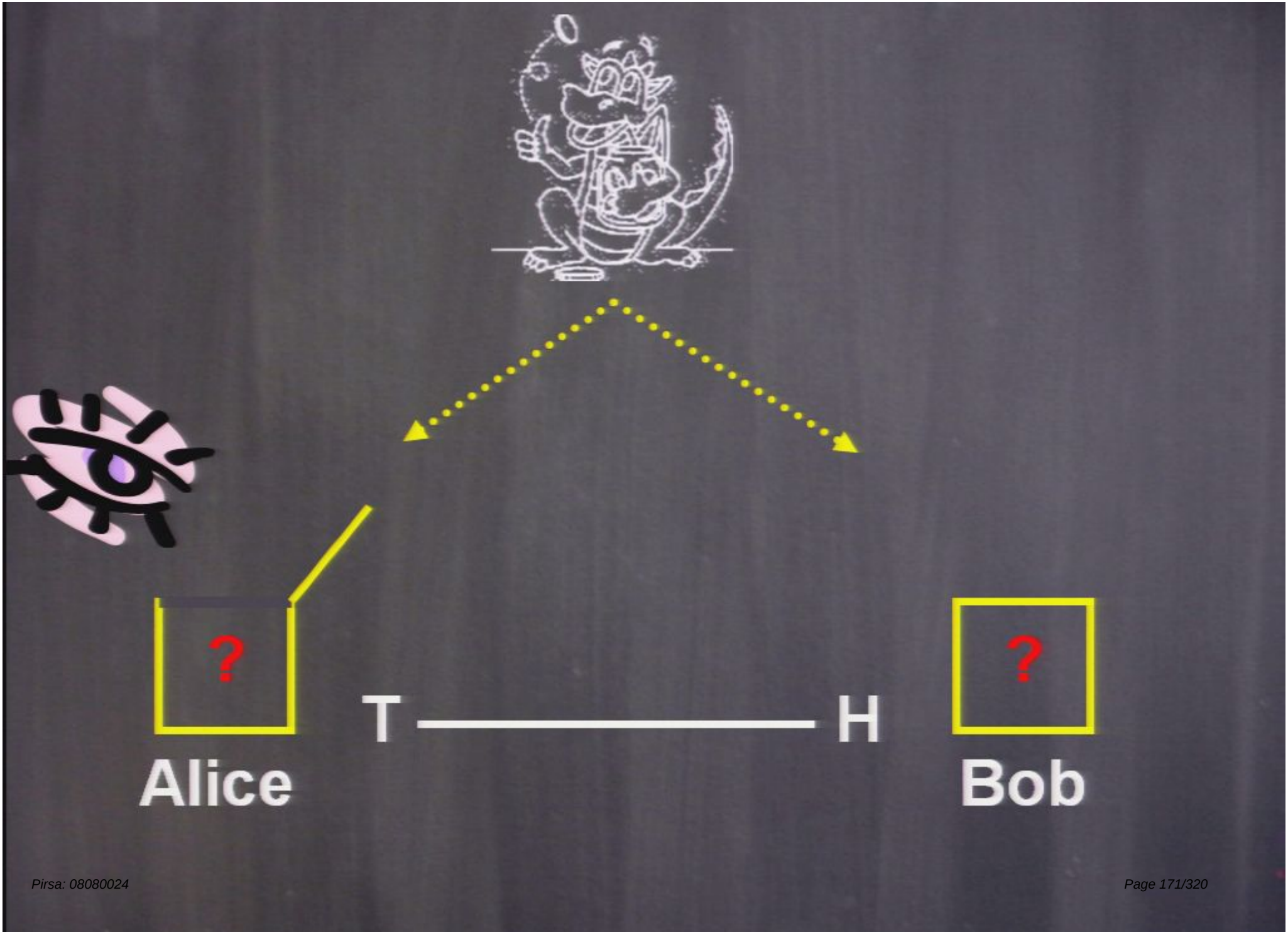
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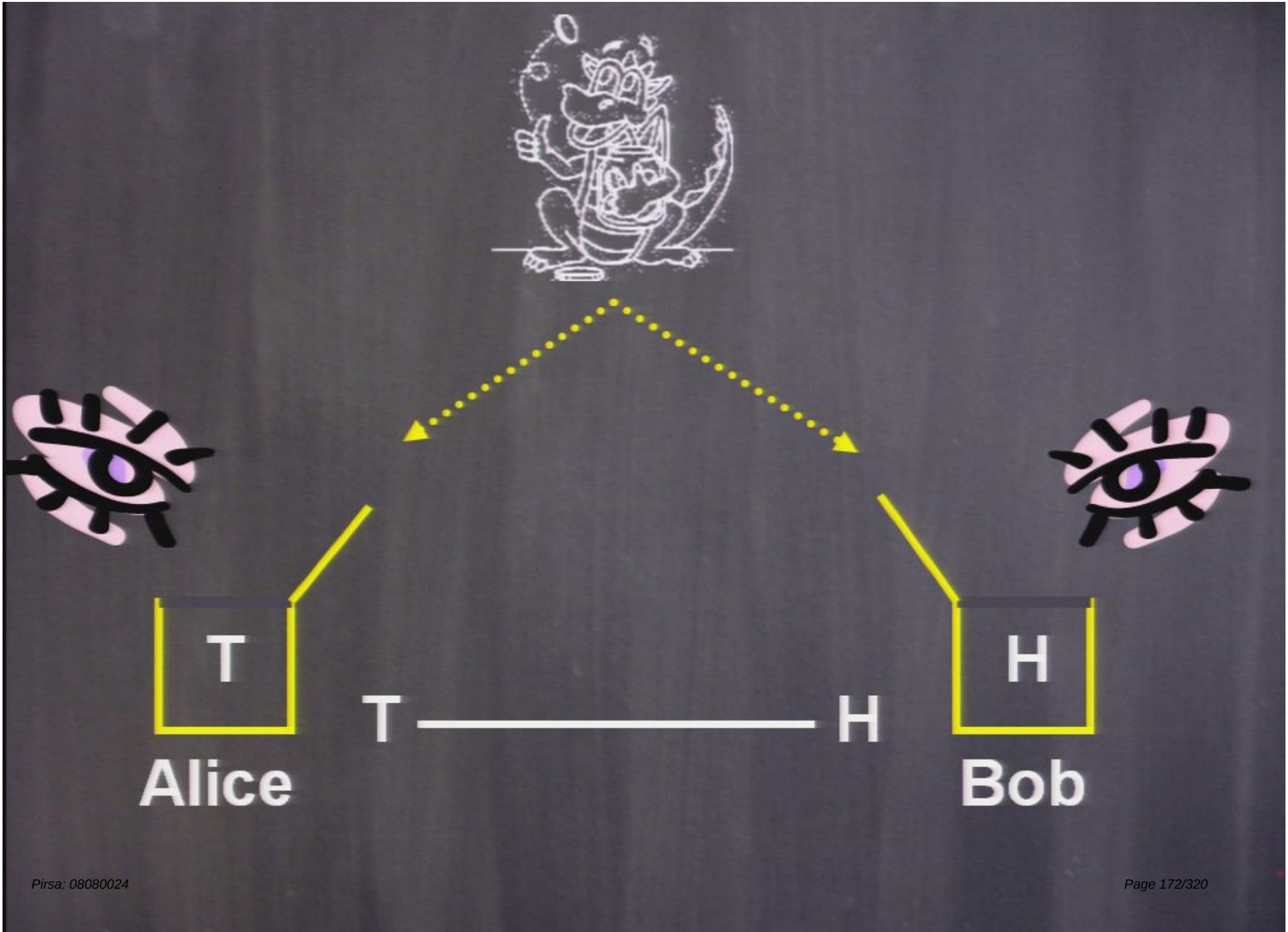
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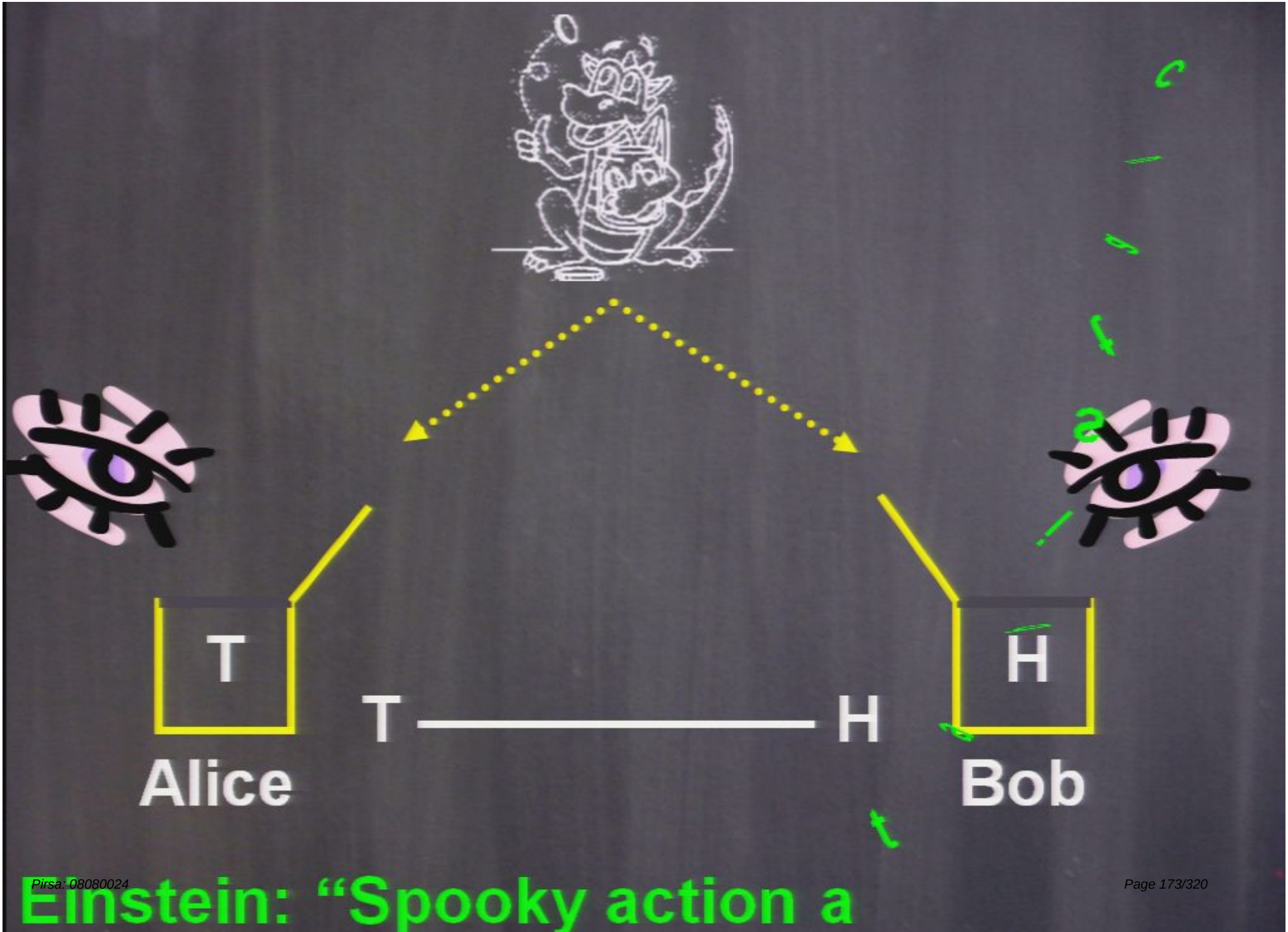
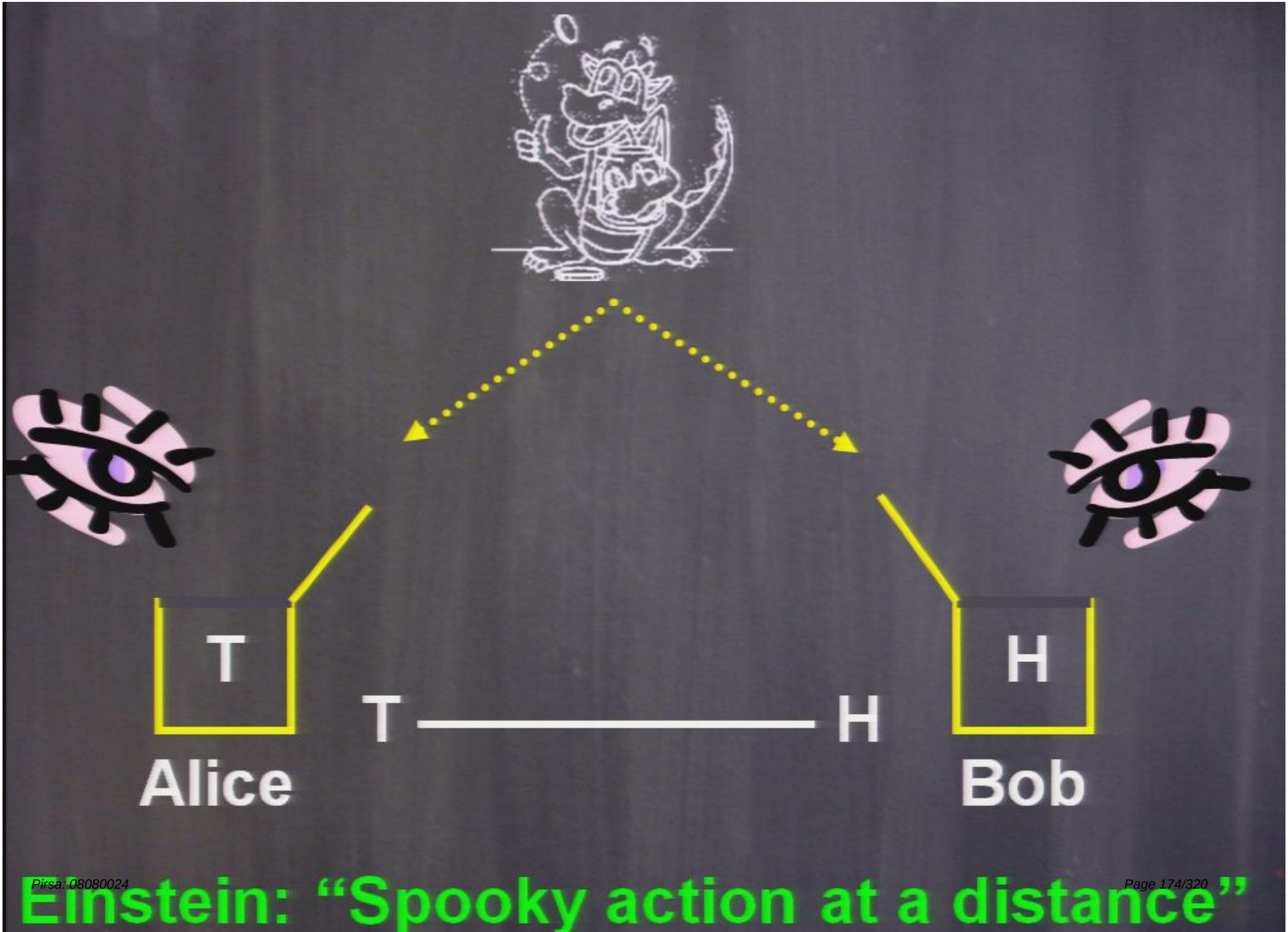
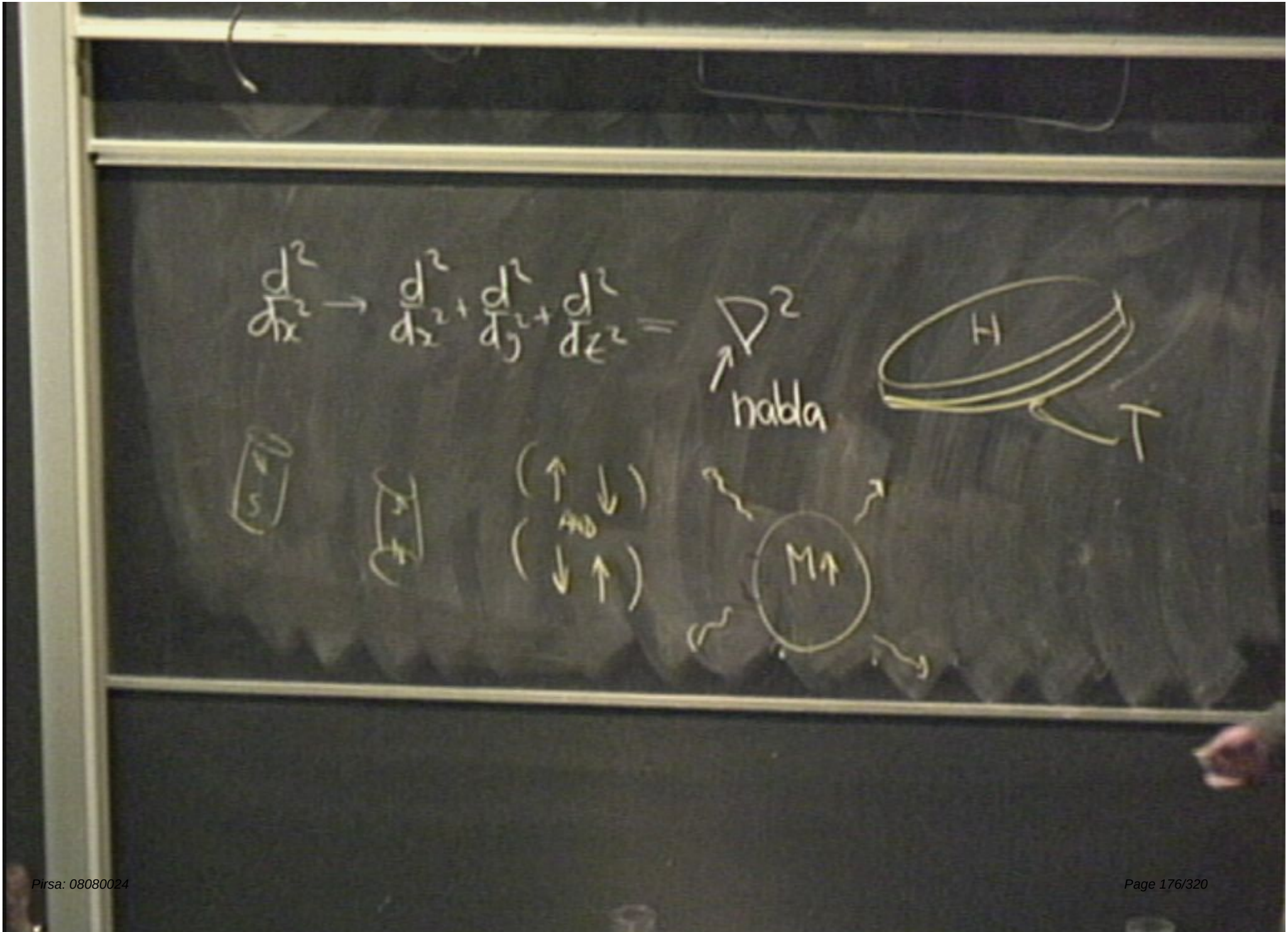


