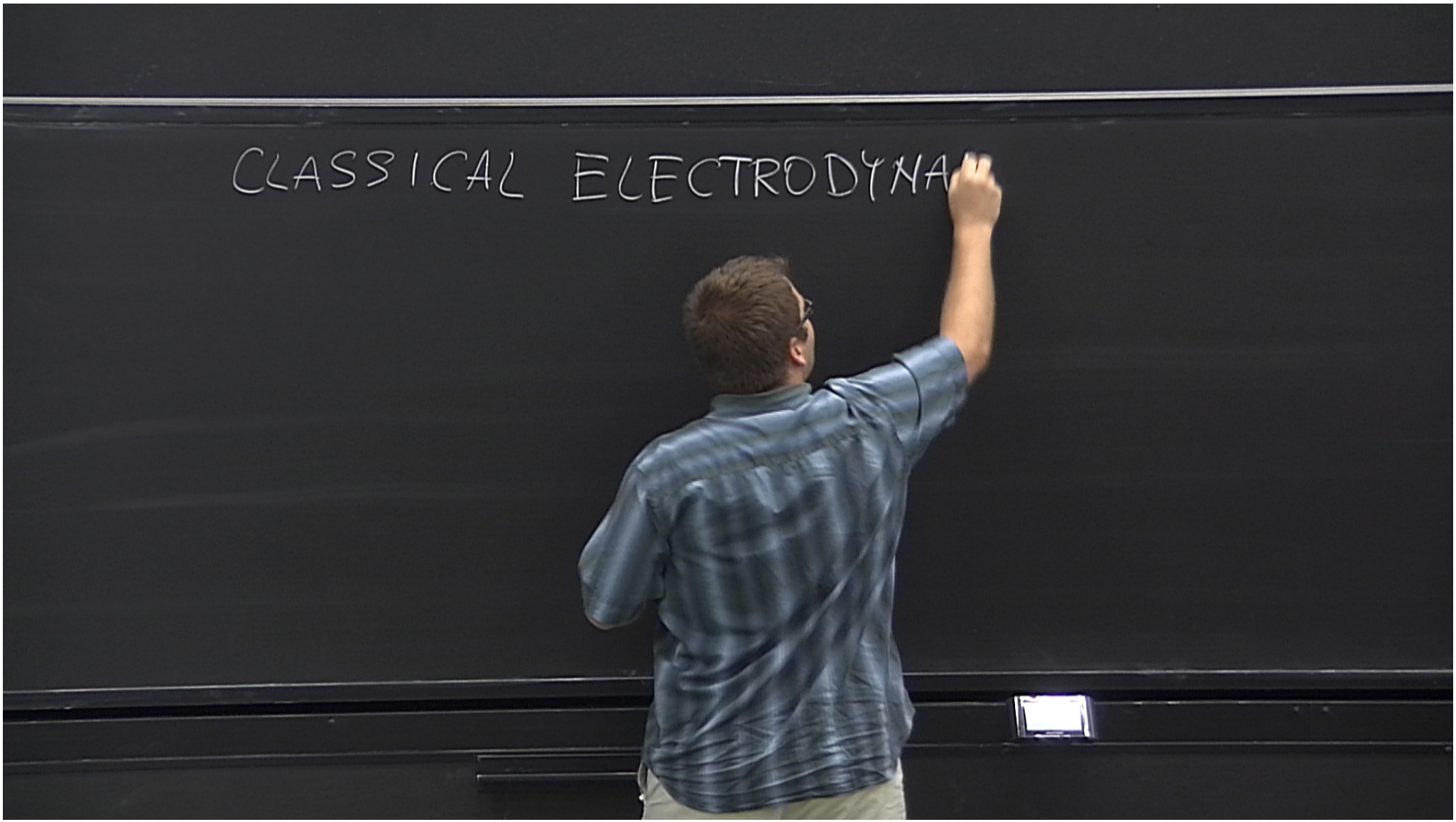
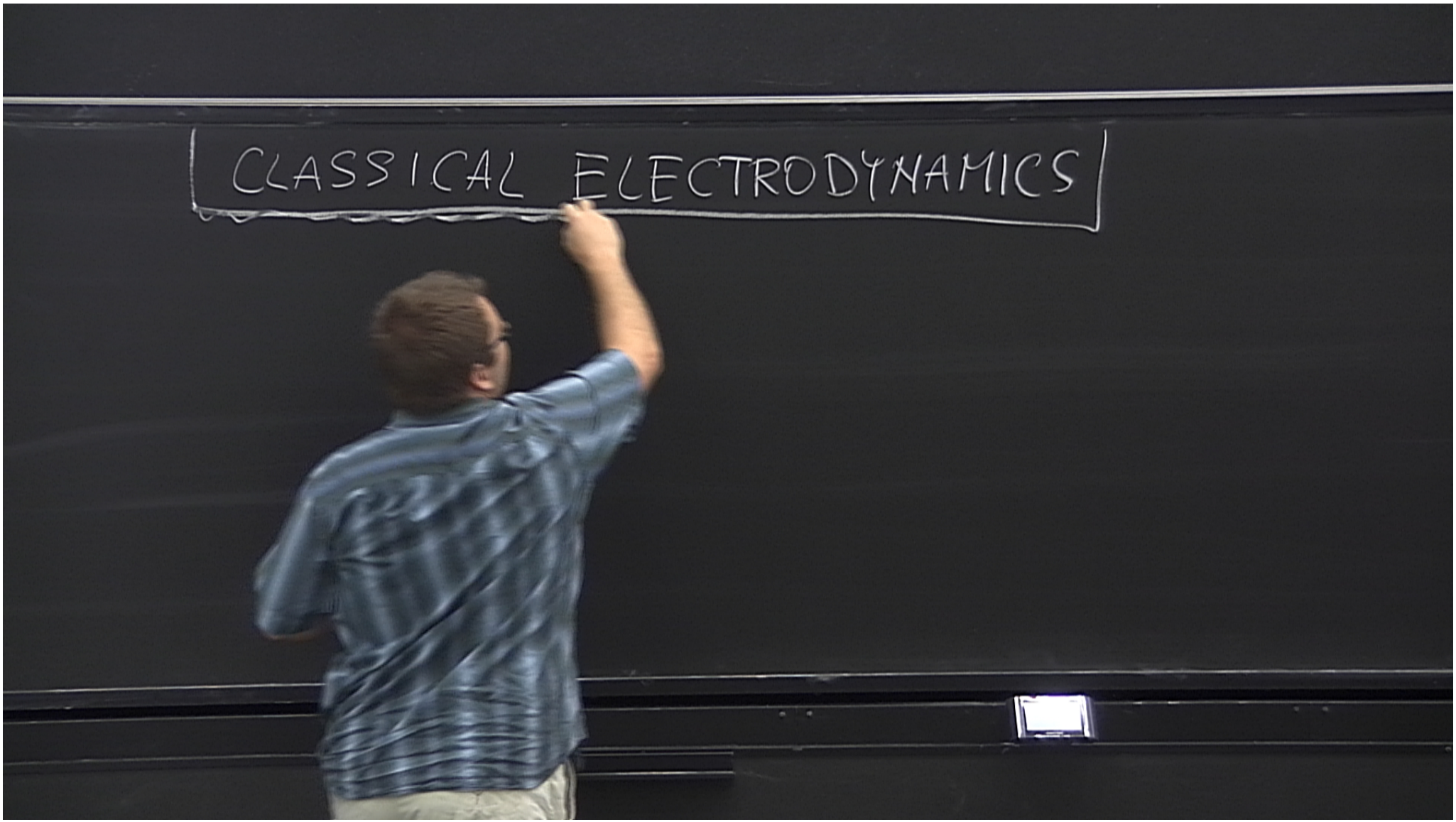
Title: Integral Transforms & Green's Functions - Lecture 3