Einstein: “Spooky action a



Einstein: "Spooky action at a distance"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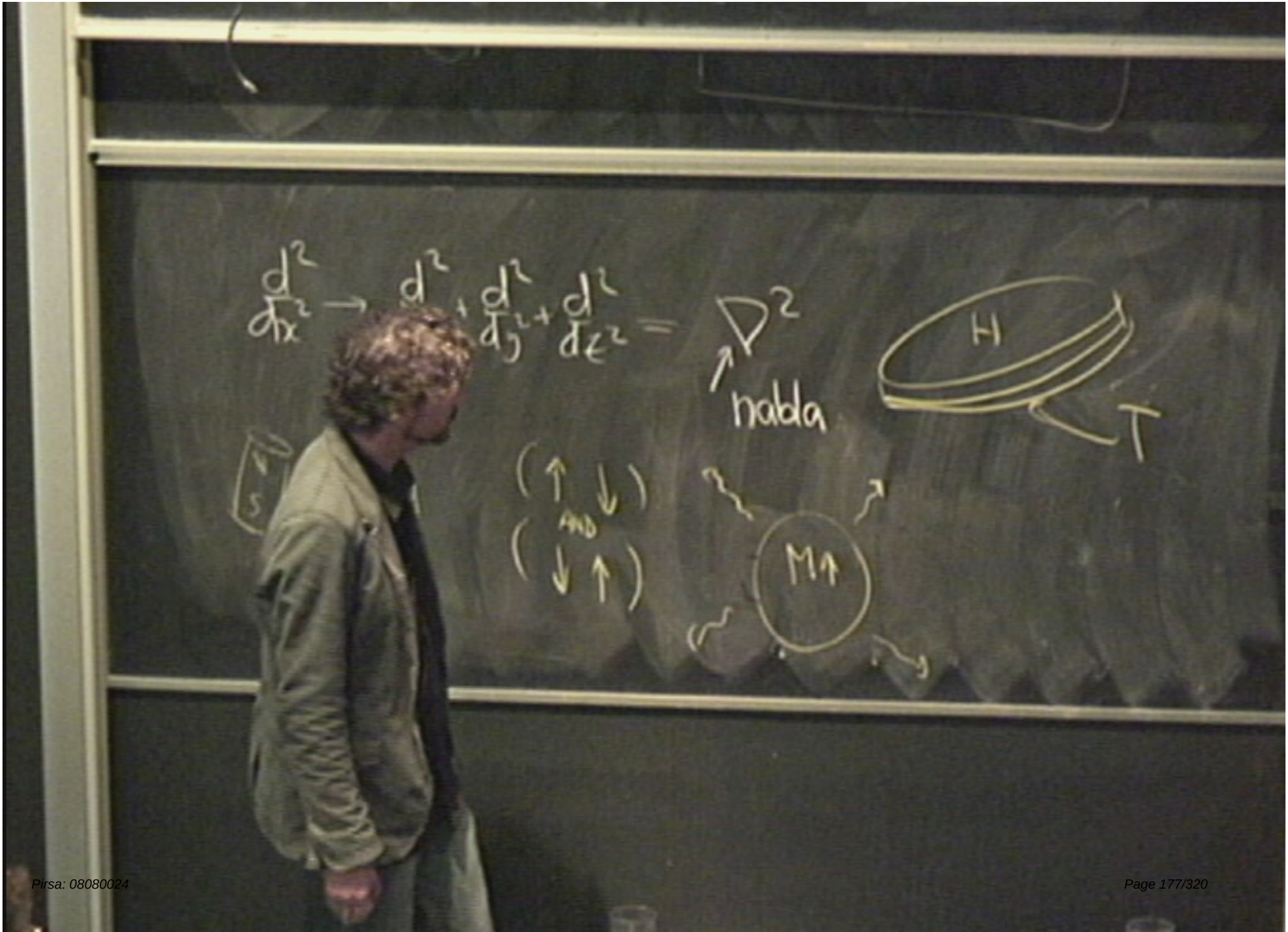
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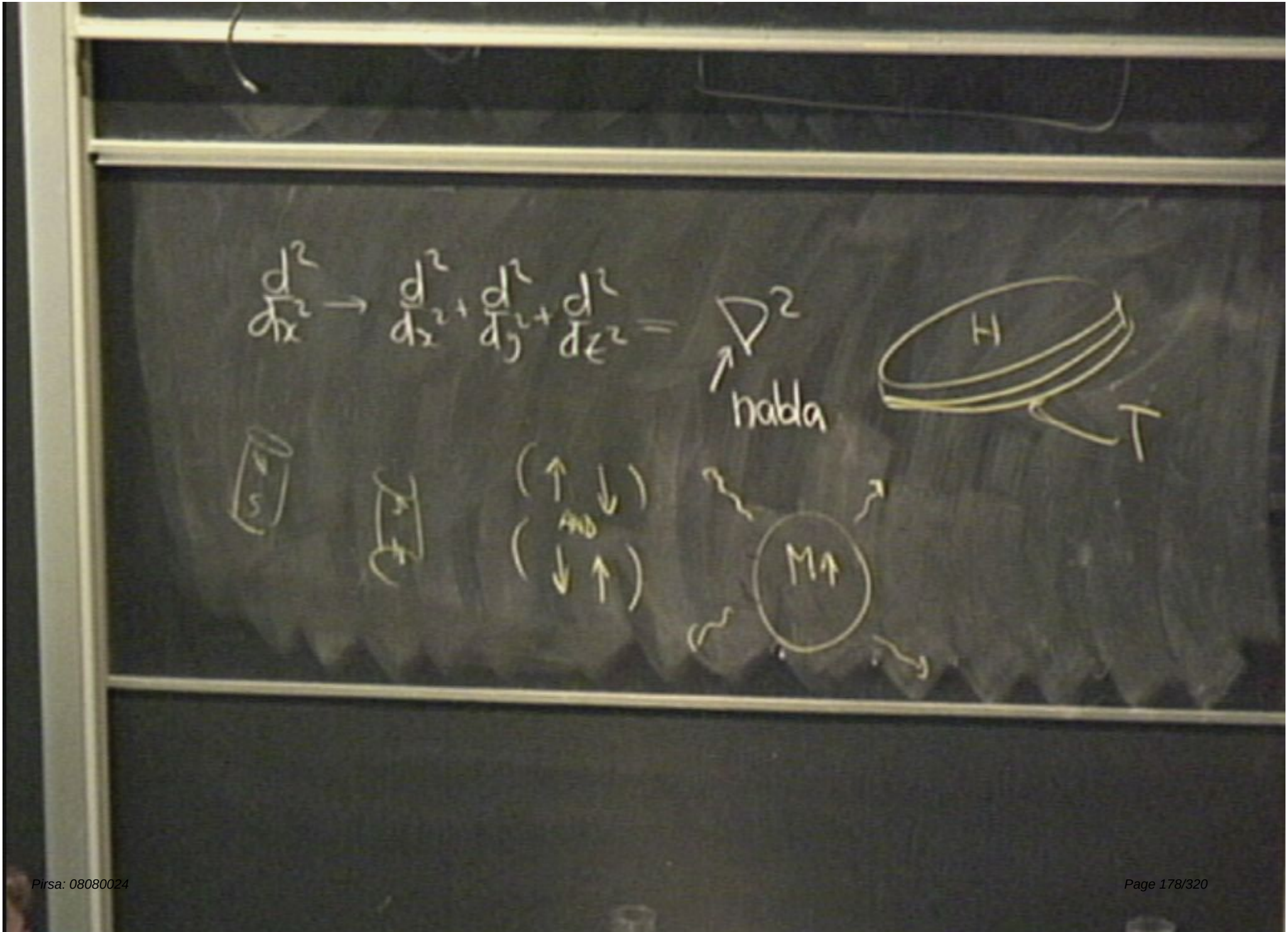
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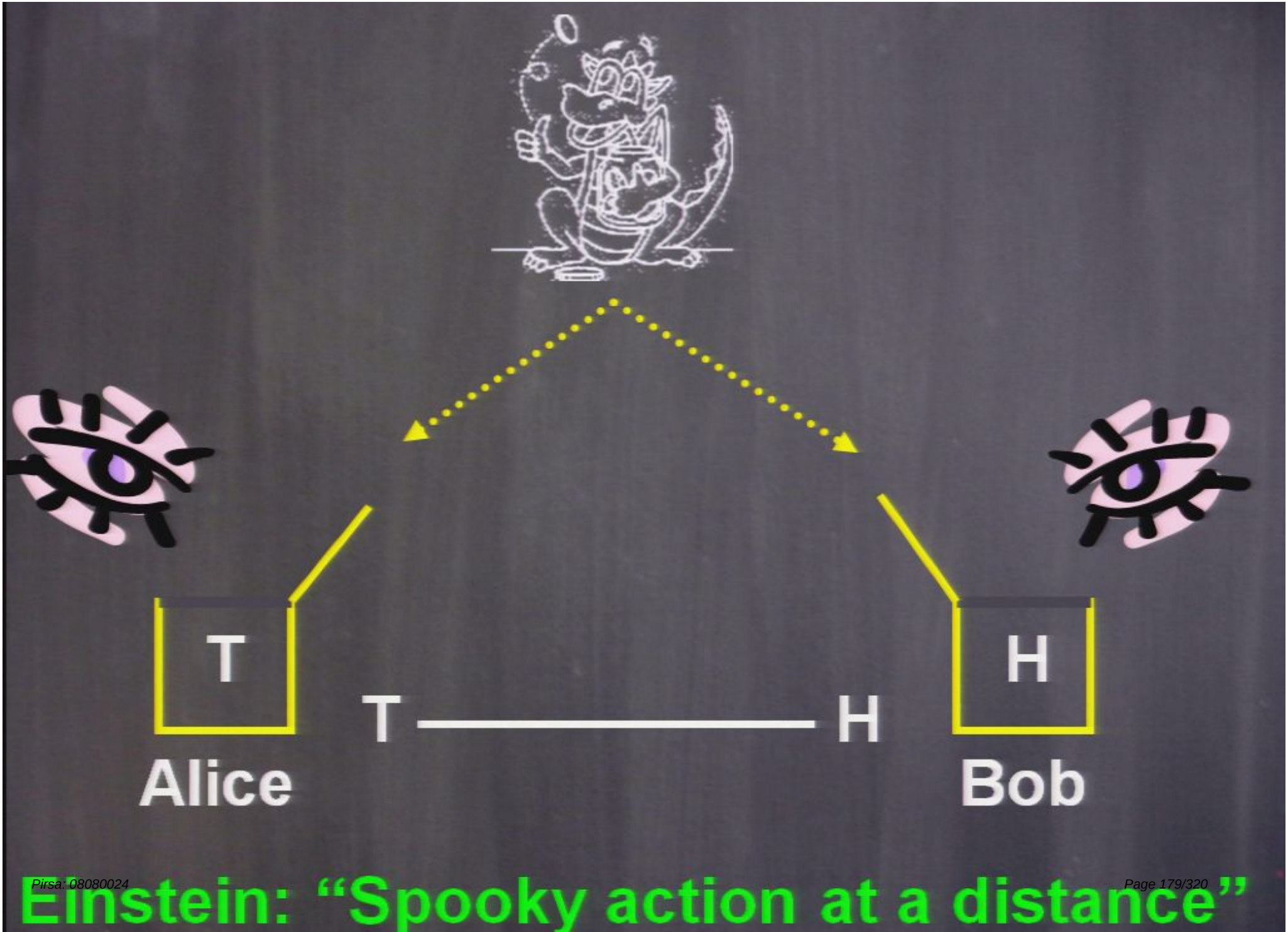
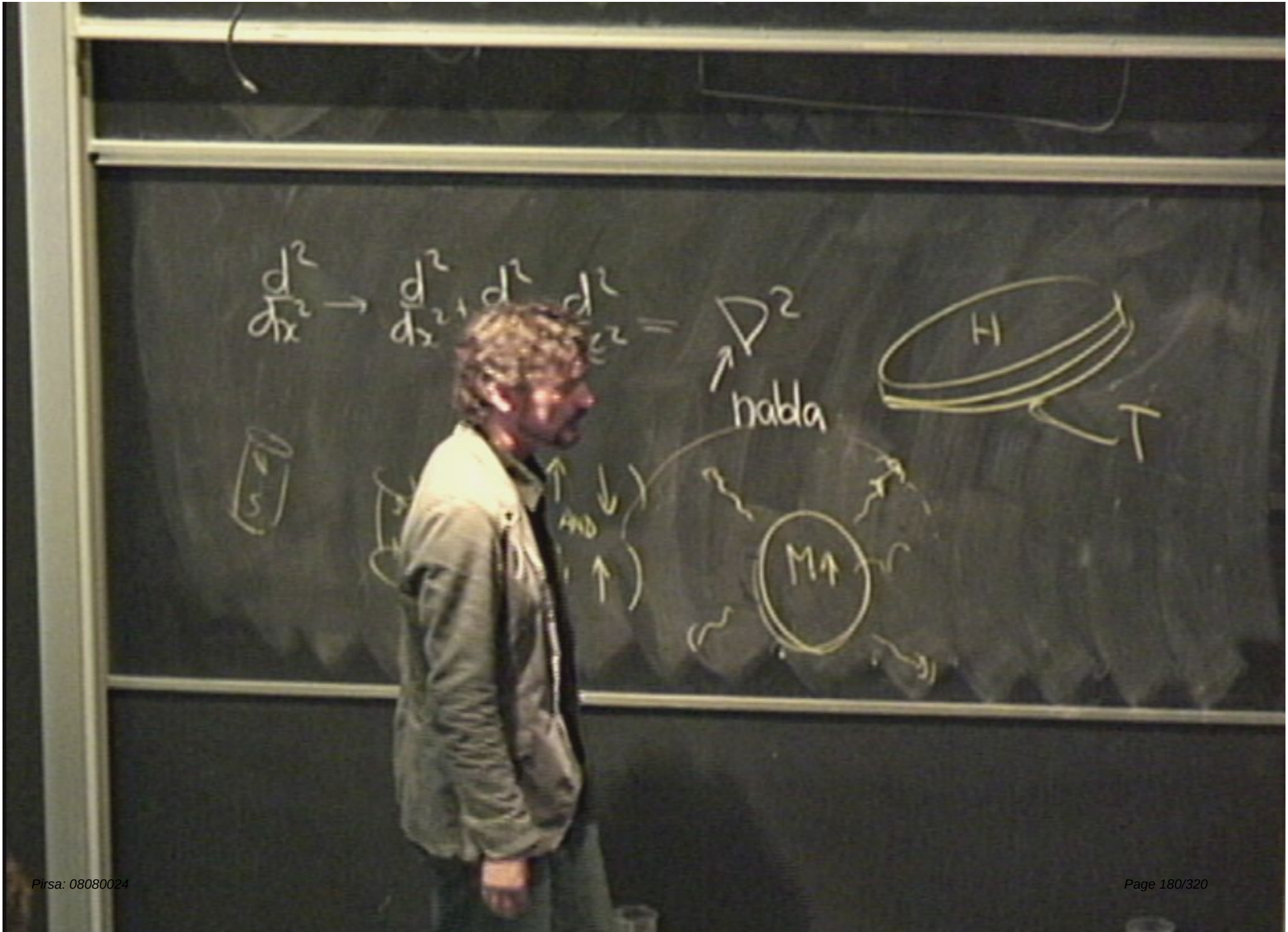


Einstein: “Spooky action at a distance”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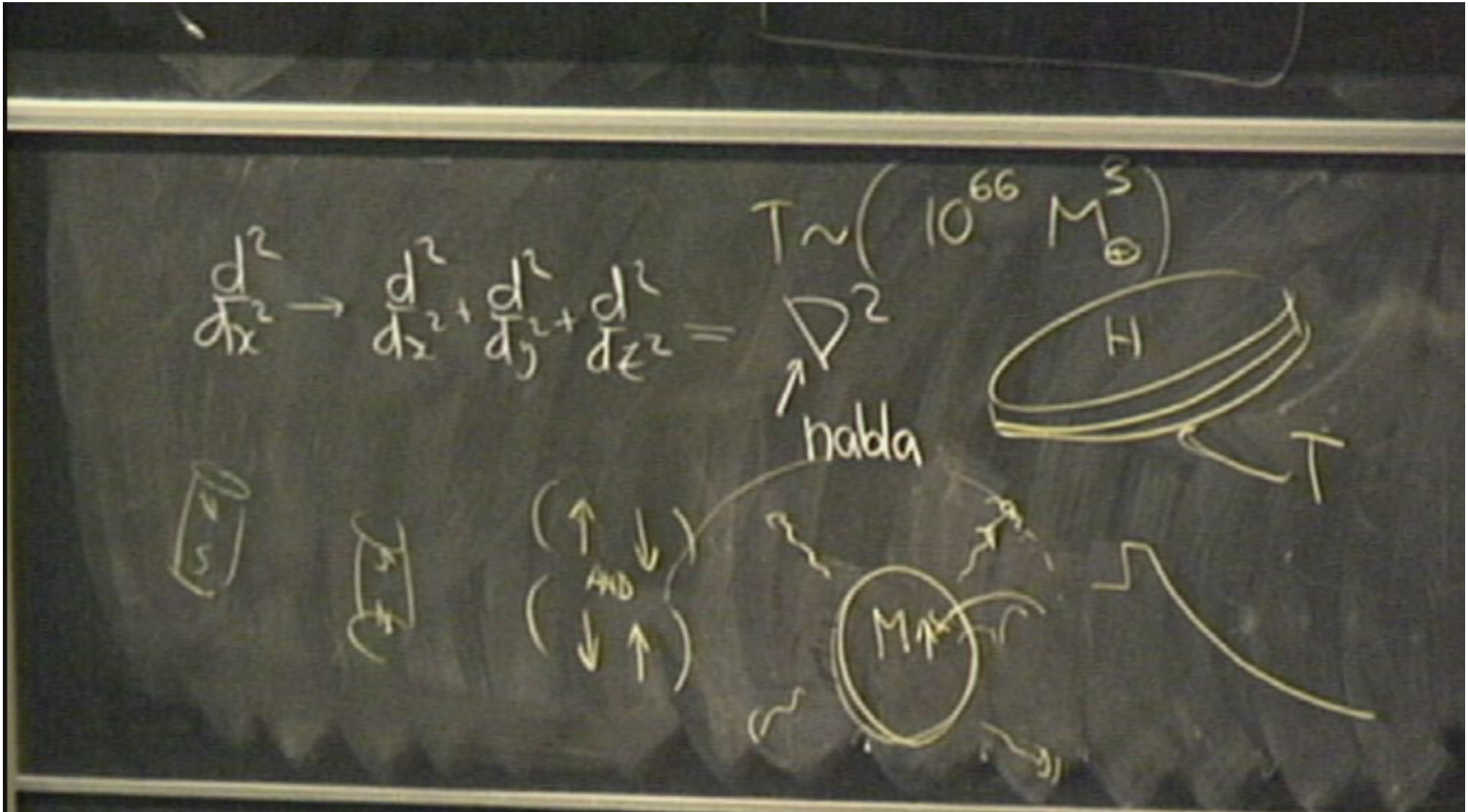
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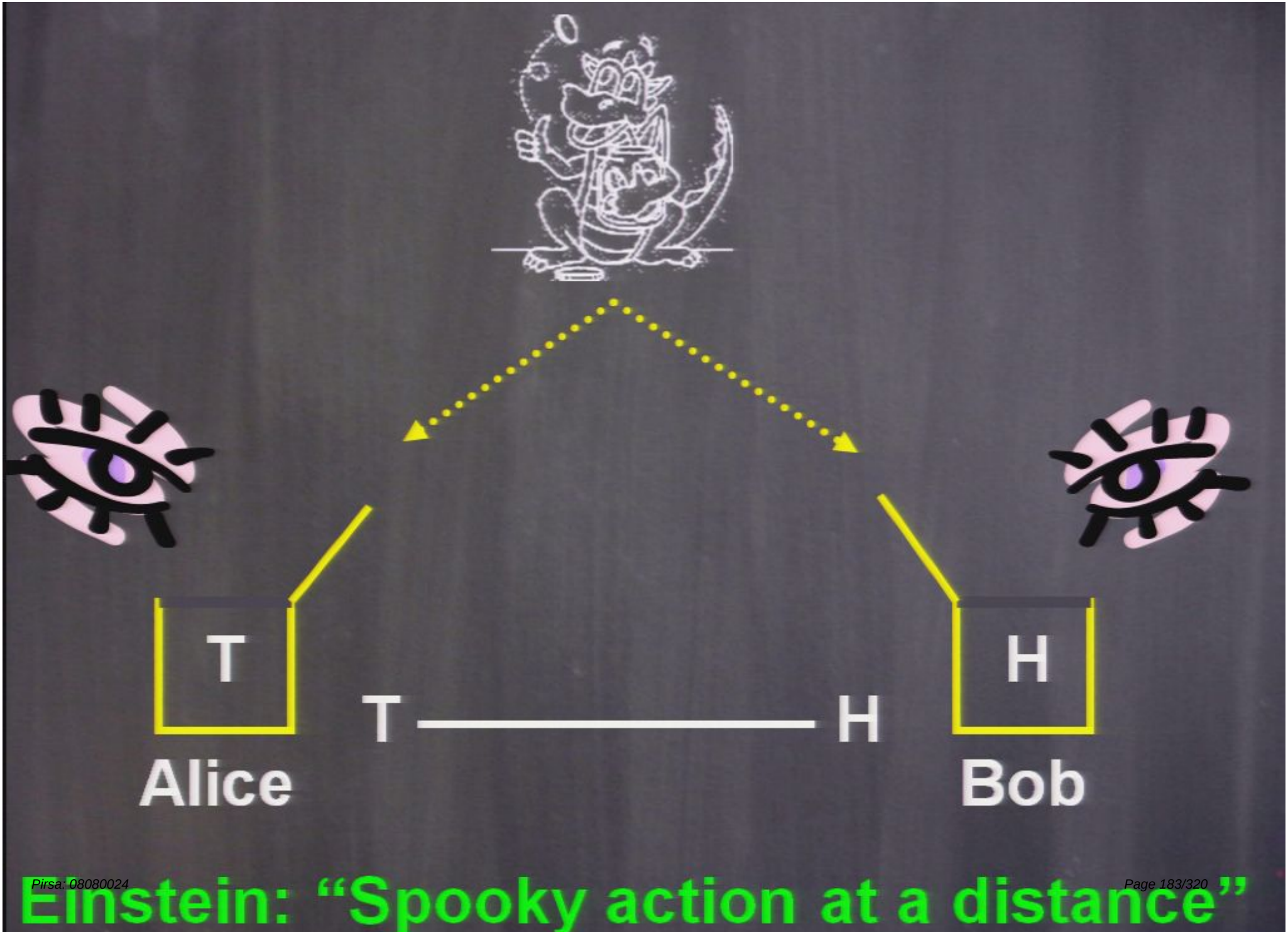

Einstein: "Spooky action at a distance"

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Quantum Teleportation

...A Love Story

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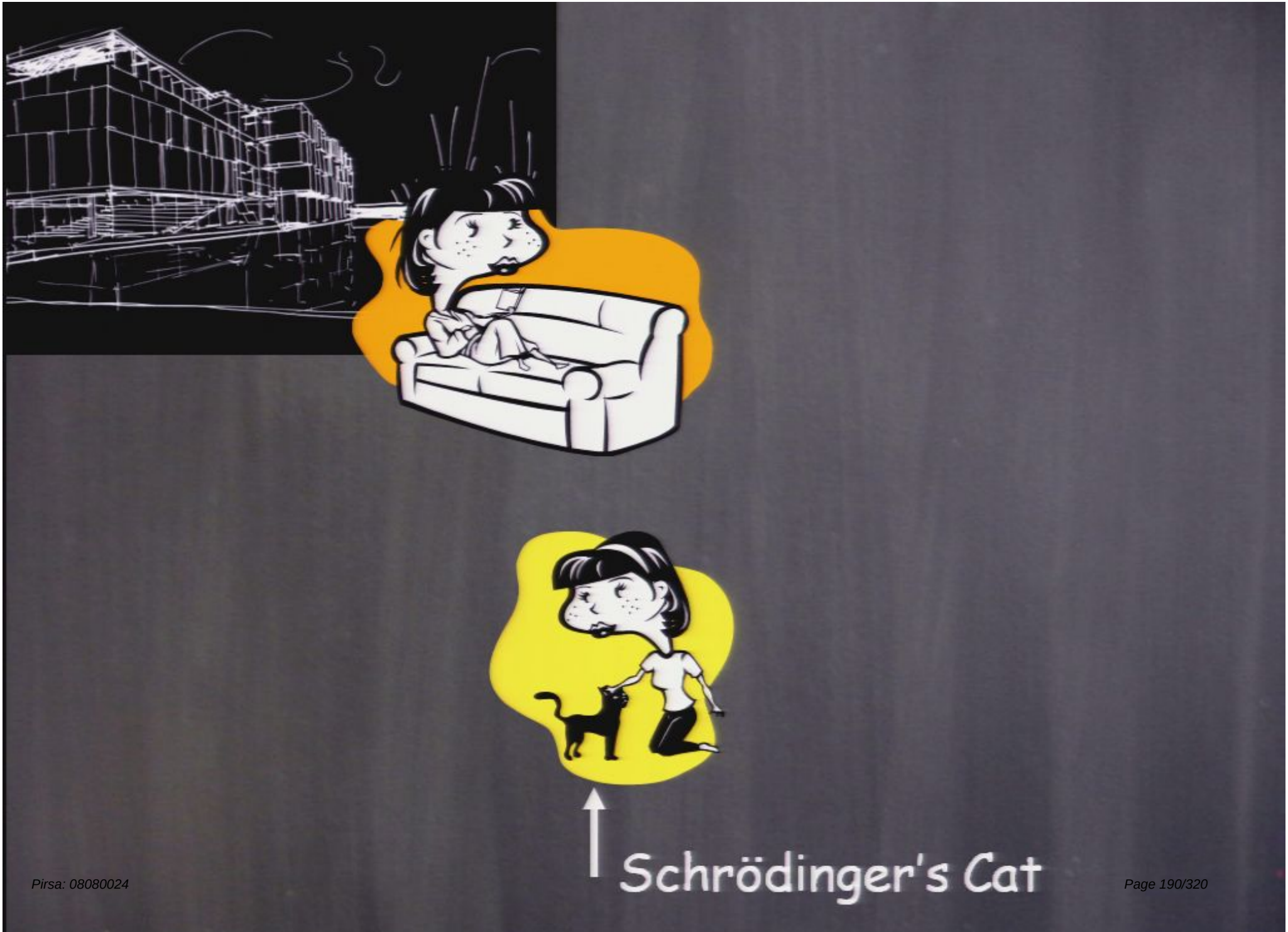
Schrödinger's Cat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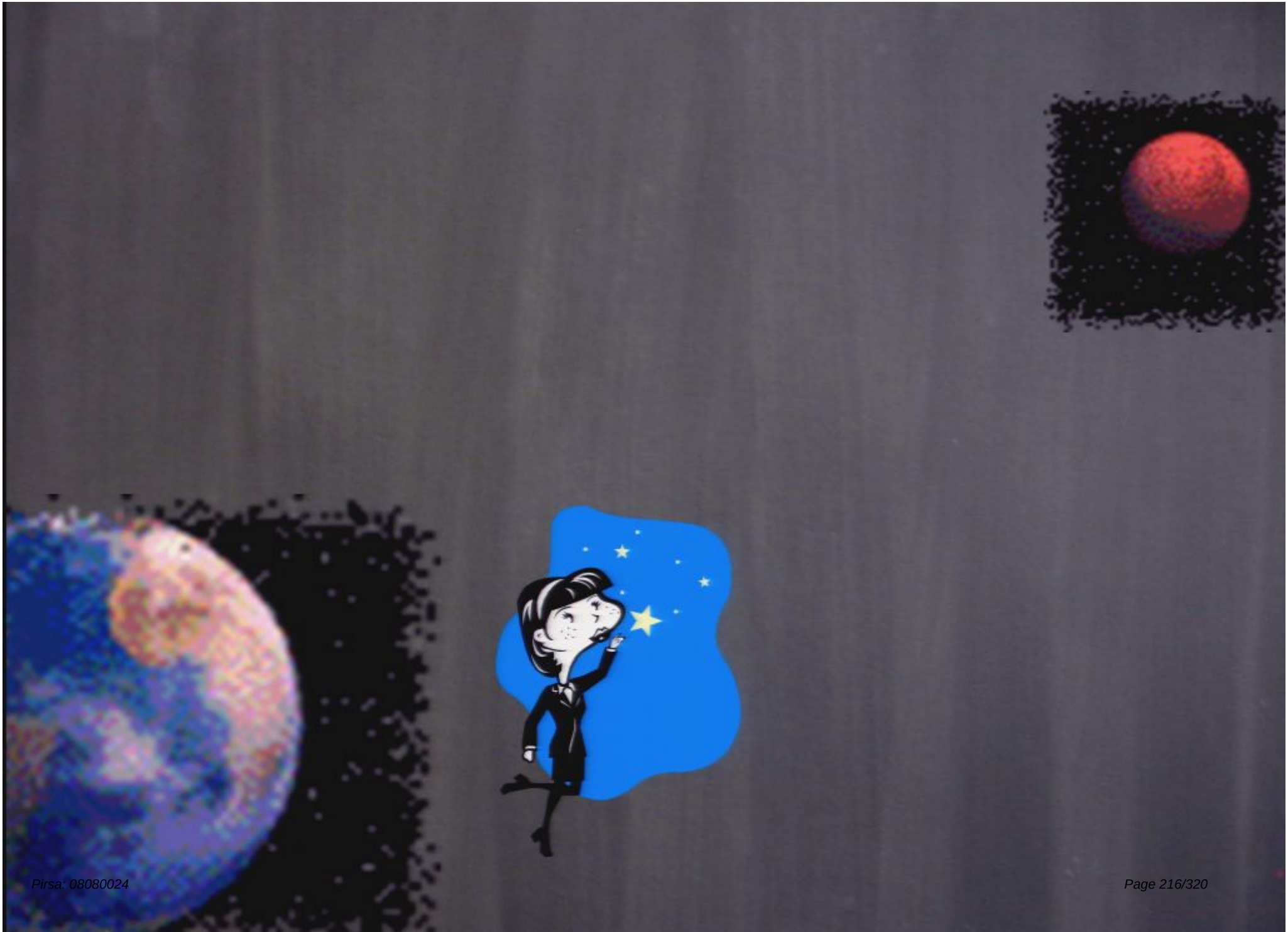

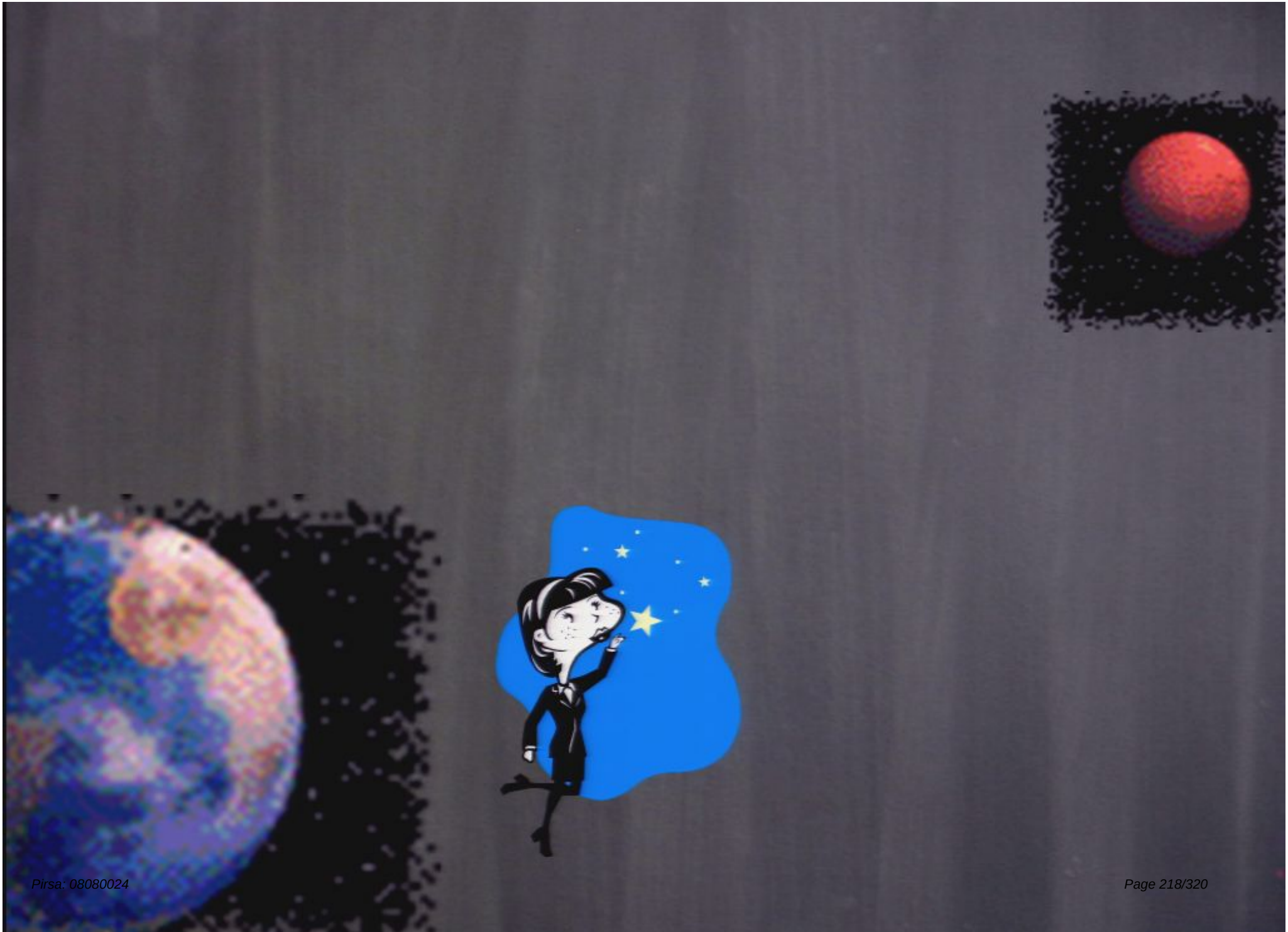

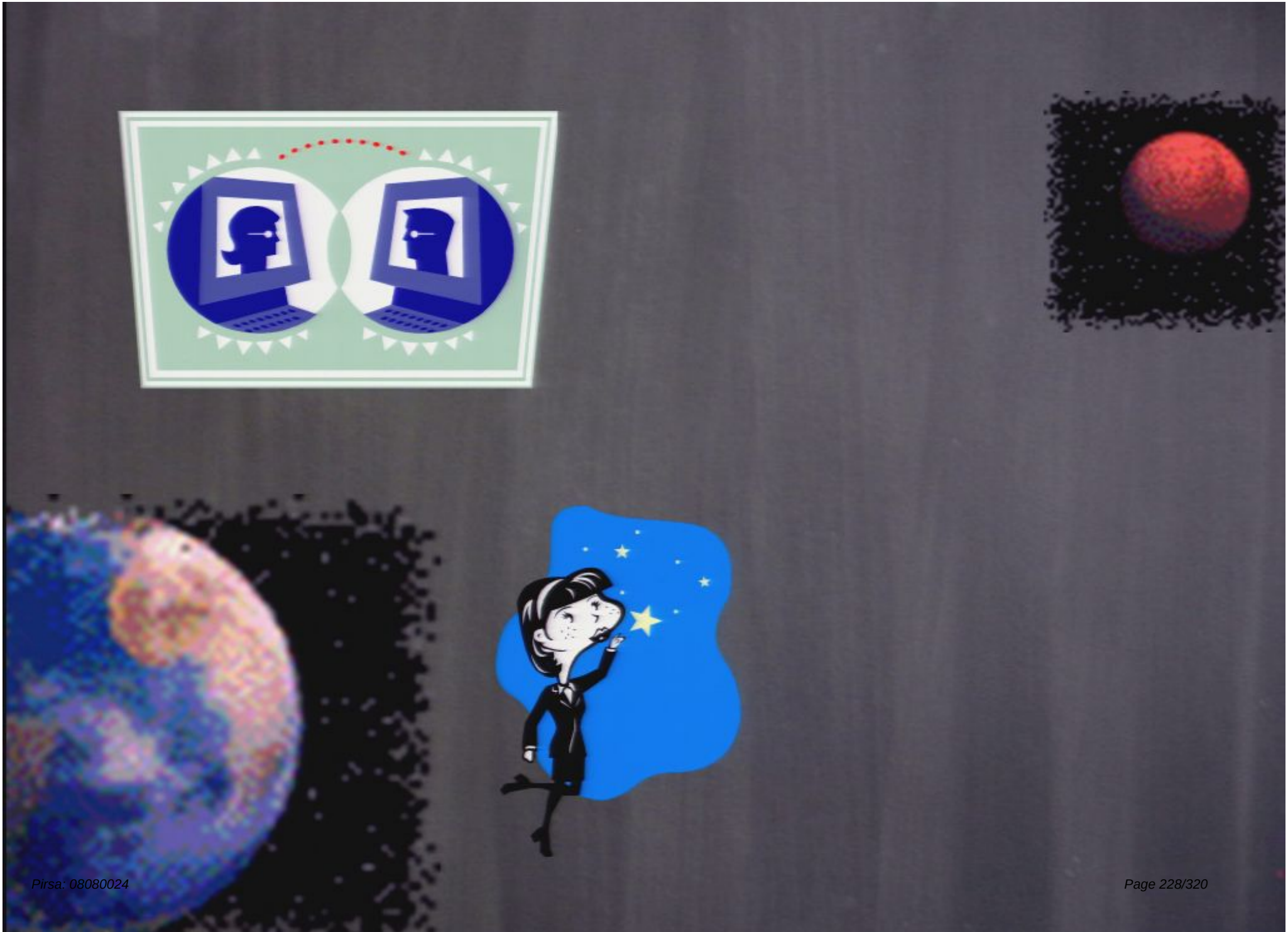

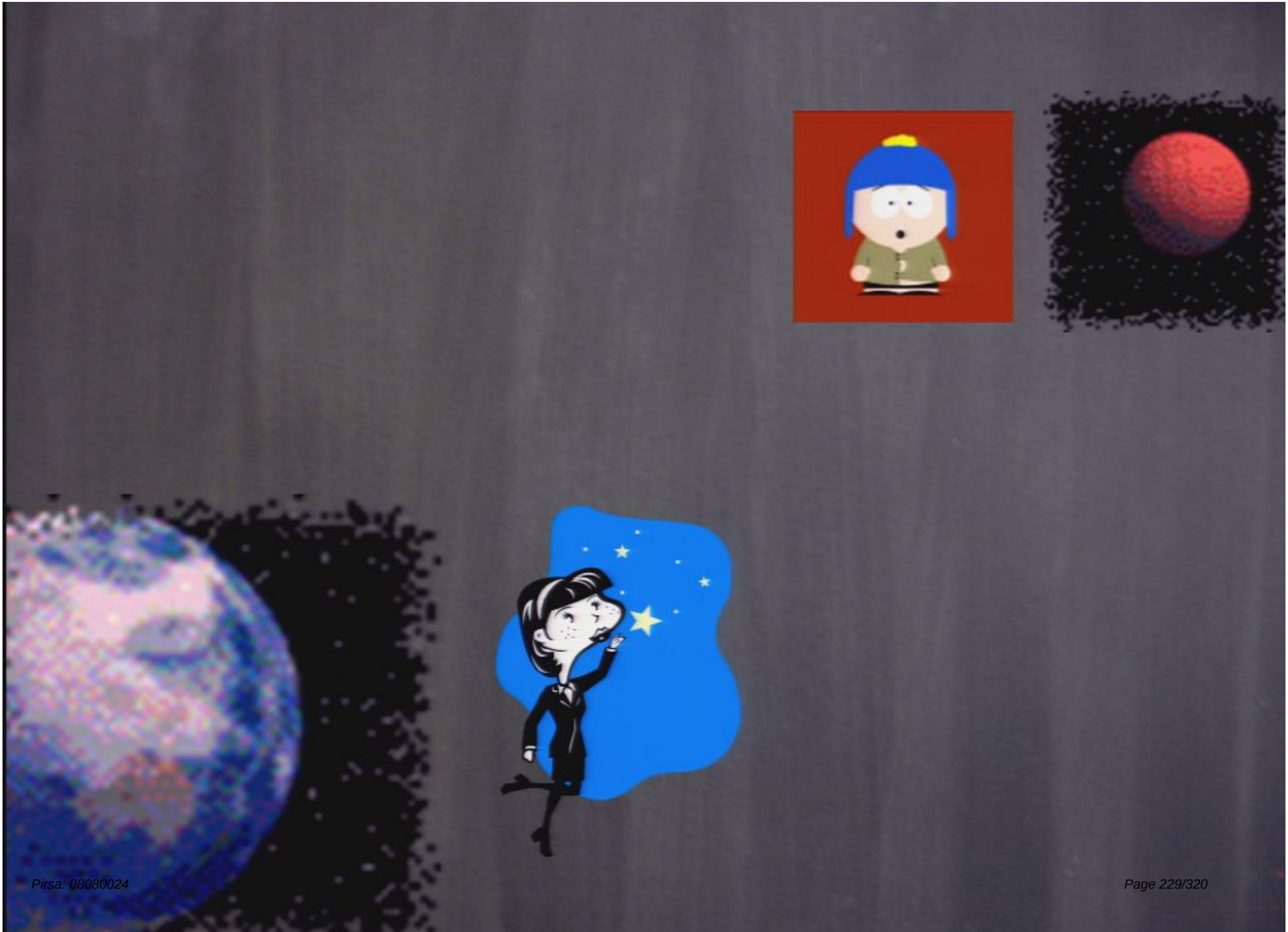

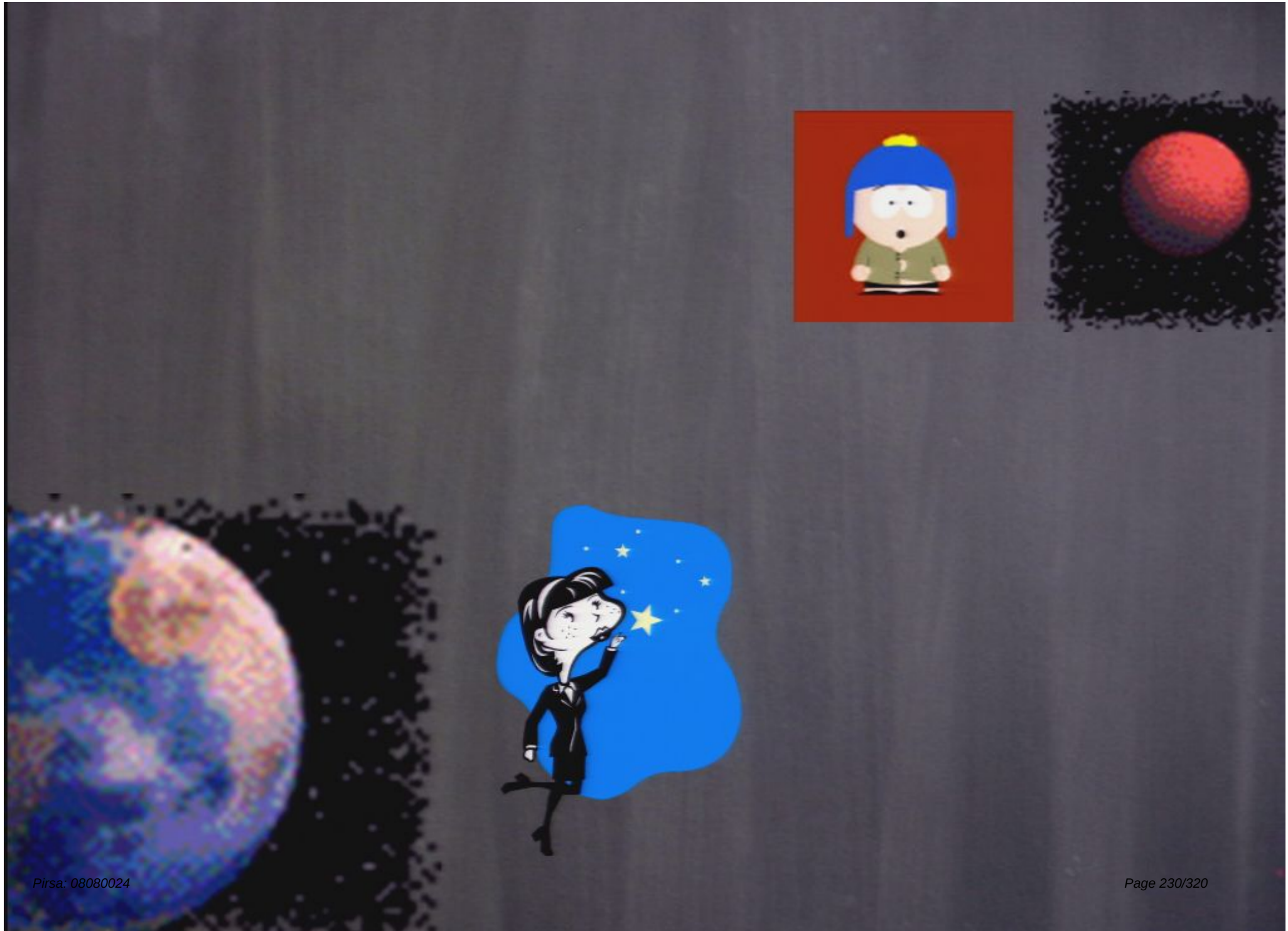

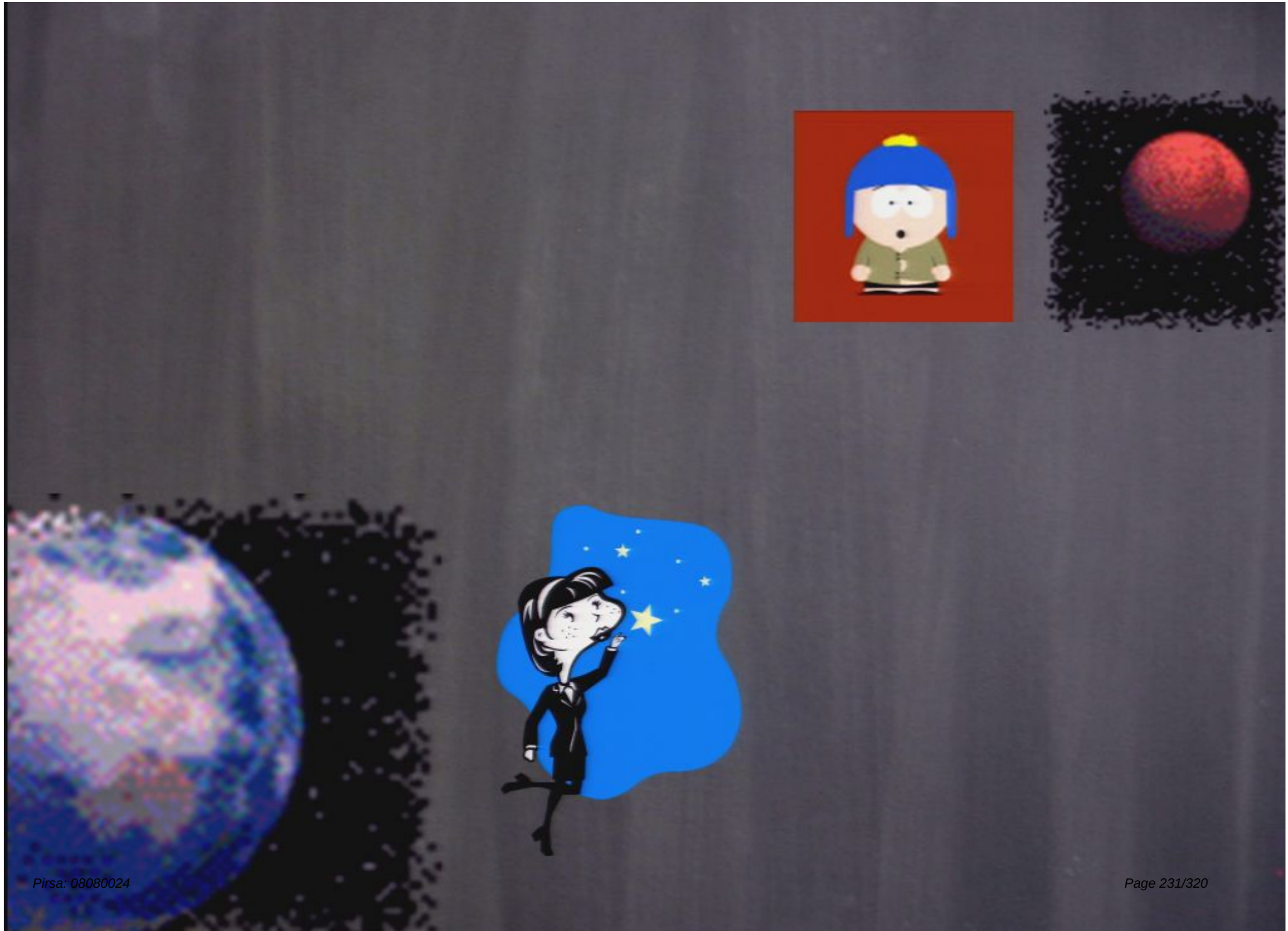

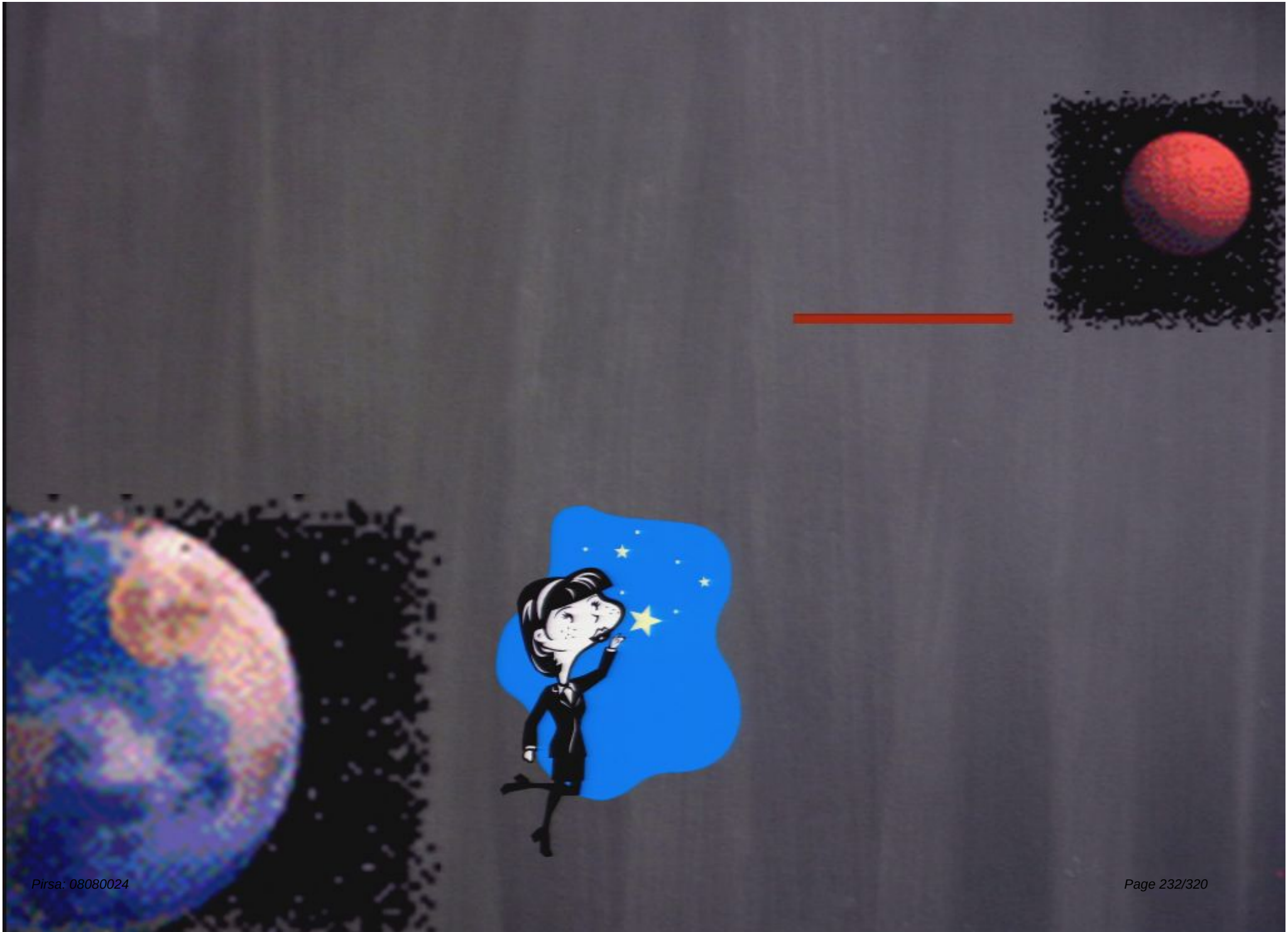

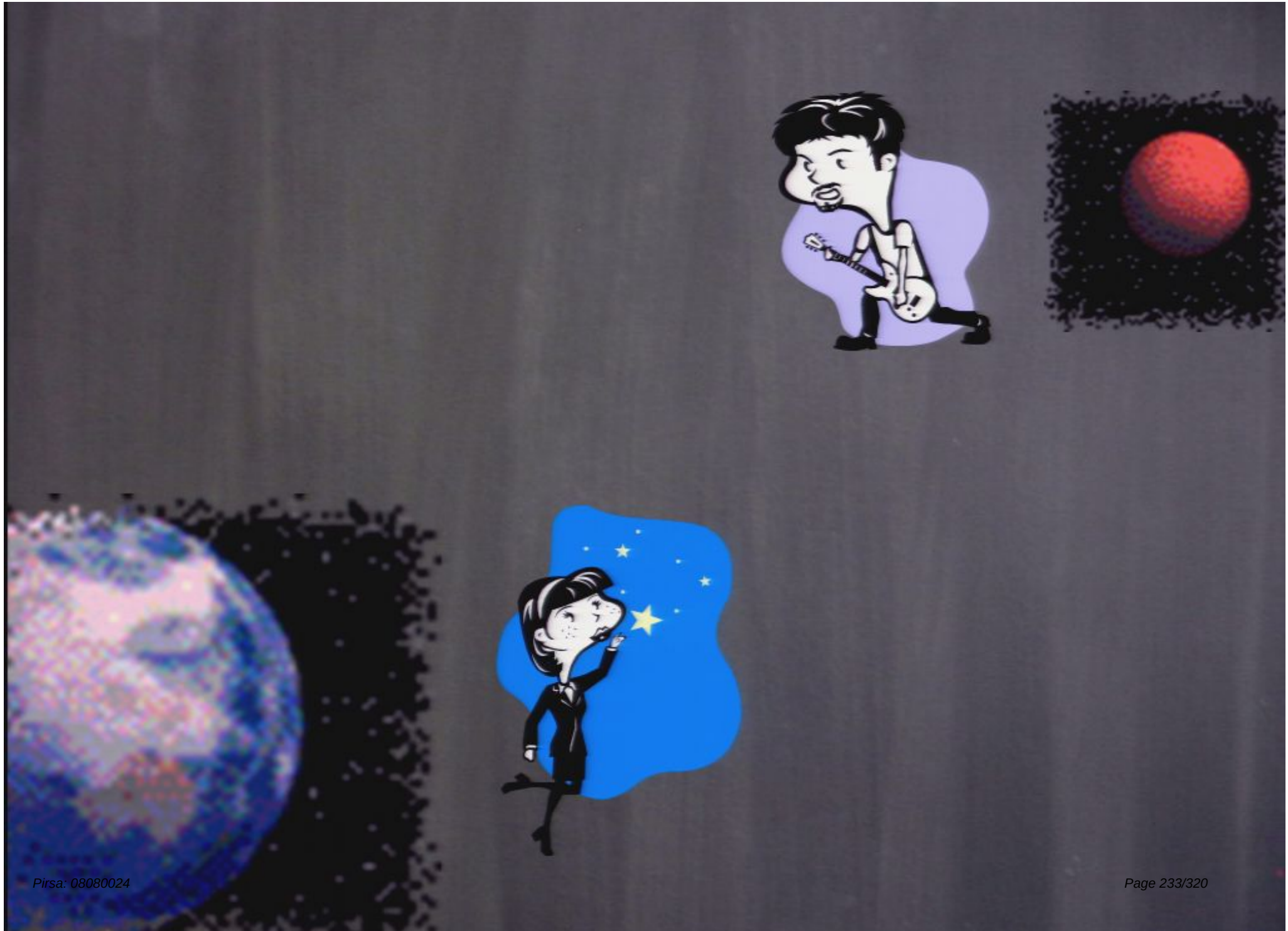

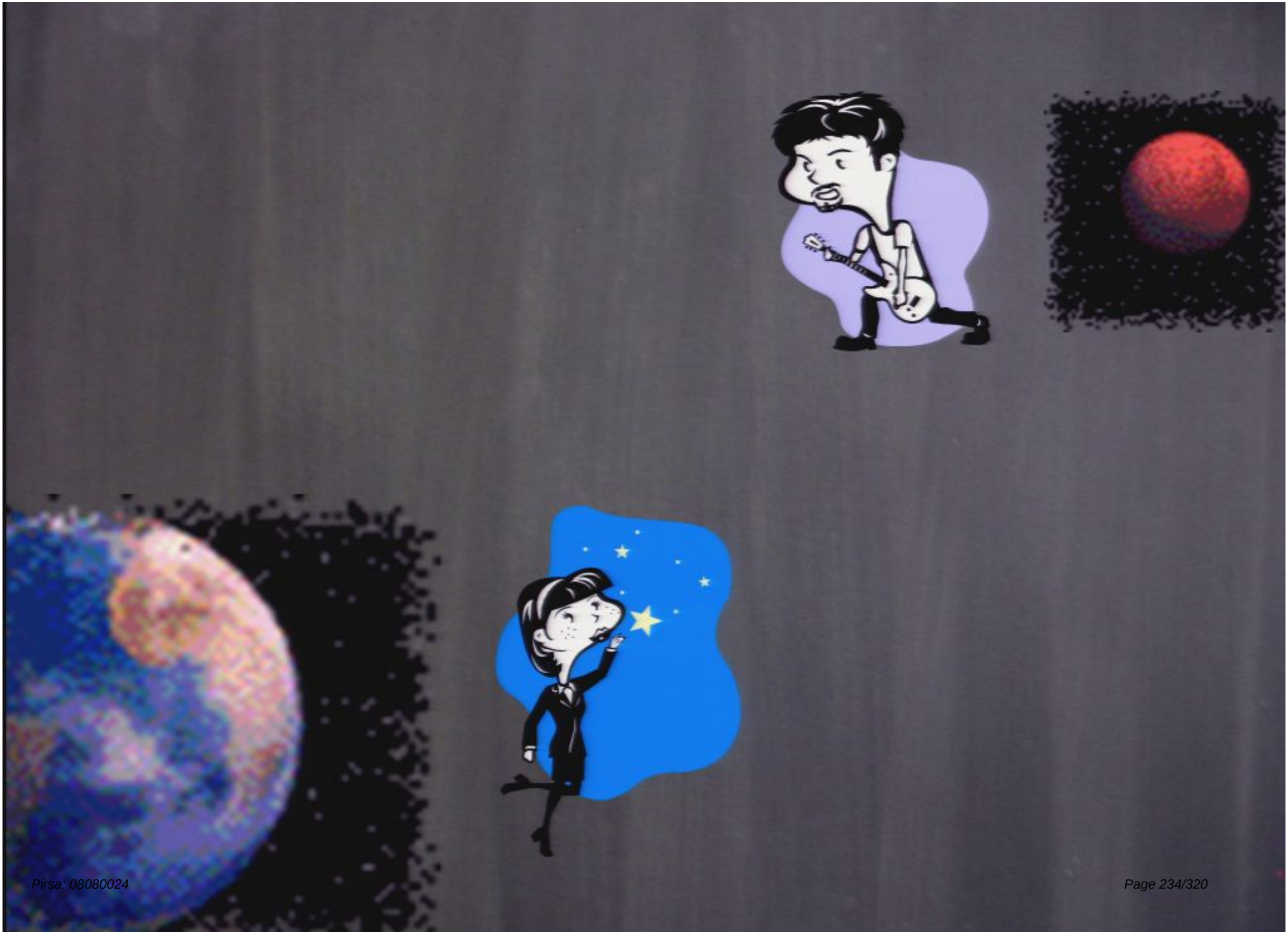

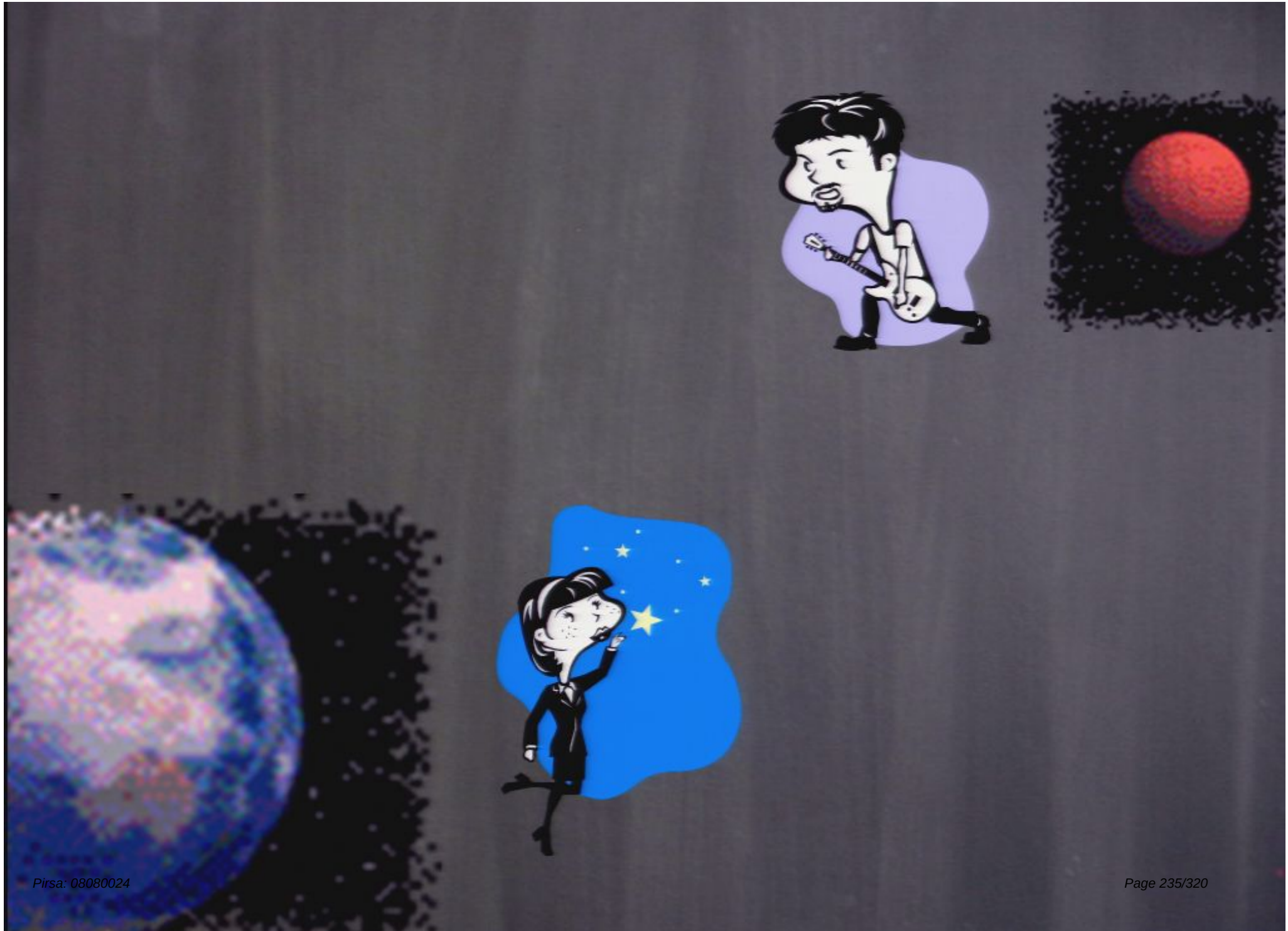

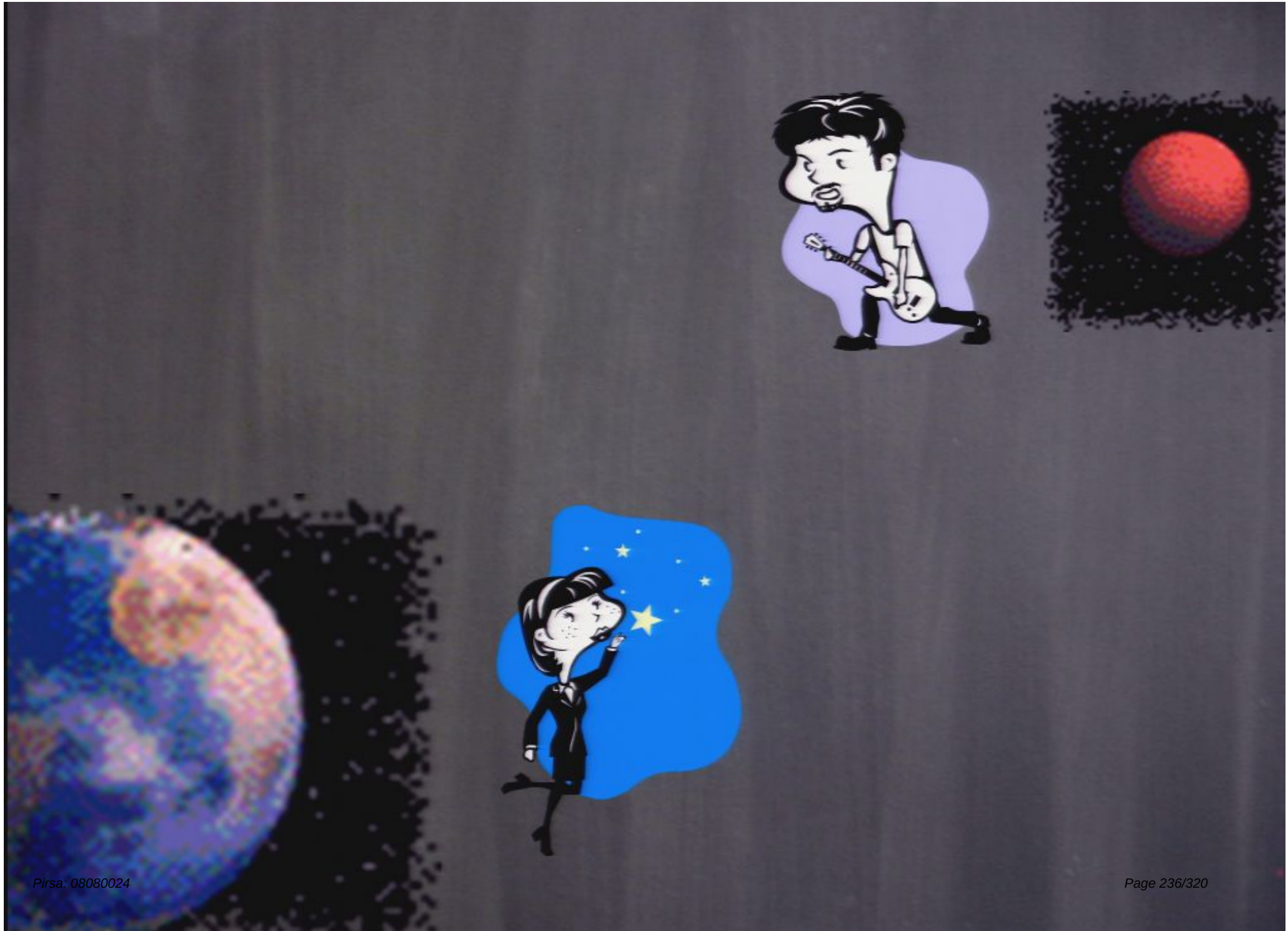

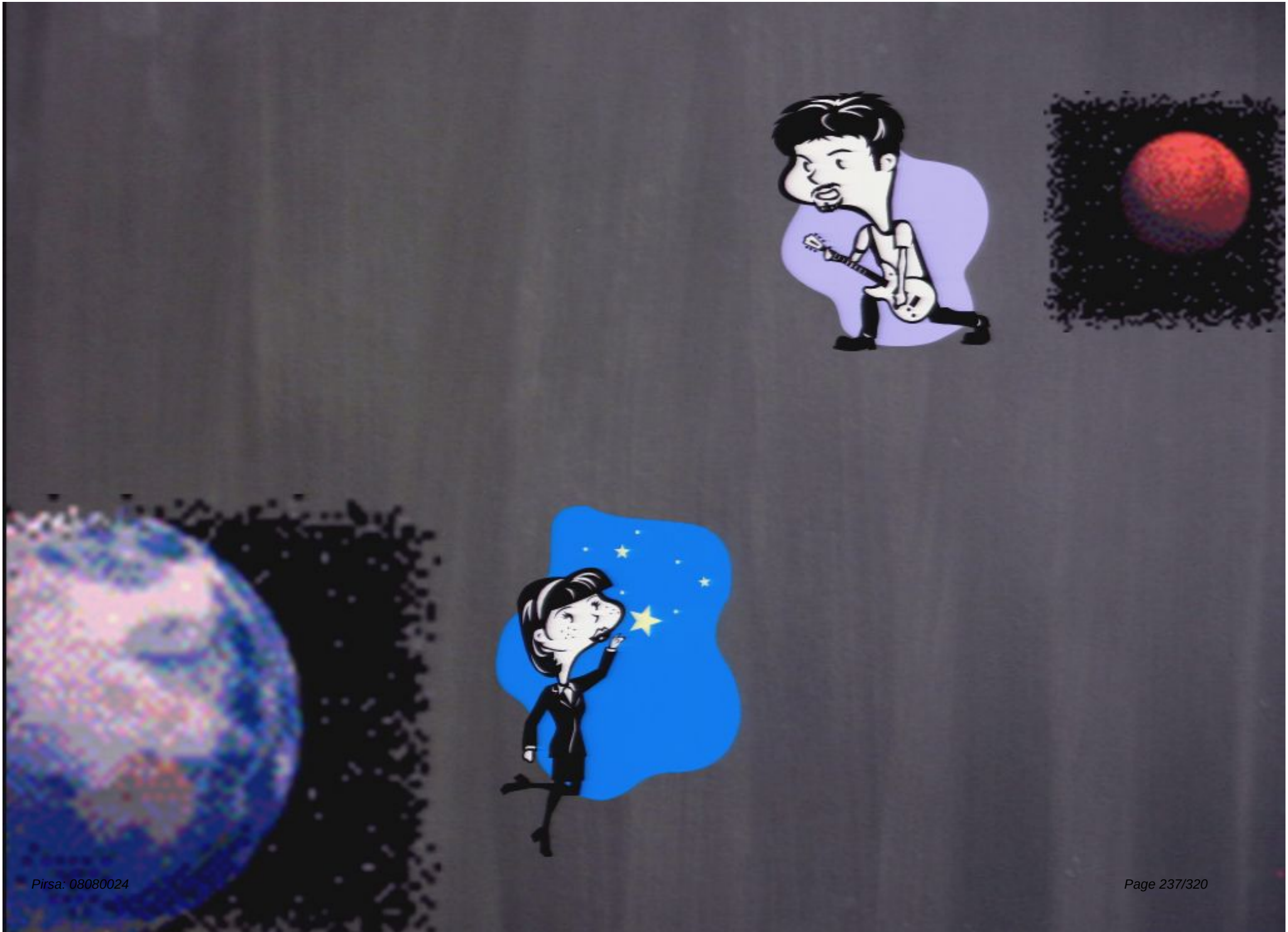

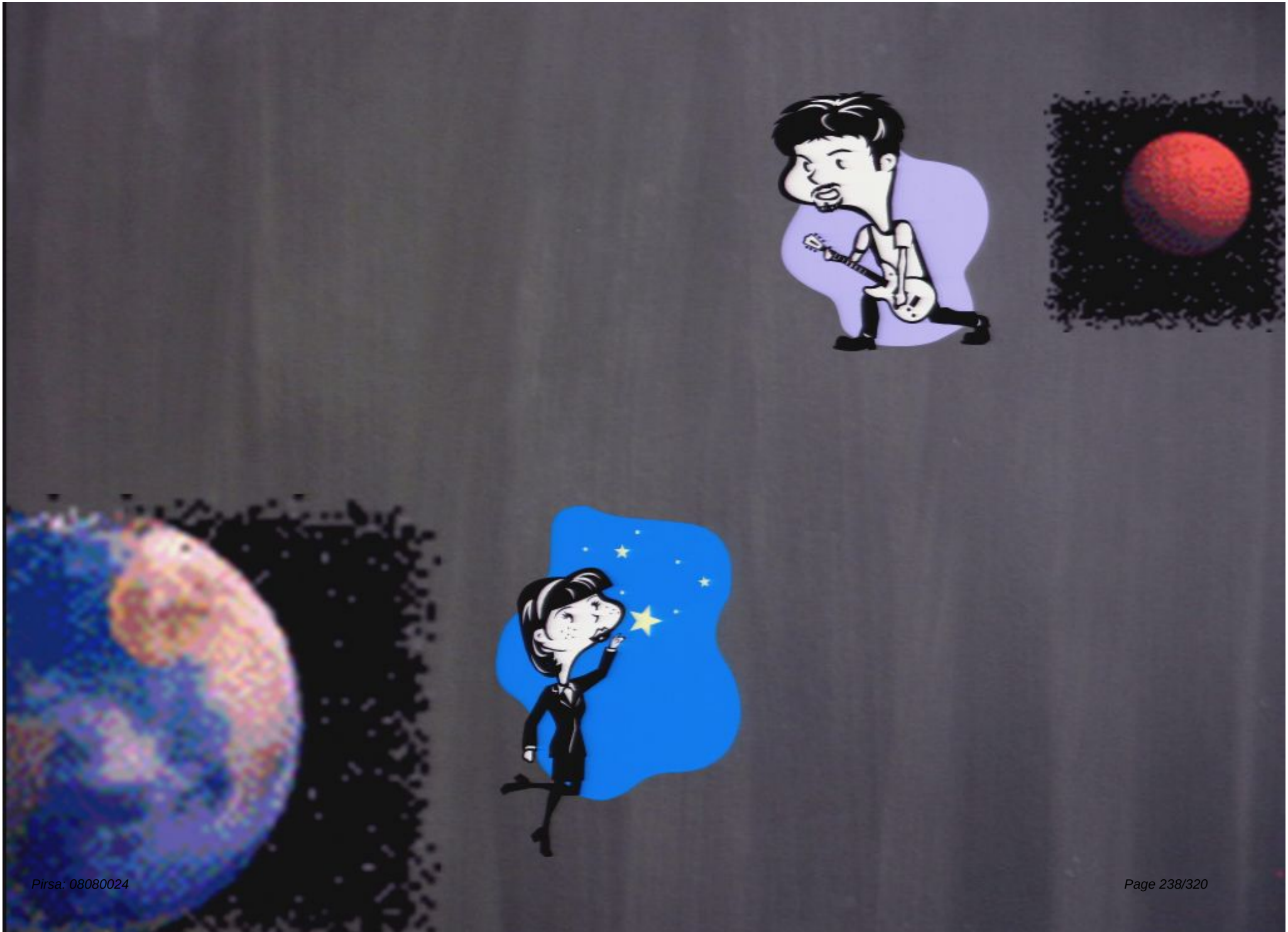

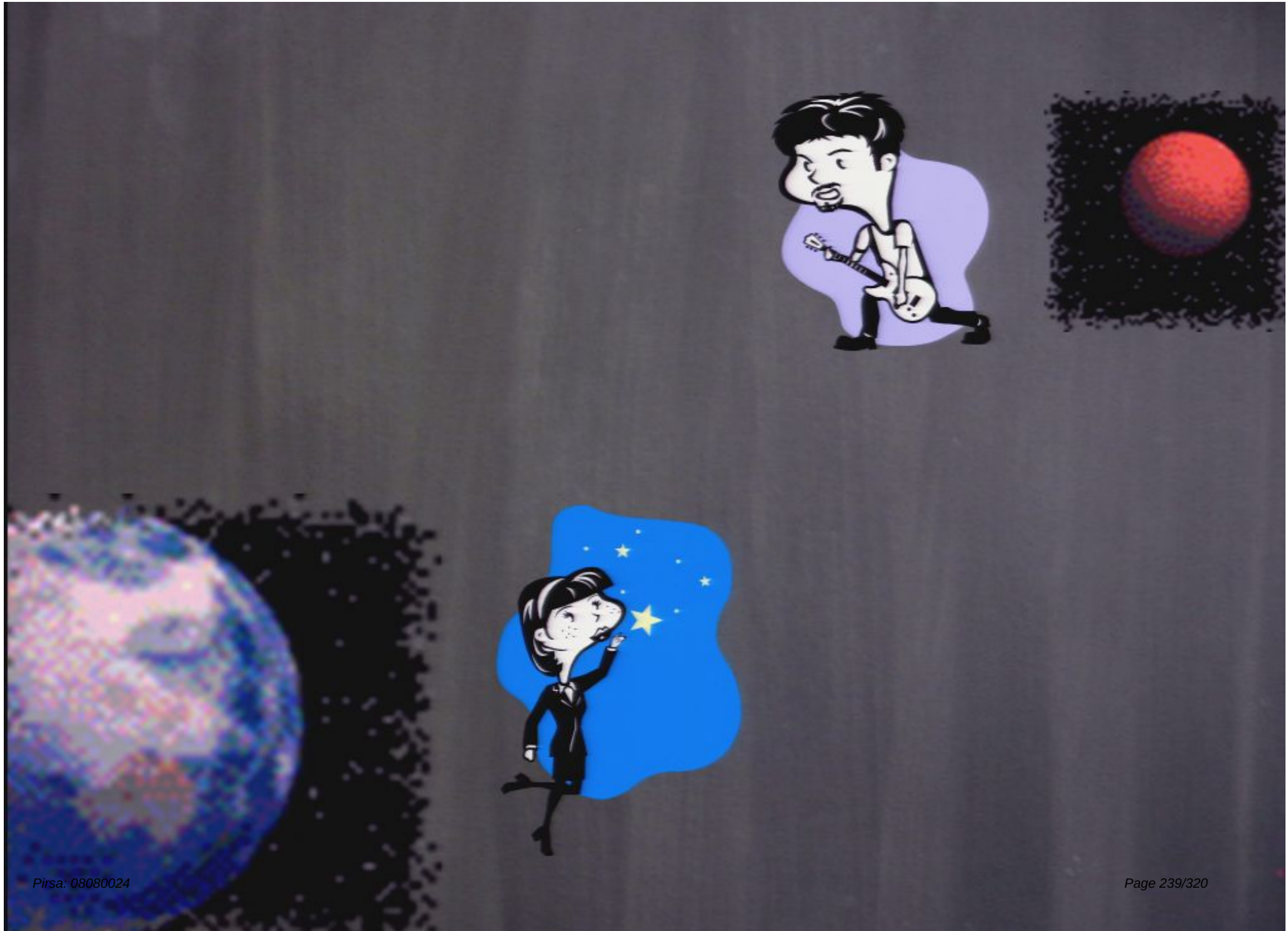

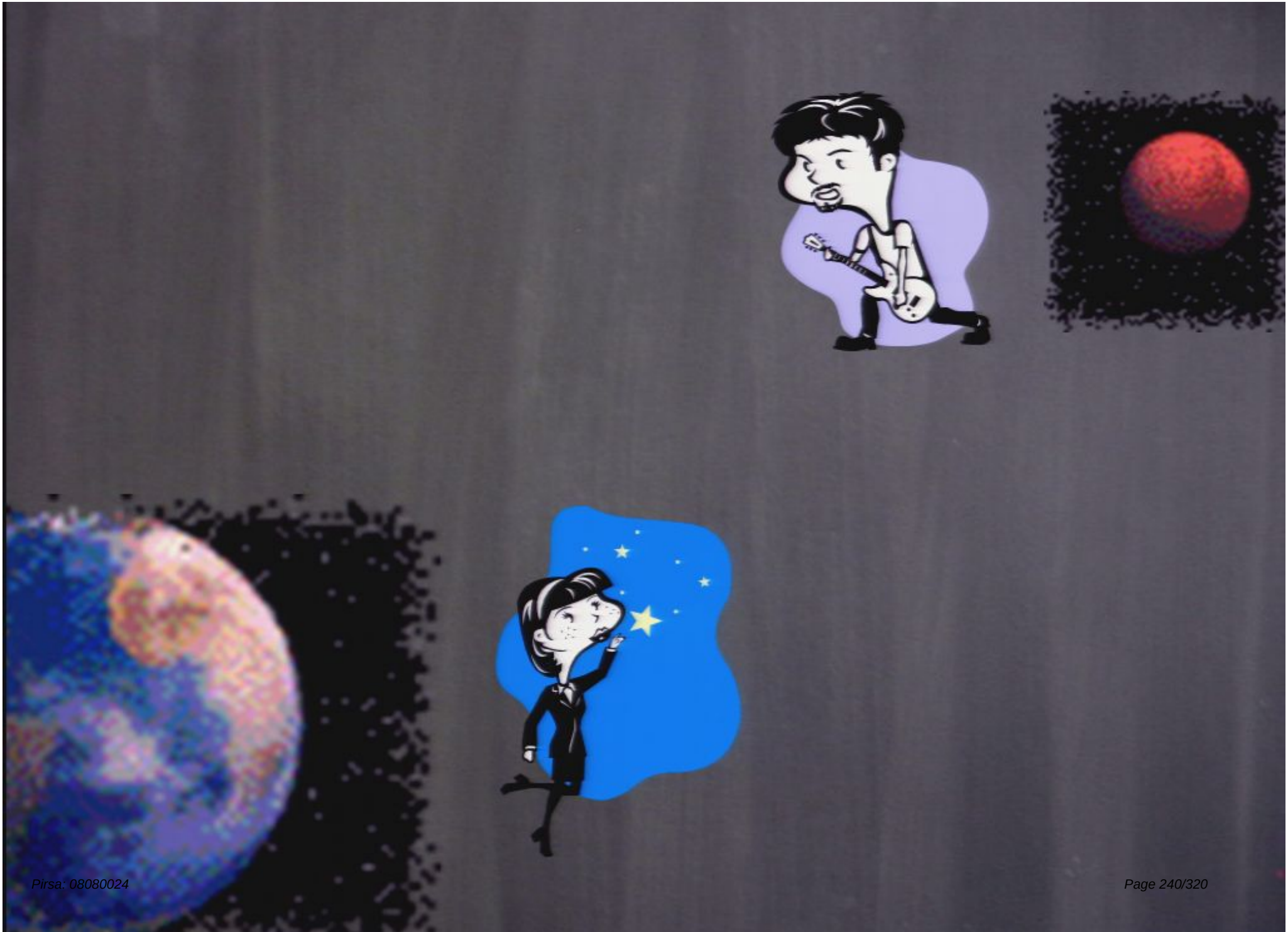

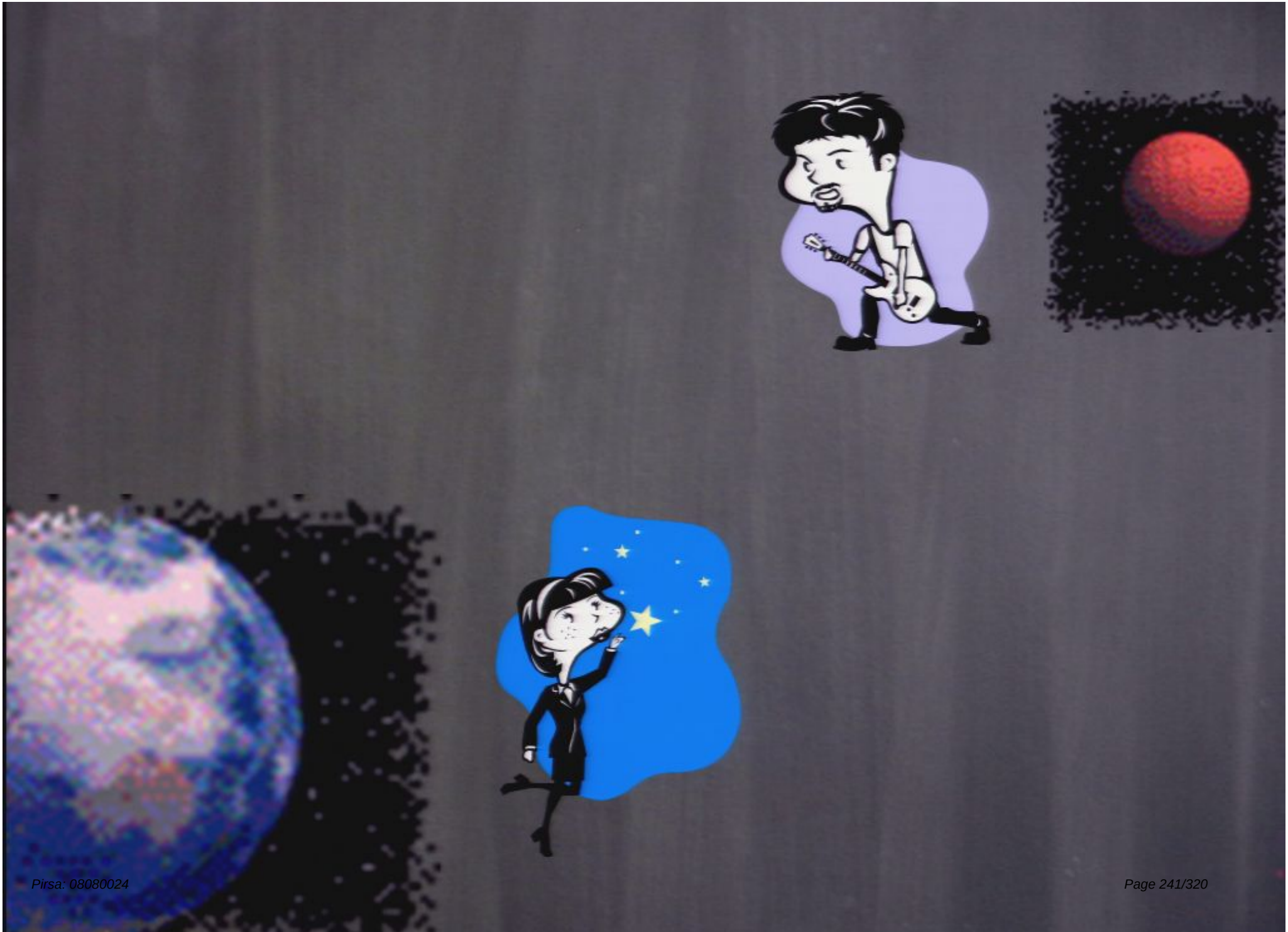

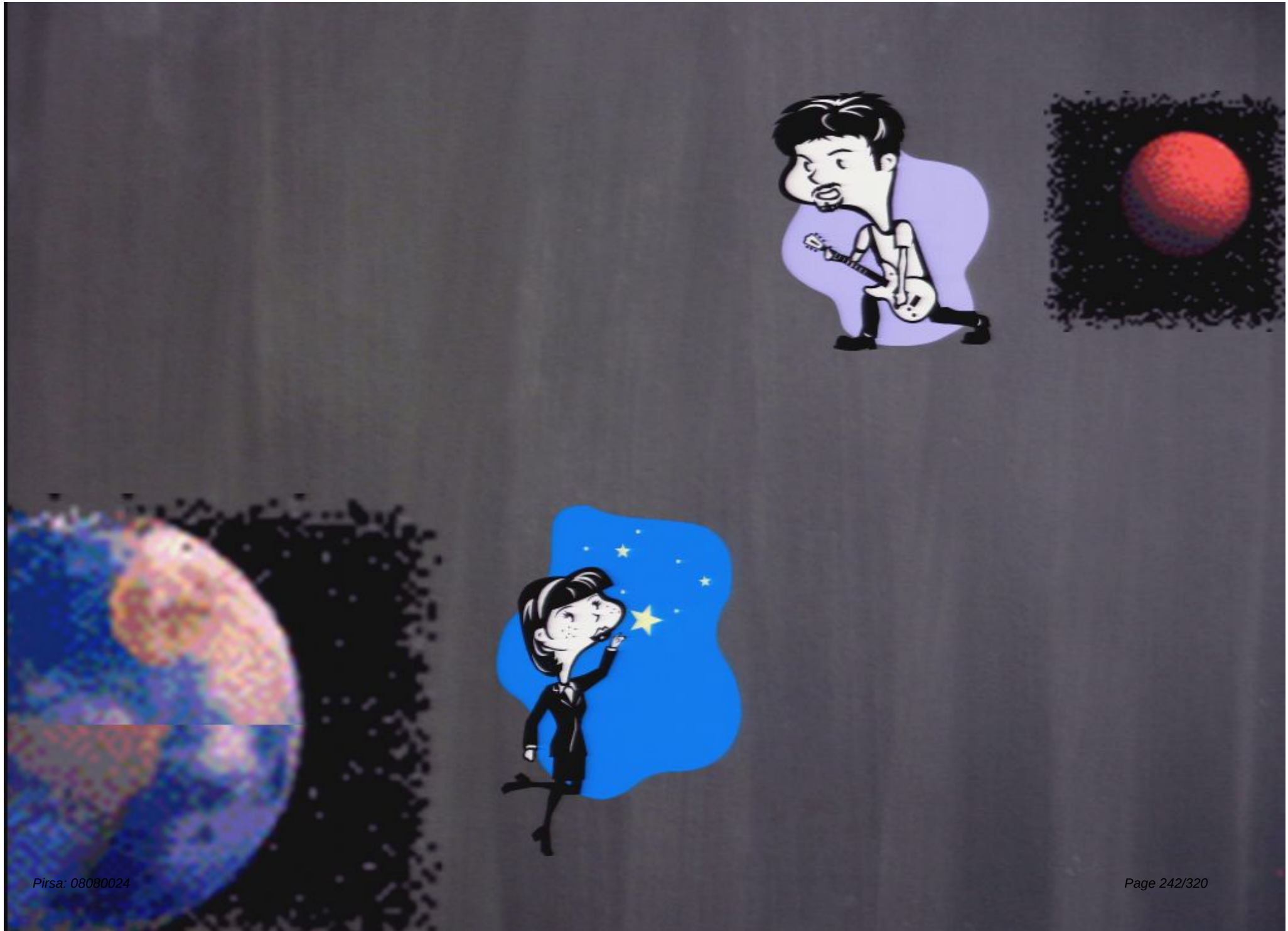

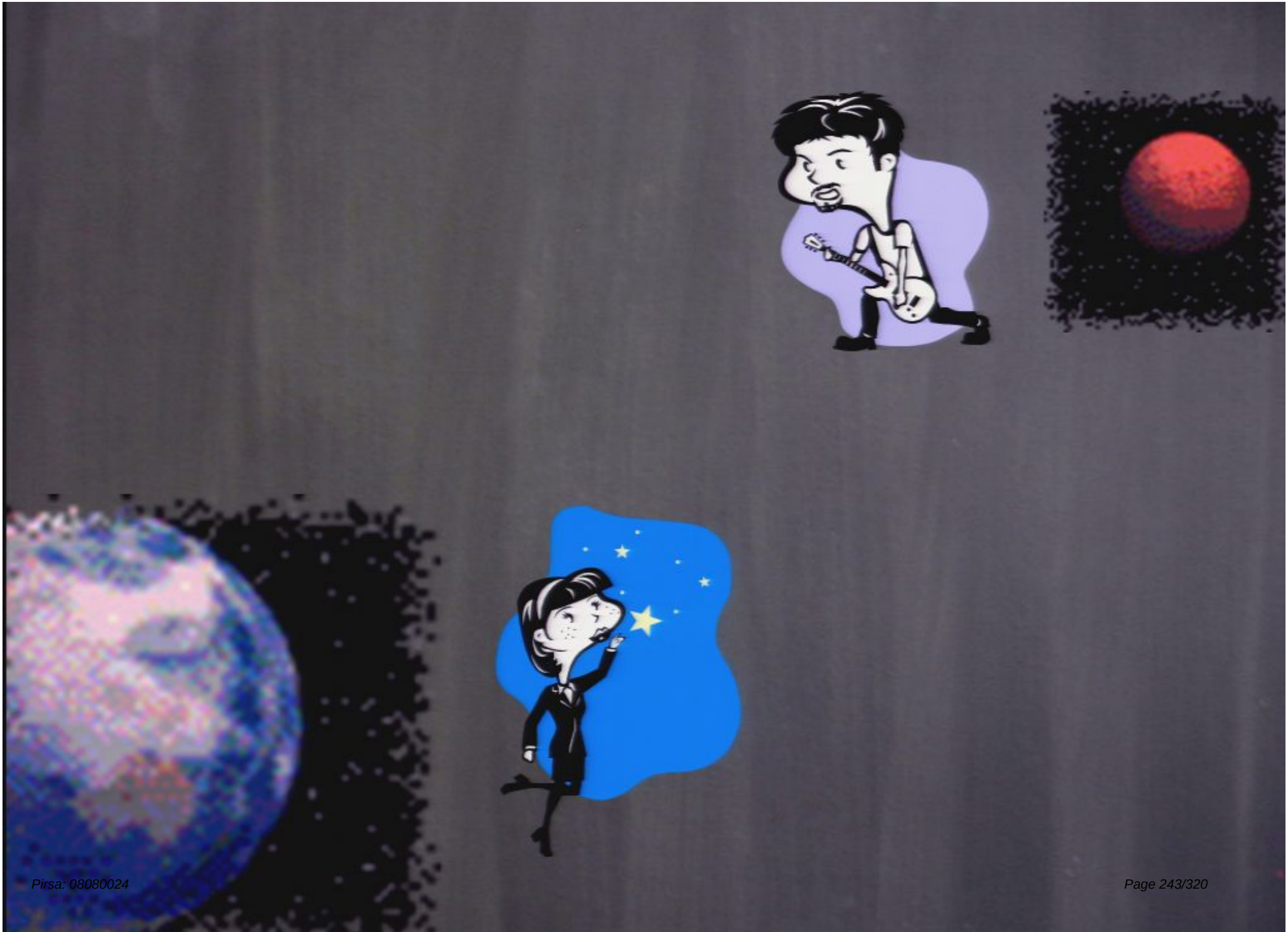

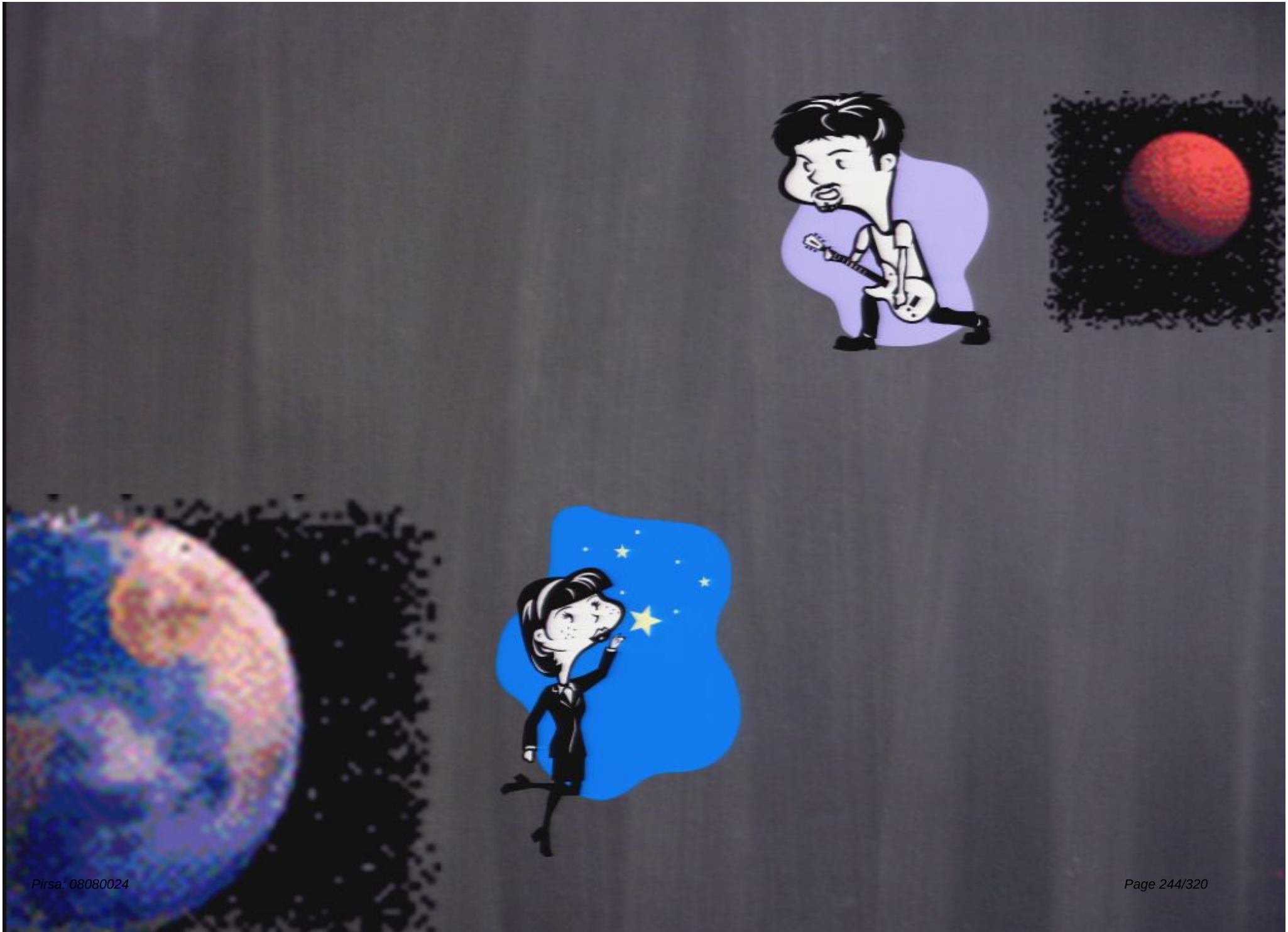

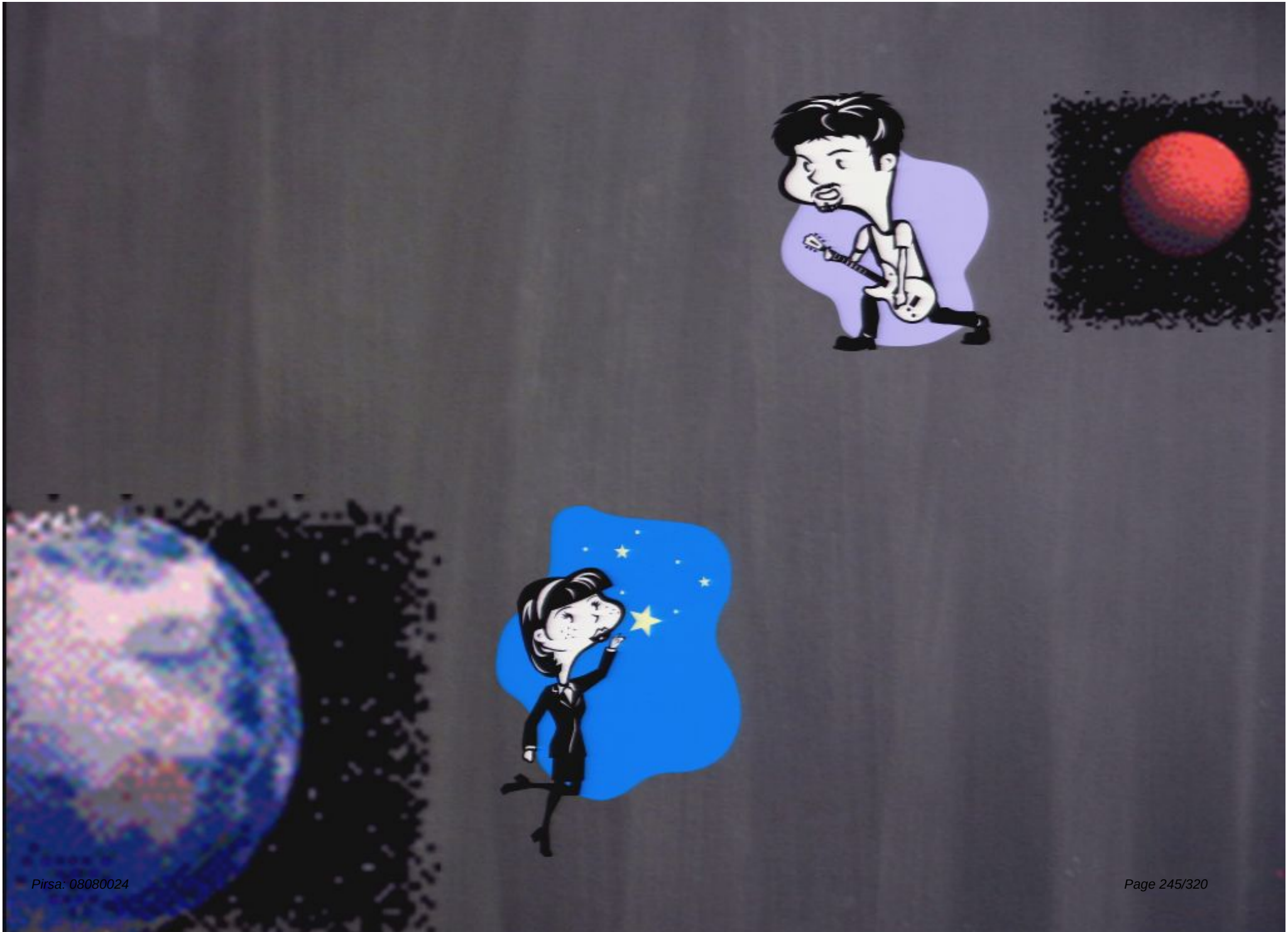

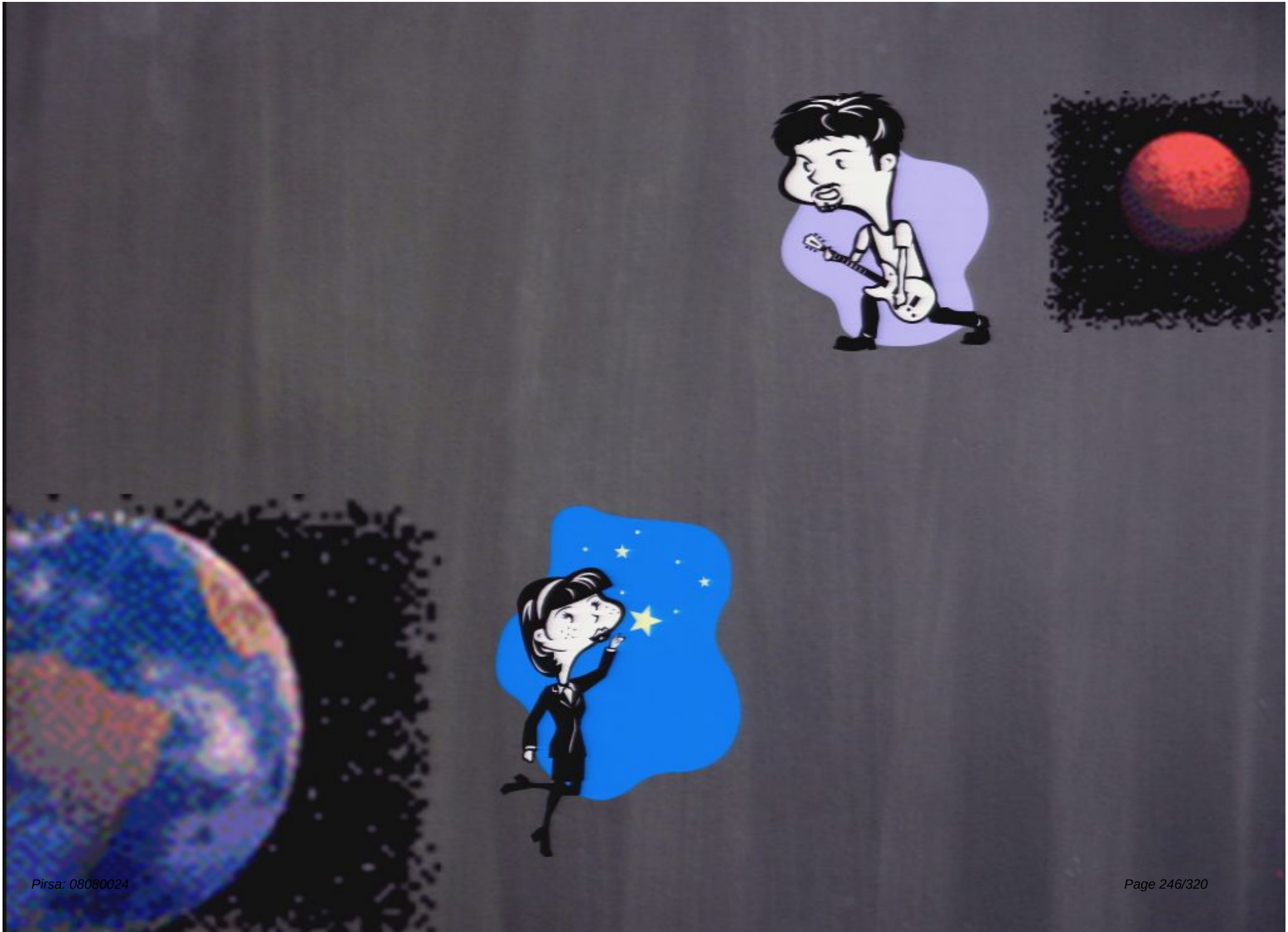

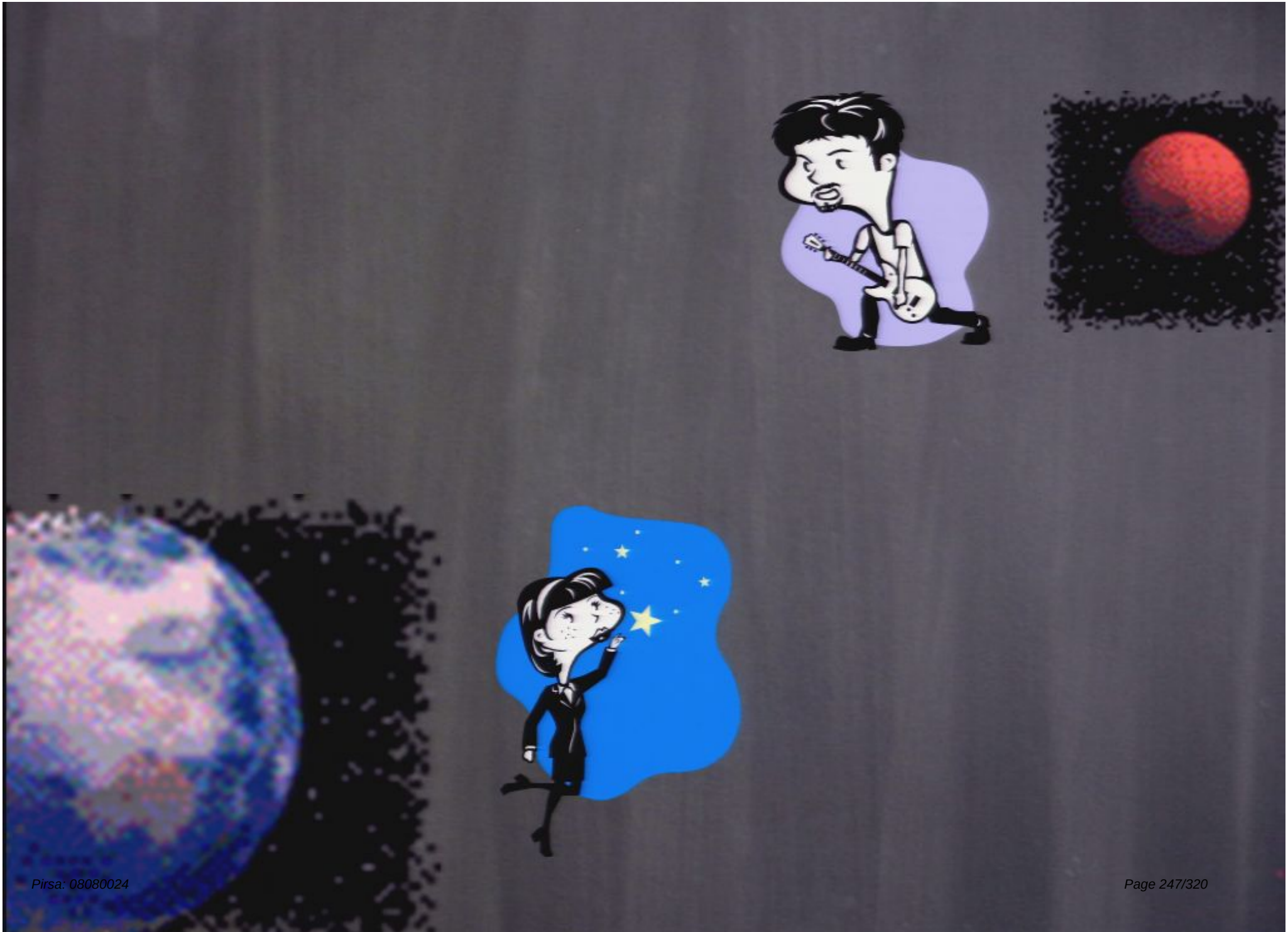

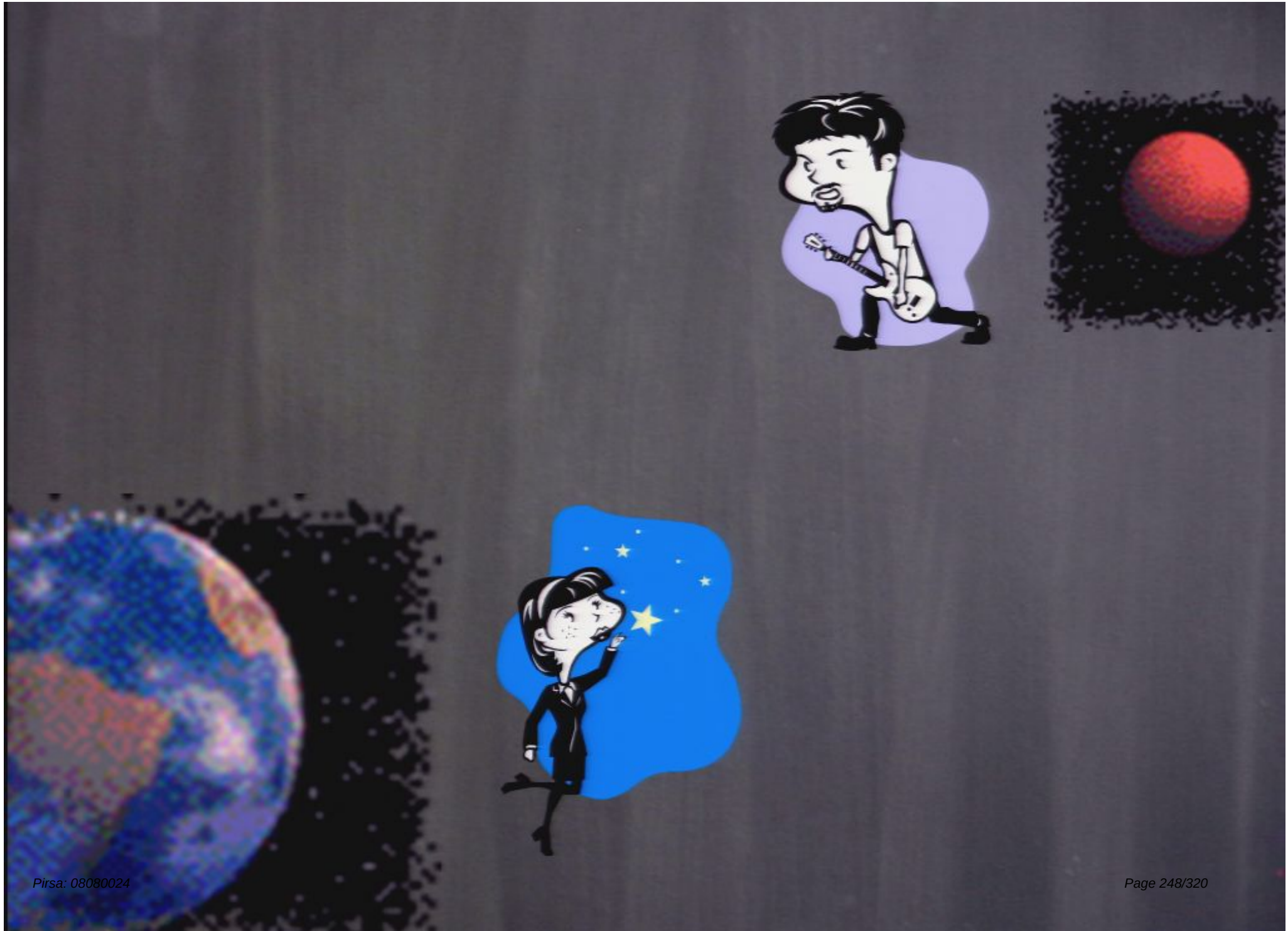

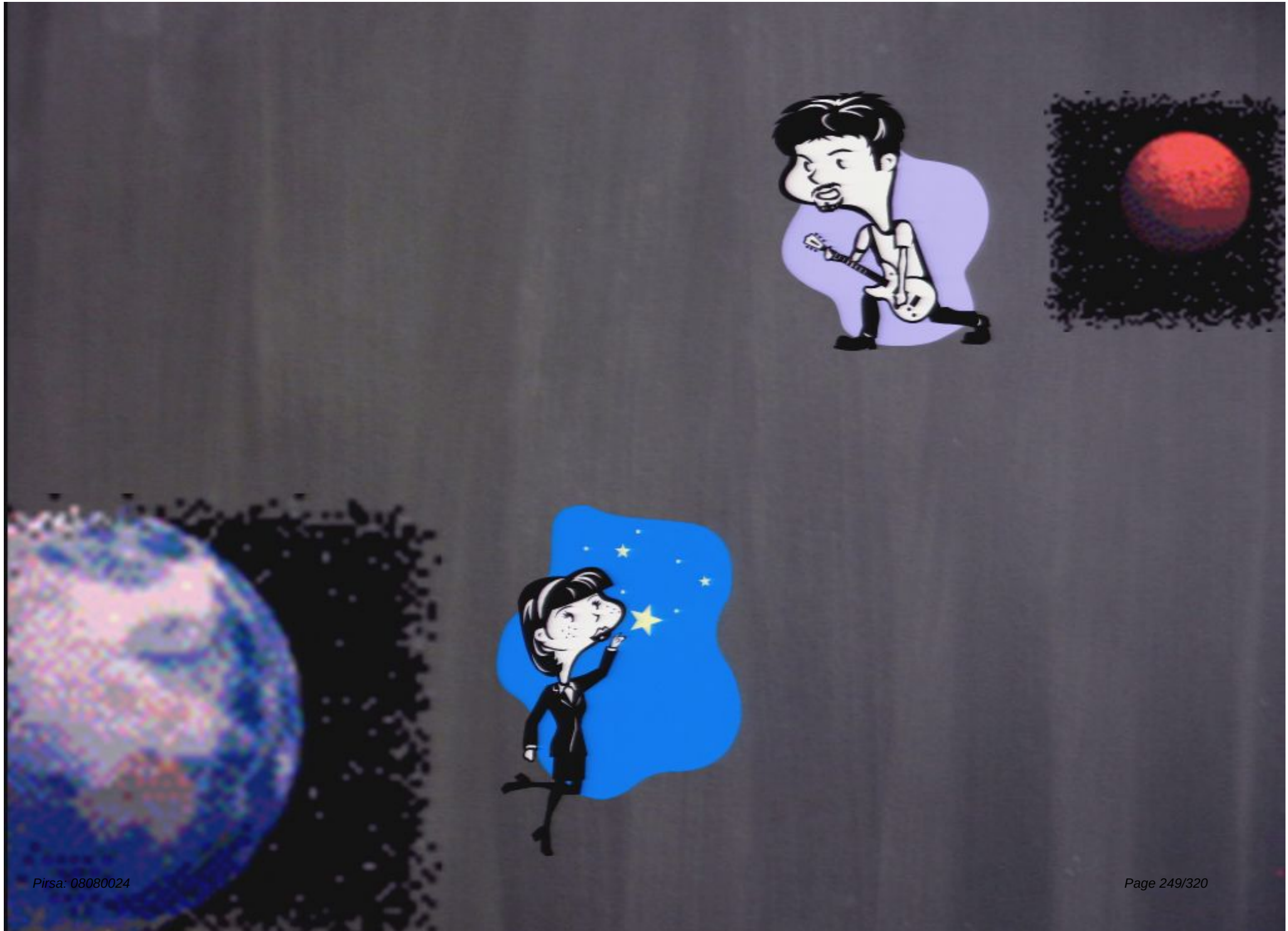

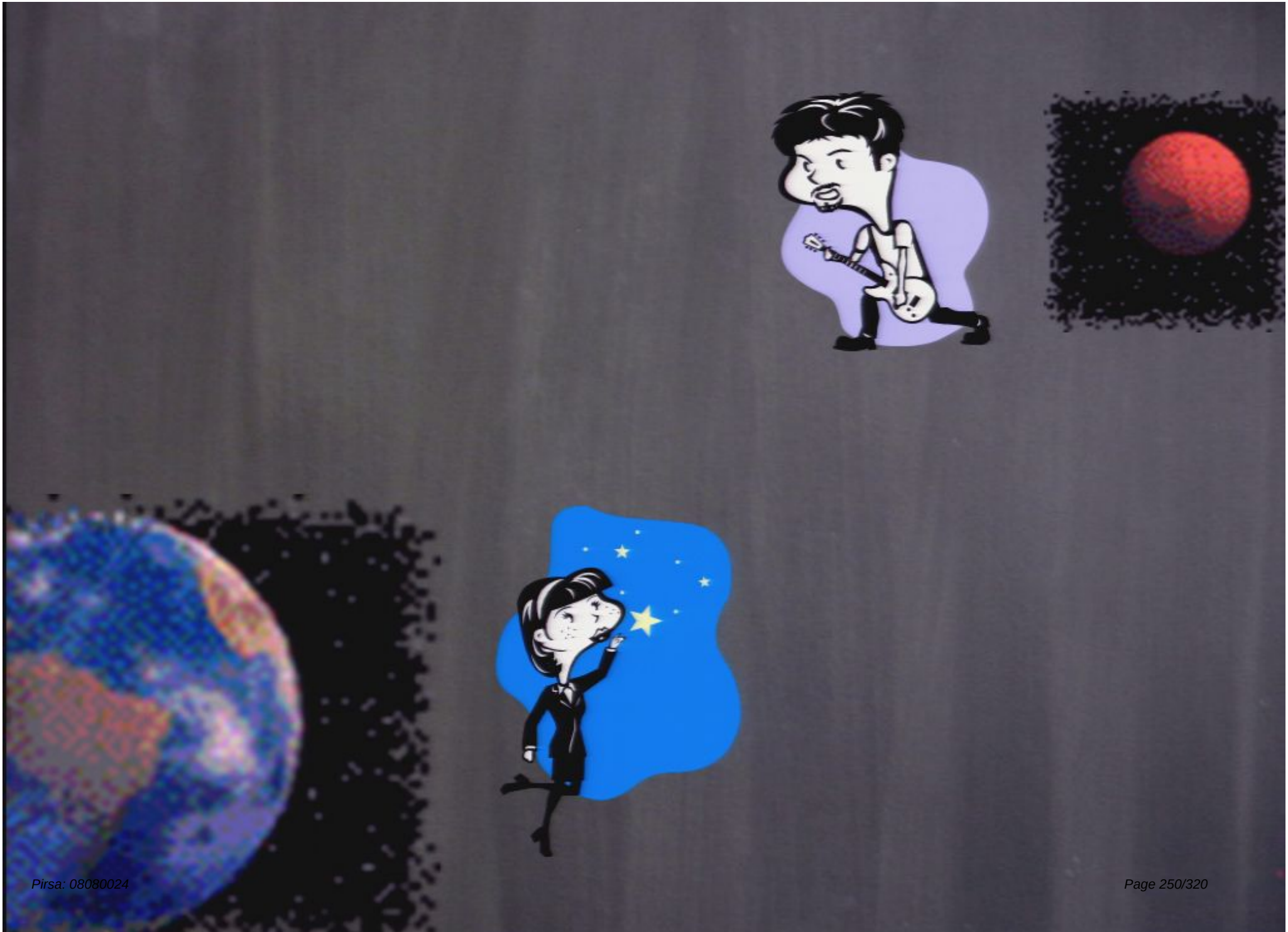

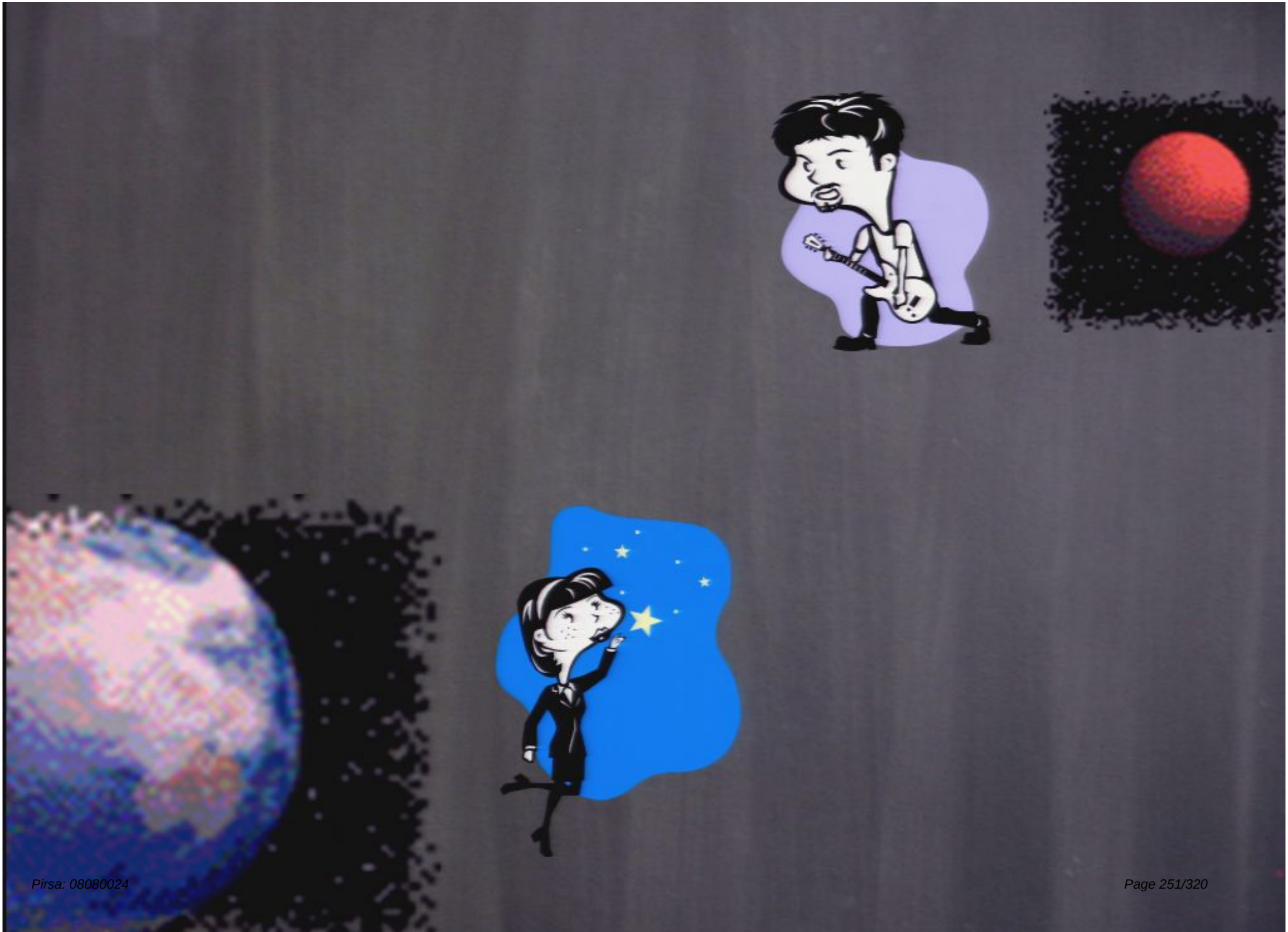

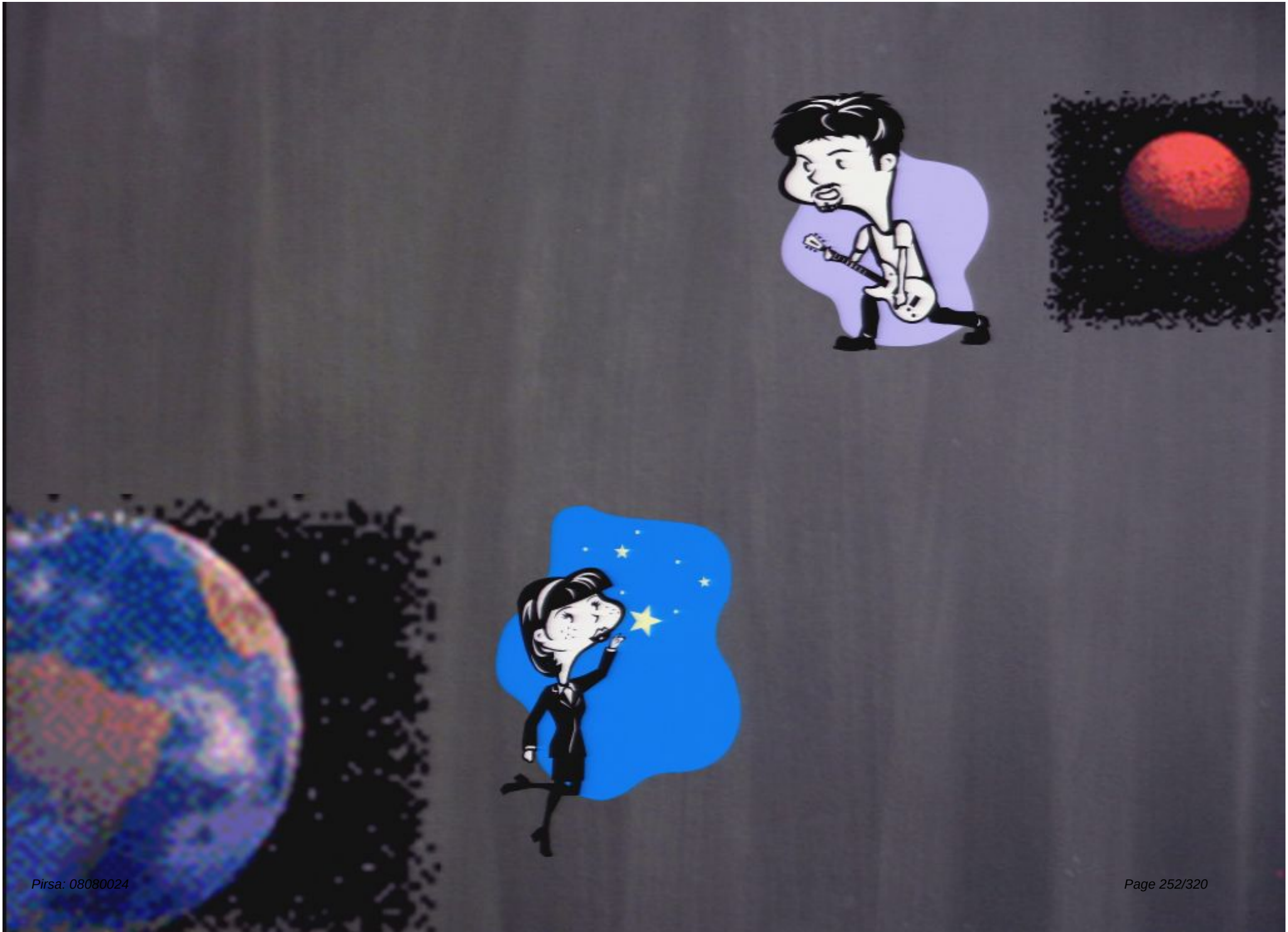

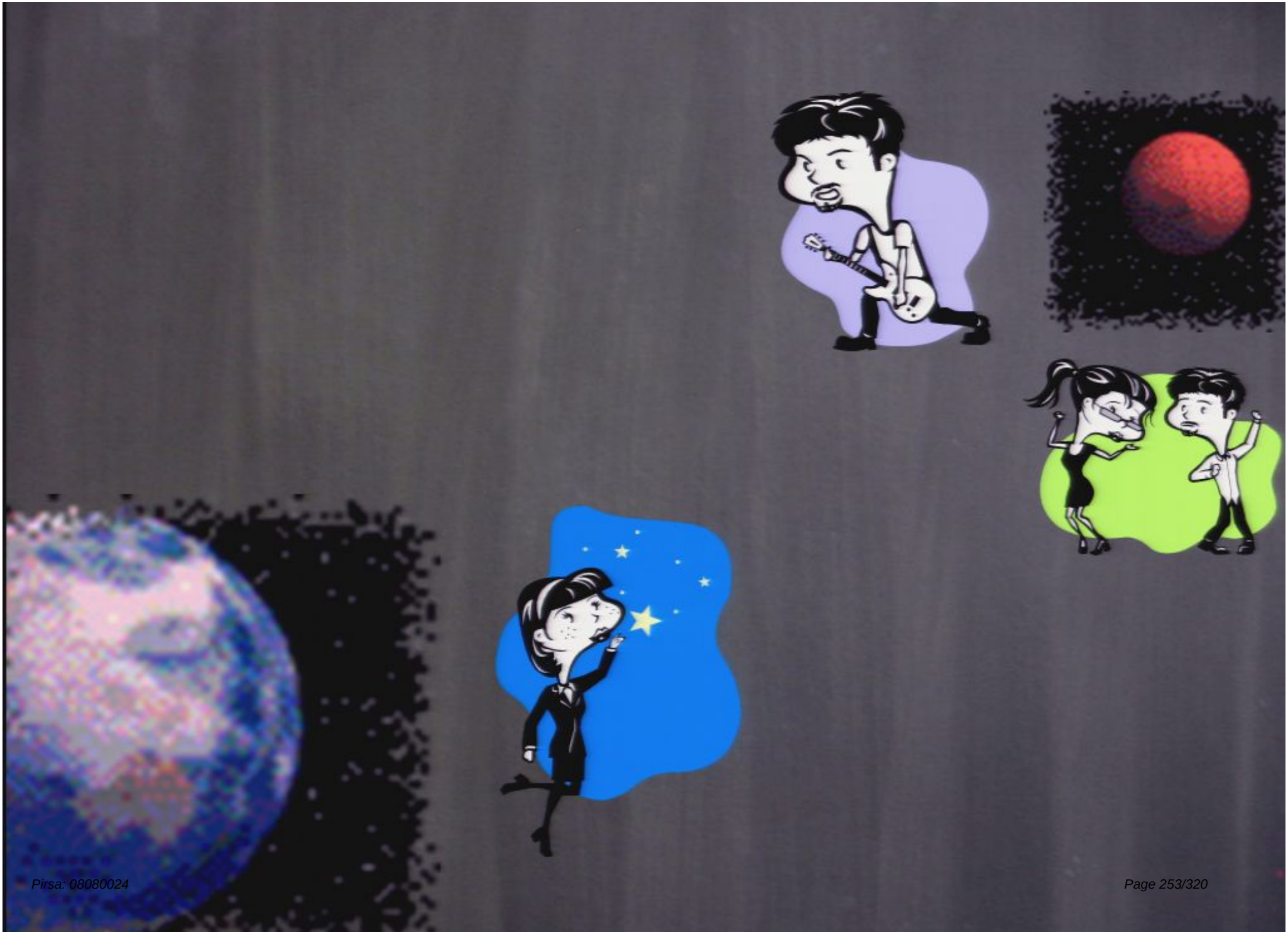

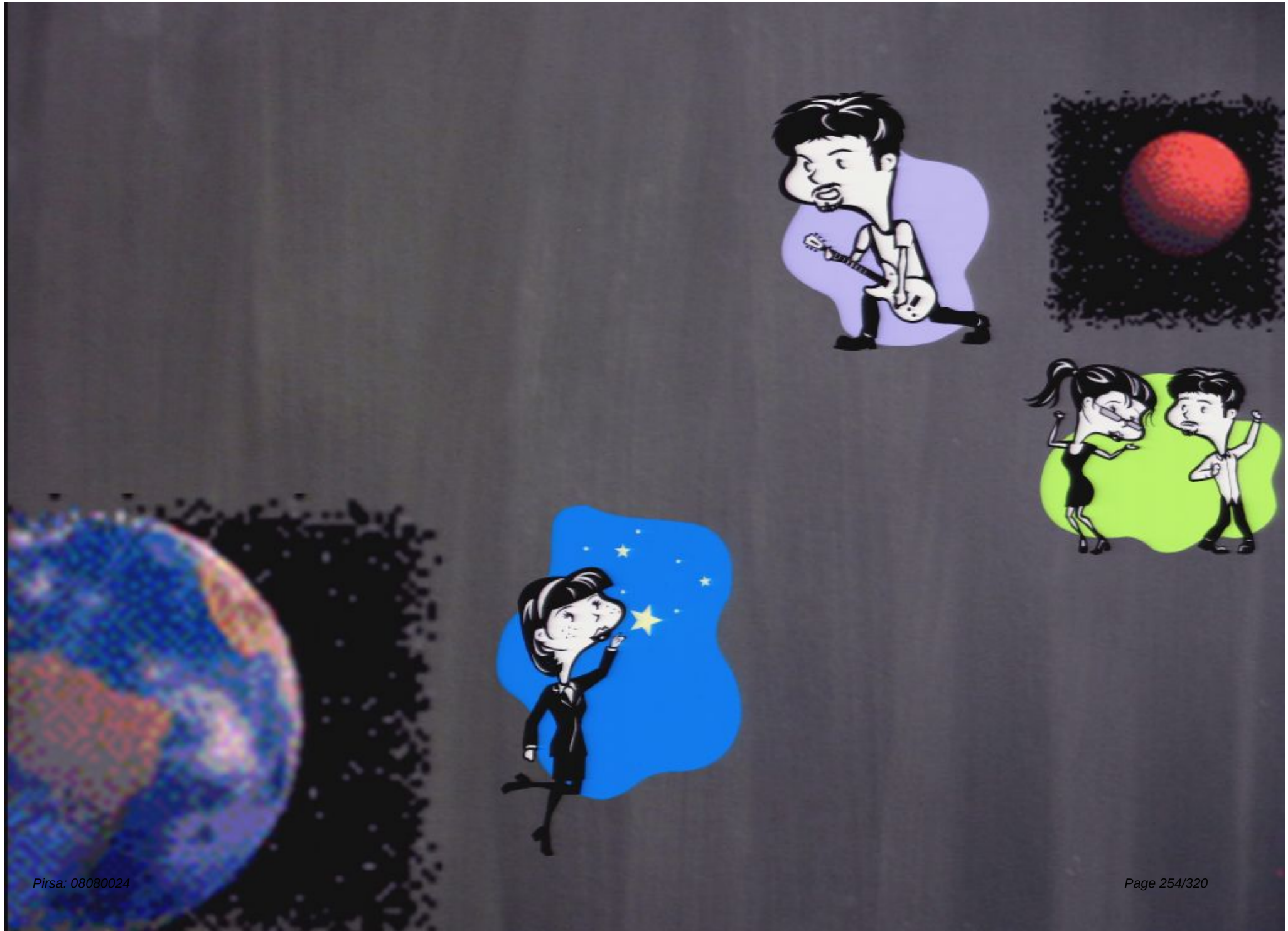

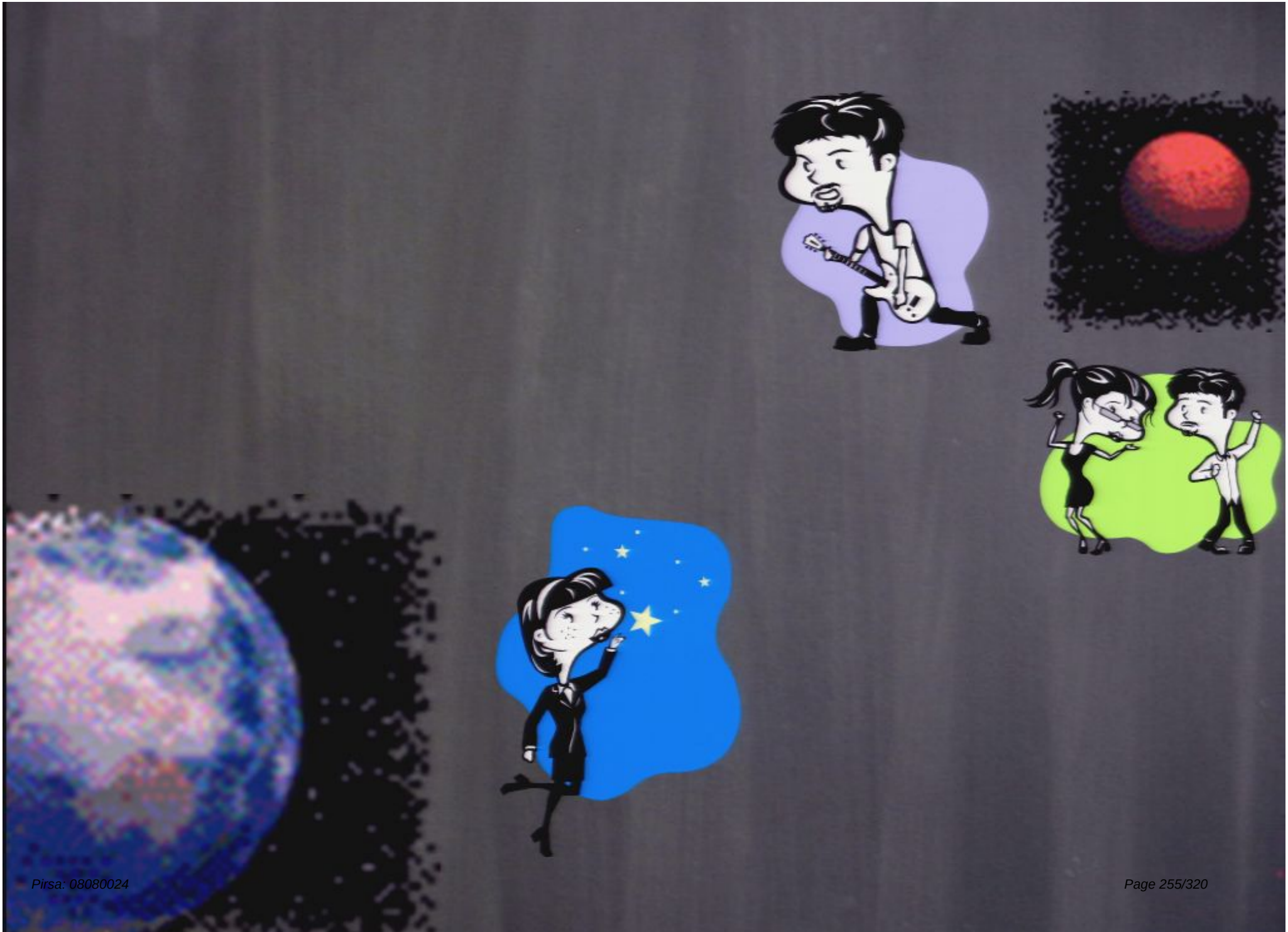

What do we mean by "teleportation"?

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Disappear Here

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Reappear There

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Disassemble into individual atoms...

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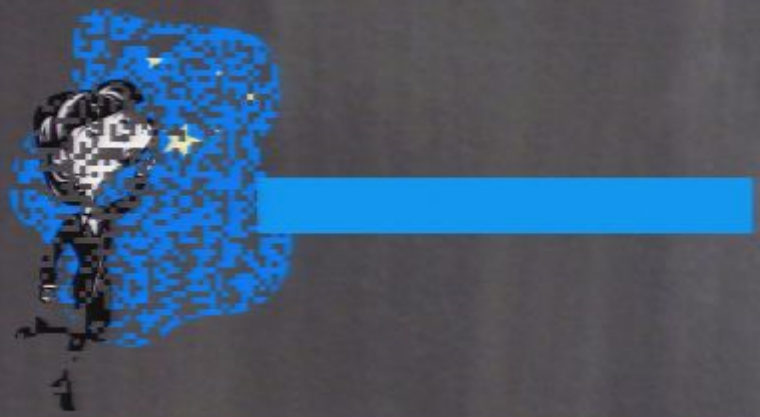

Disassemble into individual atoms...

...beam the physical atoms

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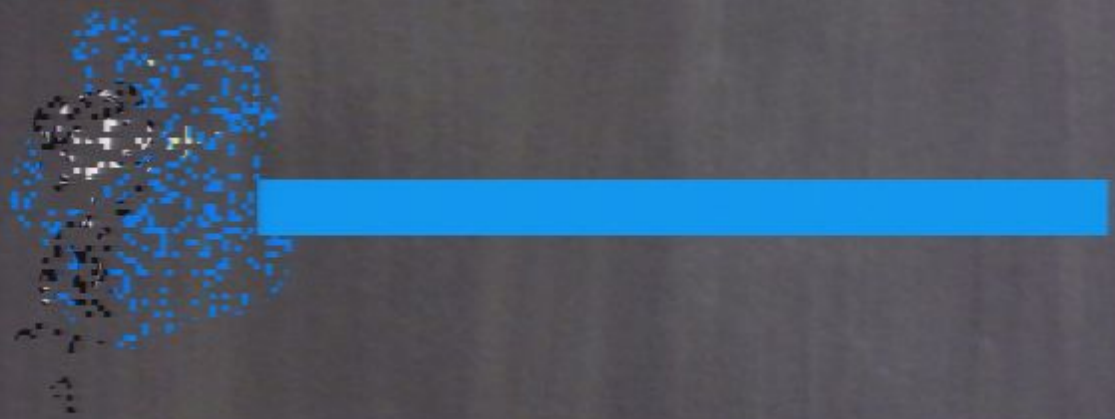

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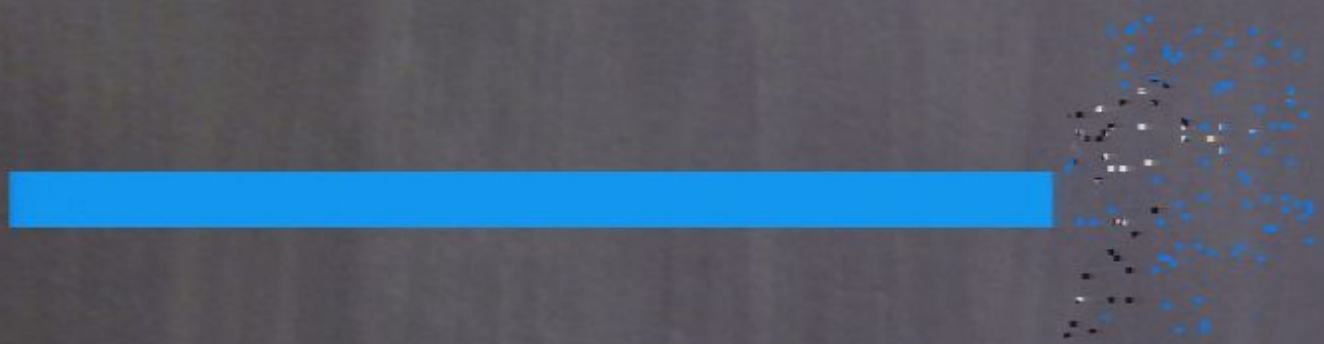

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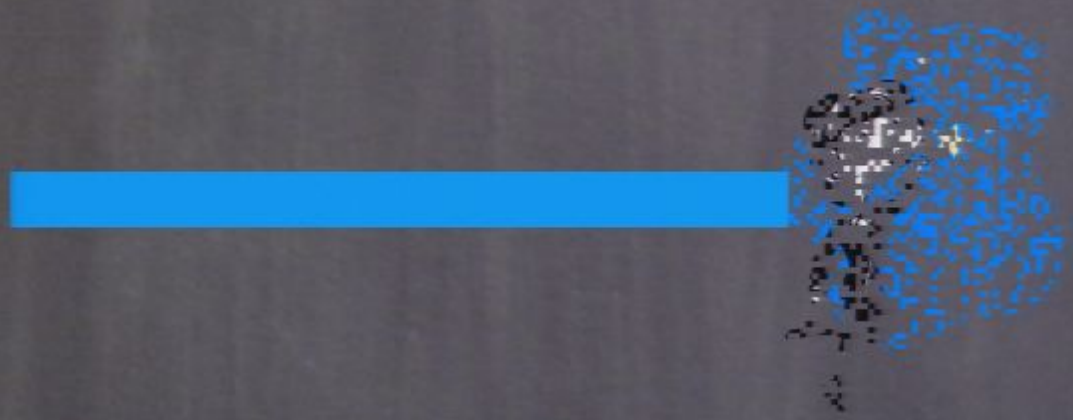

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Unnecessarily complicated!

Quantum Fact: All atoms of same type are *truly identical*

Need only send the information, not the atoms

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10010101110101110101011

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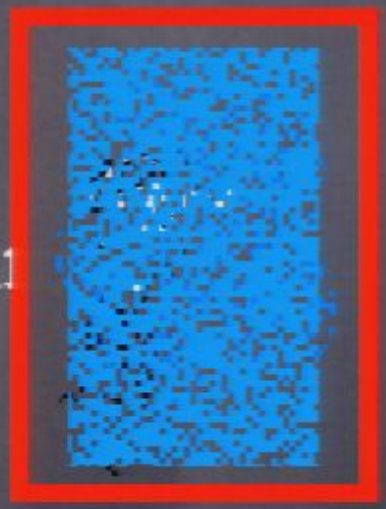

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This can't happen in our universe...

Quantum Fact: *No-Cloning Theorem*

Quantum teleportation *must* destroy the original Alice

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There can be only one Alice →

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Answer: We *can't!*

Quantum Facts: *Heisenberg Uncertainty limits the amount of information that can be extracted*

Worse: Certain quantum information cannot be measured at all!

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NO: In 1993 Charles Bennett *et al* discovered that quantum *entanglement* could be used to *send* the information without actually *measuring* it!

What do we mean by "teleportation"?

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- ✓ Send only information; reassemble using atoms on Mars
- ✓ The original Alice is destroyed (teleporting, not copying)
- ✓ Quantum teleportation is possible using entanglement

Quantum Teleportation

Here's how it works:

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Warning: The Following is Science *Fiction*

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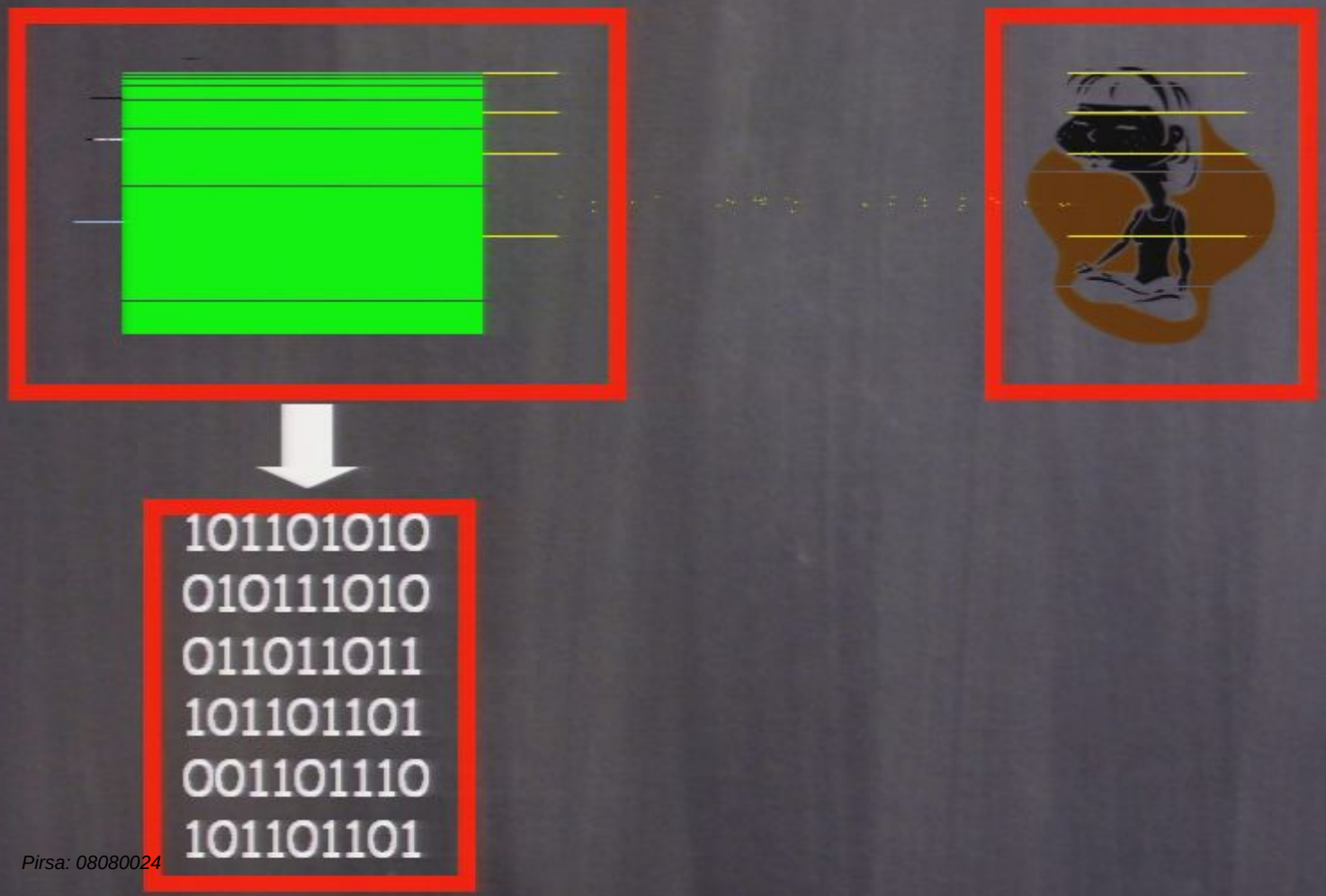

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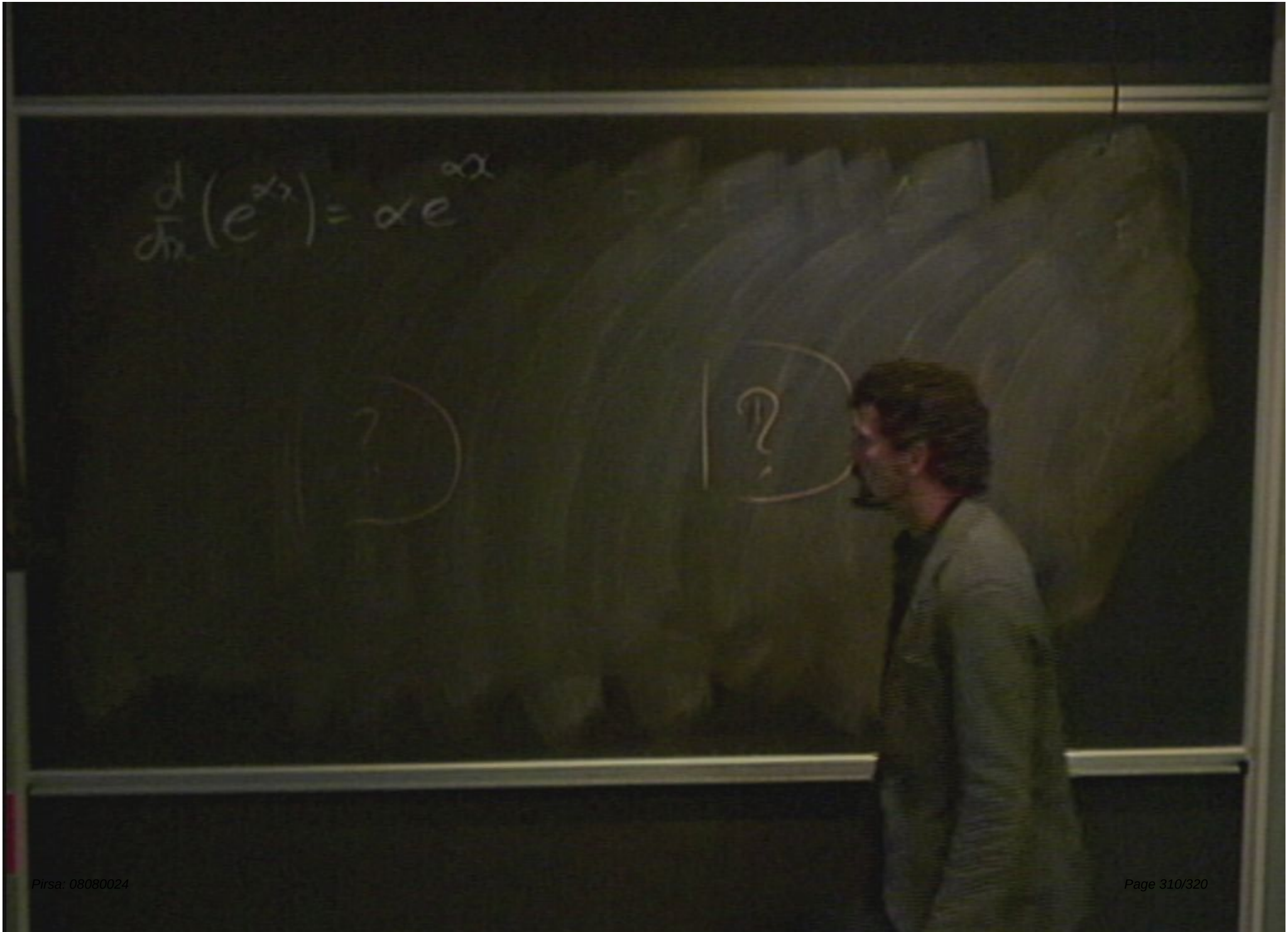
$\frac{d}{dx}(e^{\alpha x}) = \alpha e^{\alpha x}$
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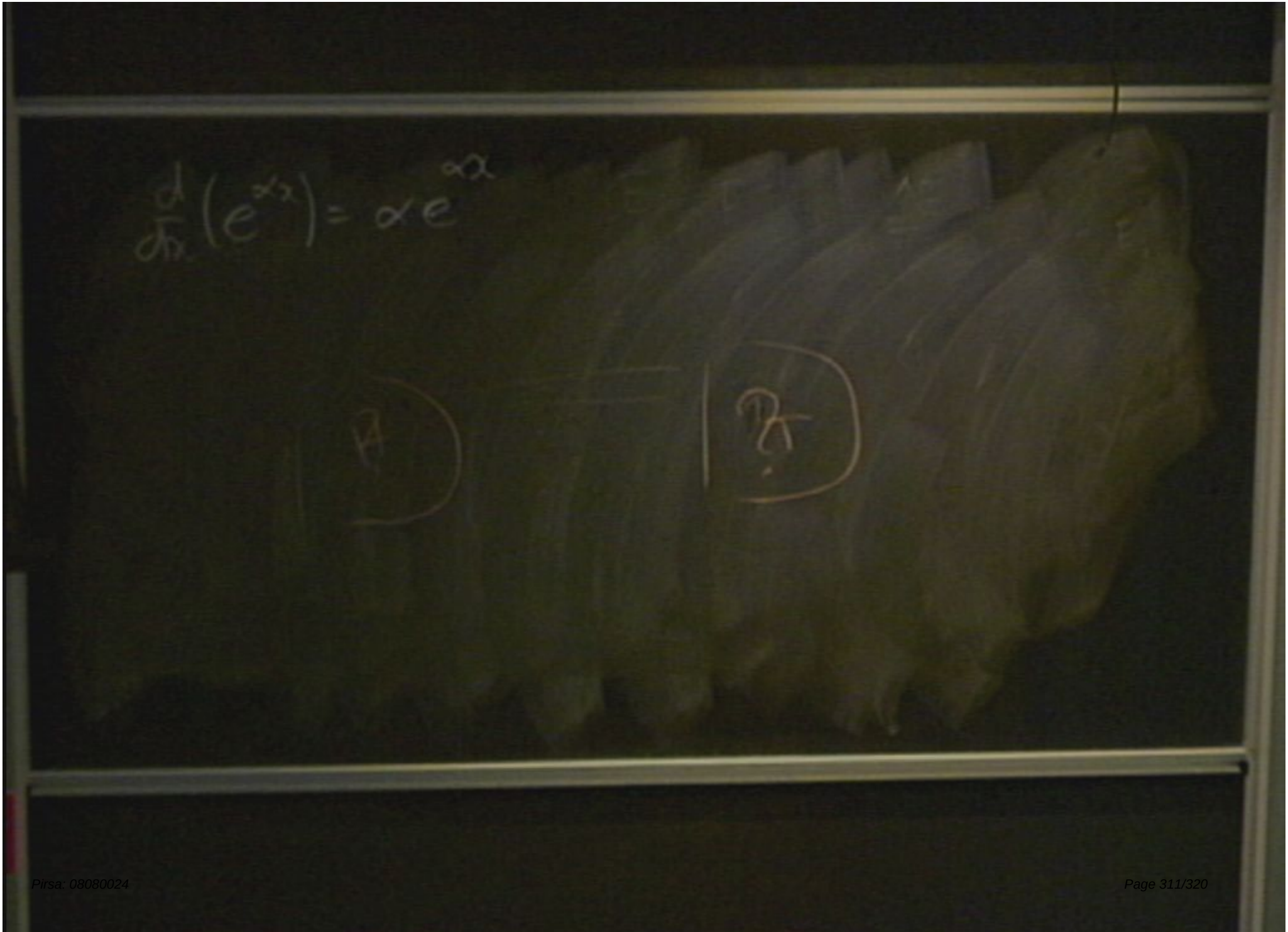
|?D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A
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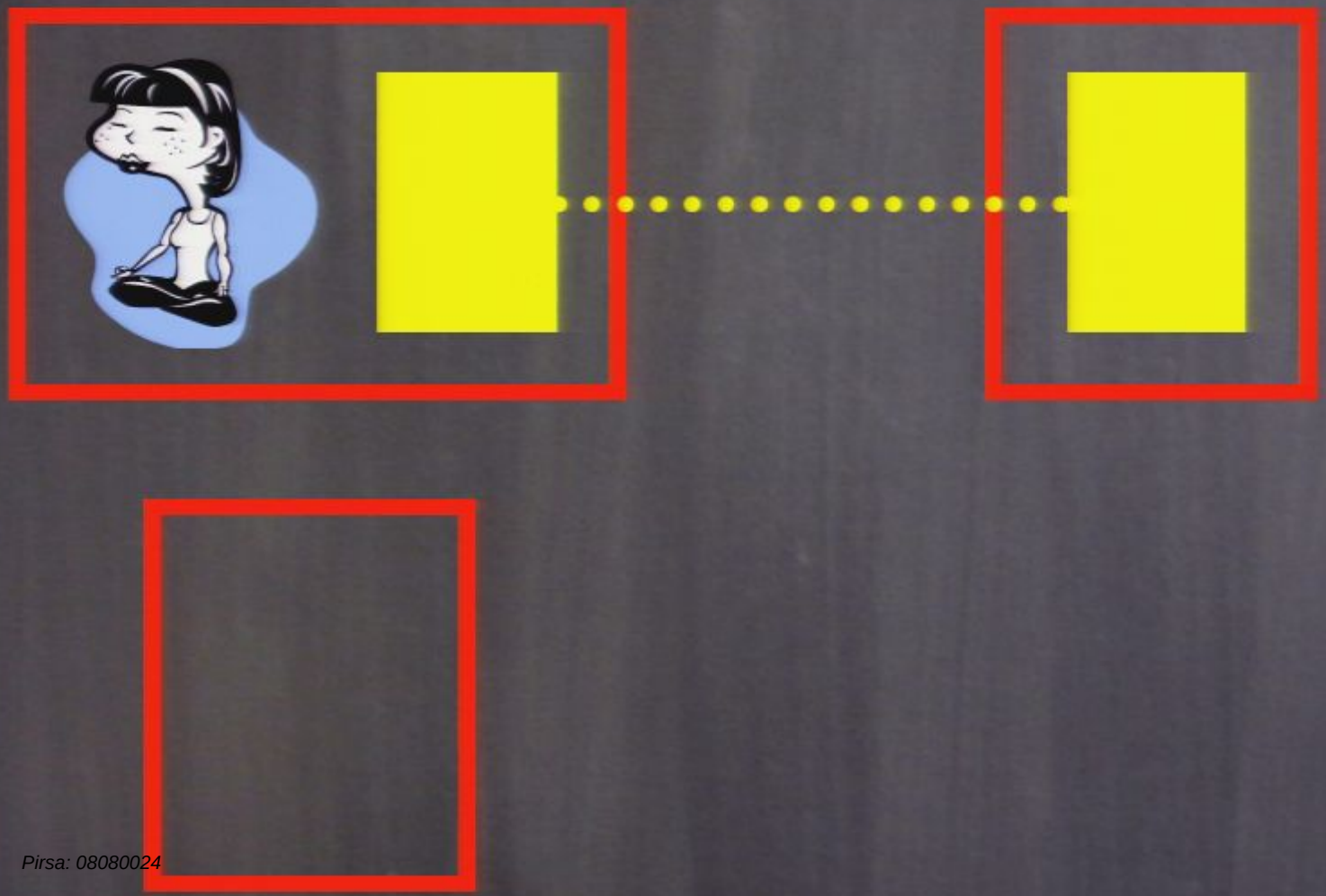

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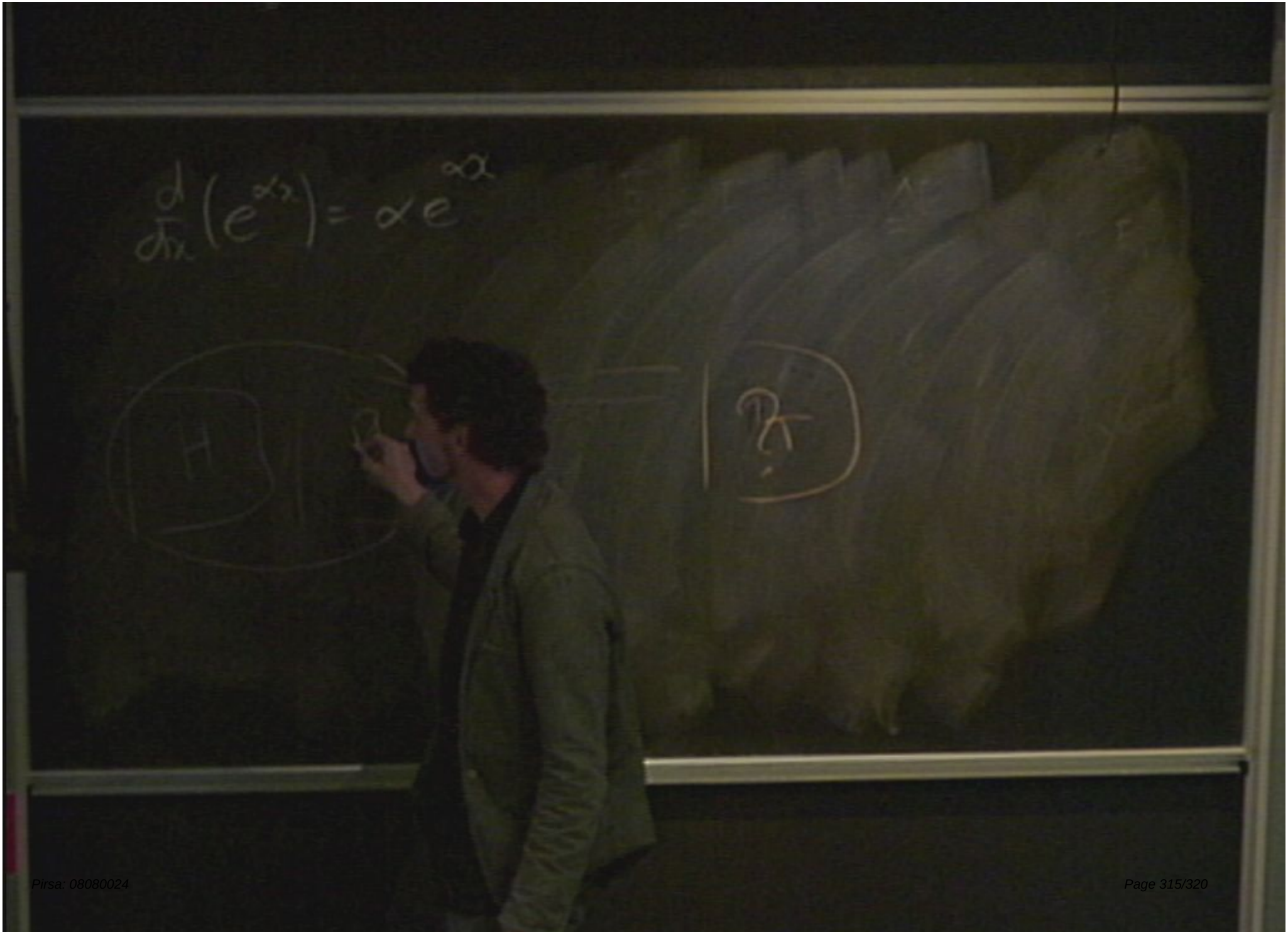
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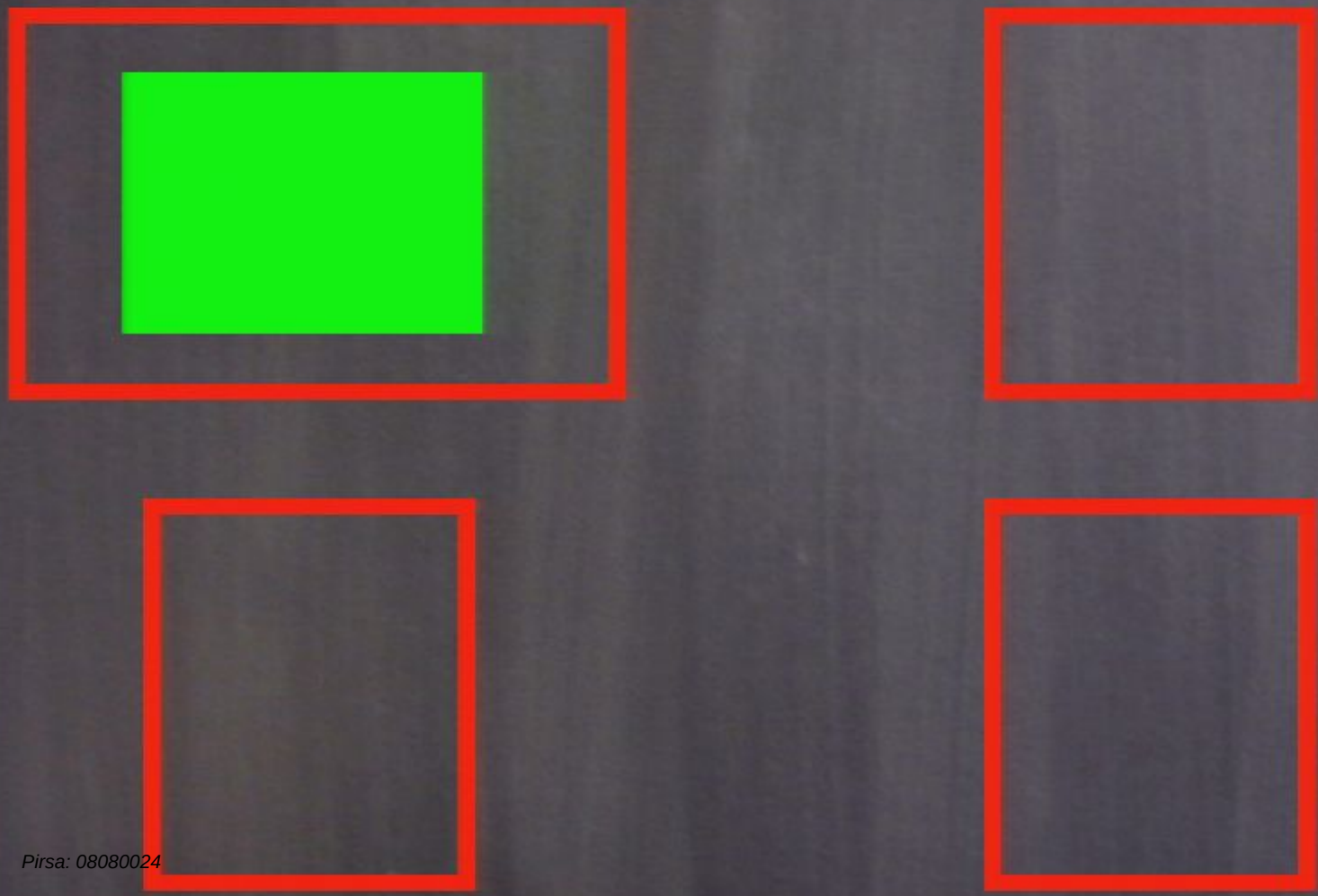

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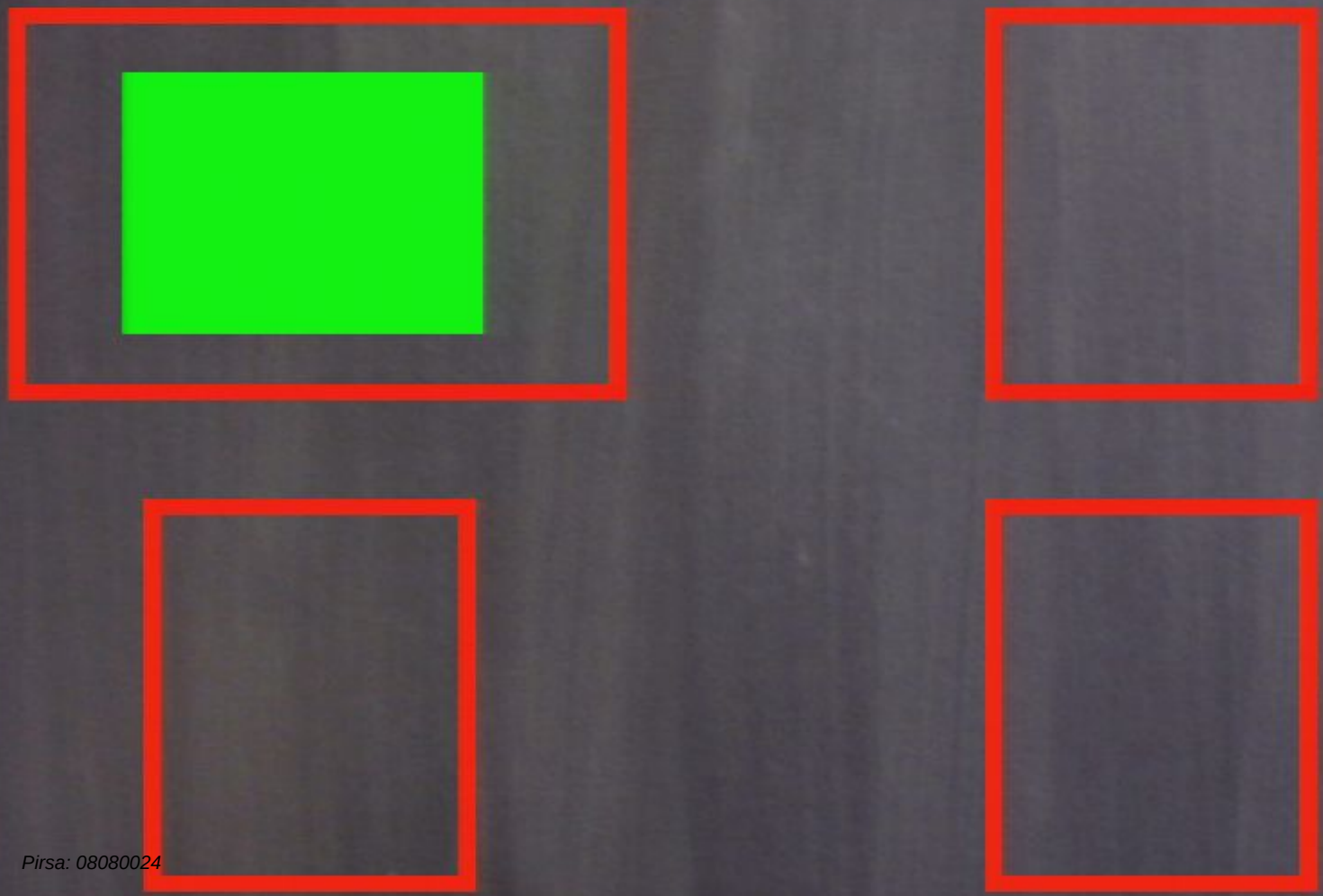

A *quantum identical* version of Alice on Mars!