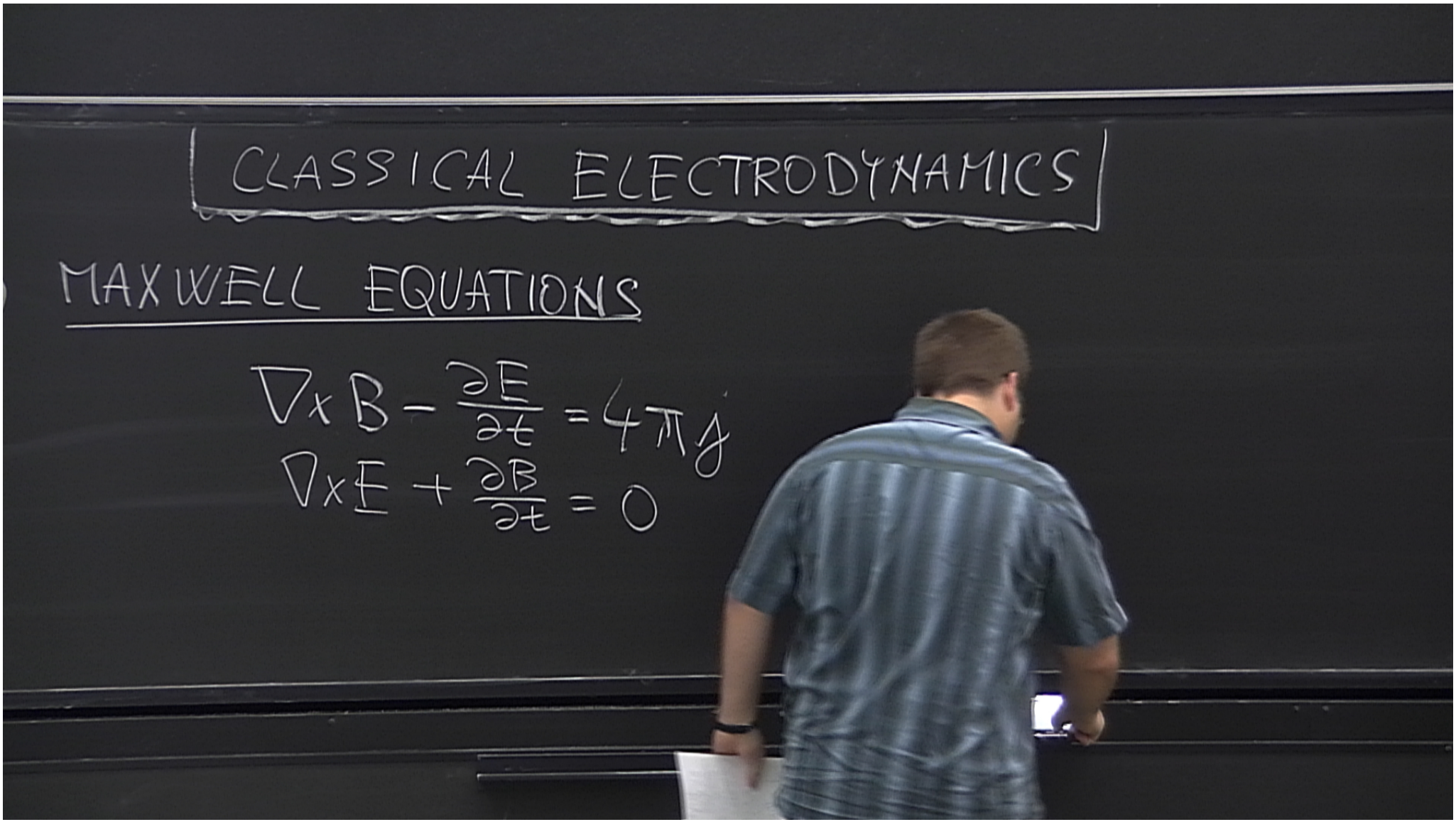
Date: Aug 29, 2012 09:00 AM

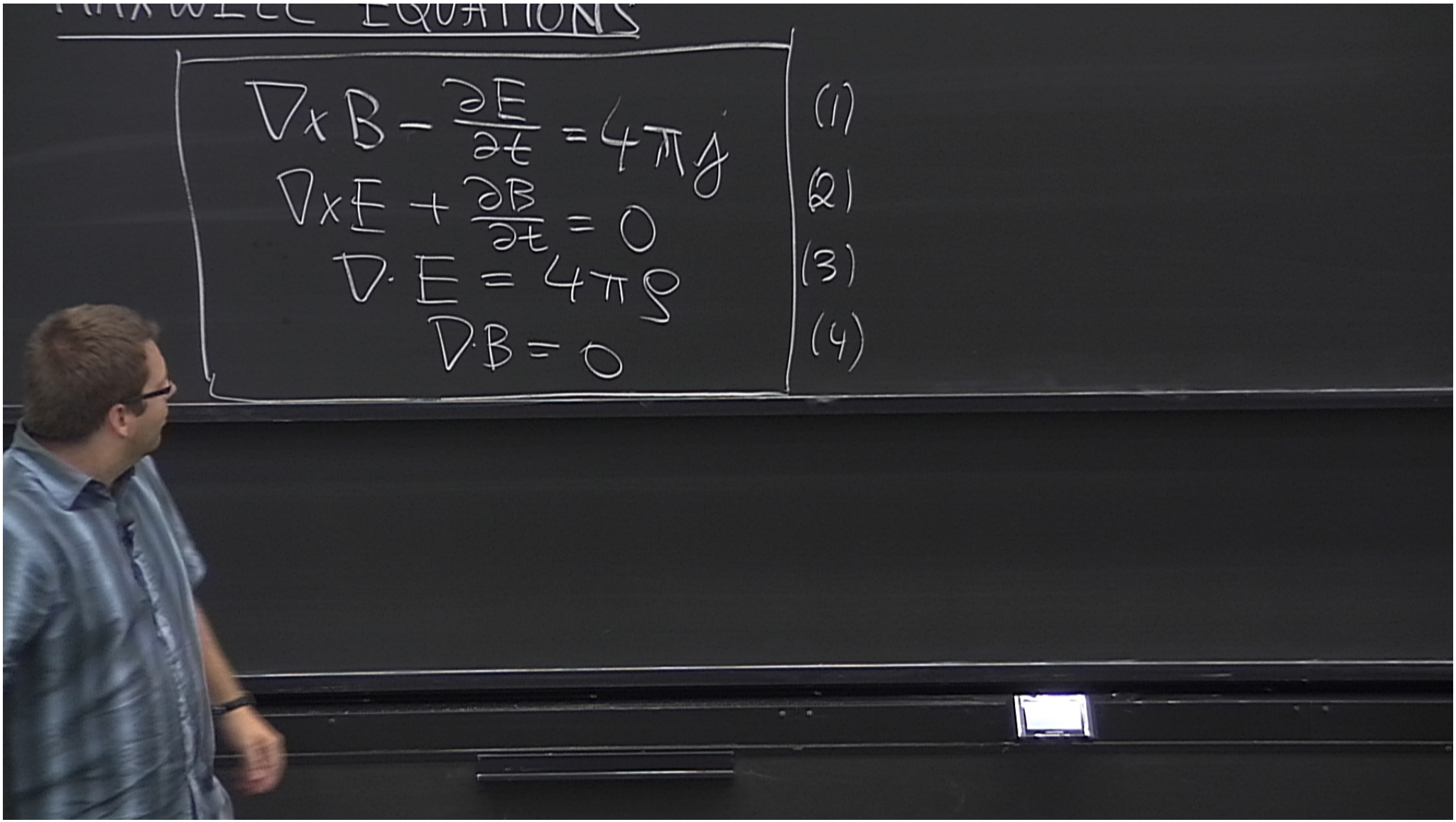
URL: http://pirsa.org/12080030

Abstract:


CLASSICAL ELECTRODYNA


CLASSICAL ELECTRODYNAMICS


CLASSICAL ELECTRODYNAMICS
MAXWELL EQUATIONS
$\nabla \times B - \frac{\partial E}{\partial t} = 4\pi j$
$\nabla \times E + \frac{\partial B}{\partial t} = 0$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$\nabla \cdot E = 4\pi \rho$ (3)
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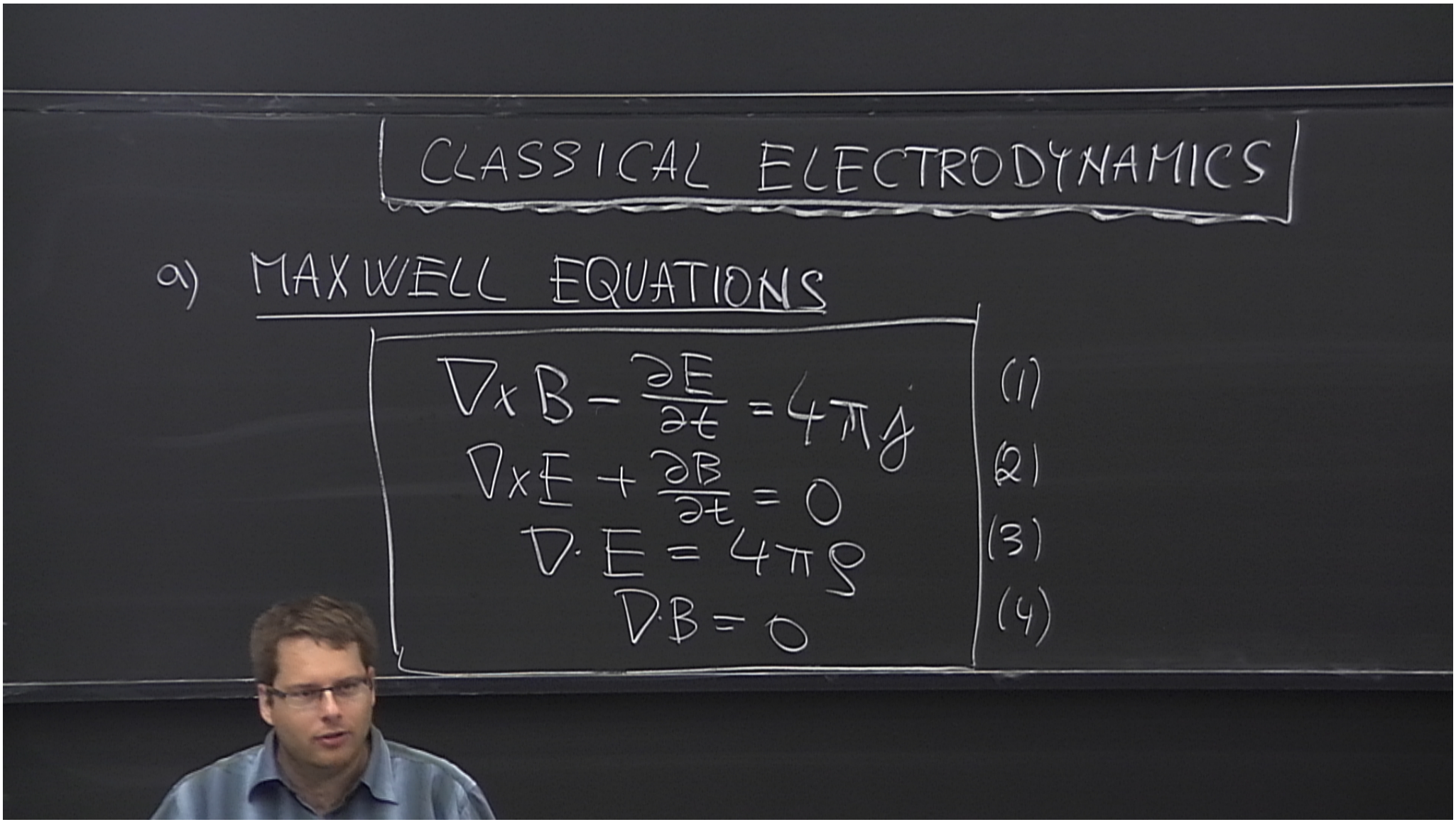
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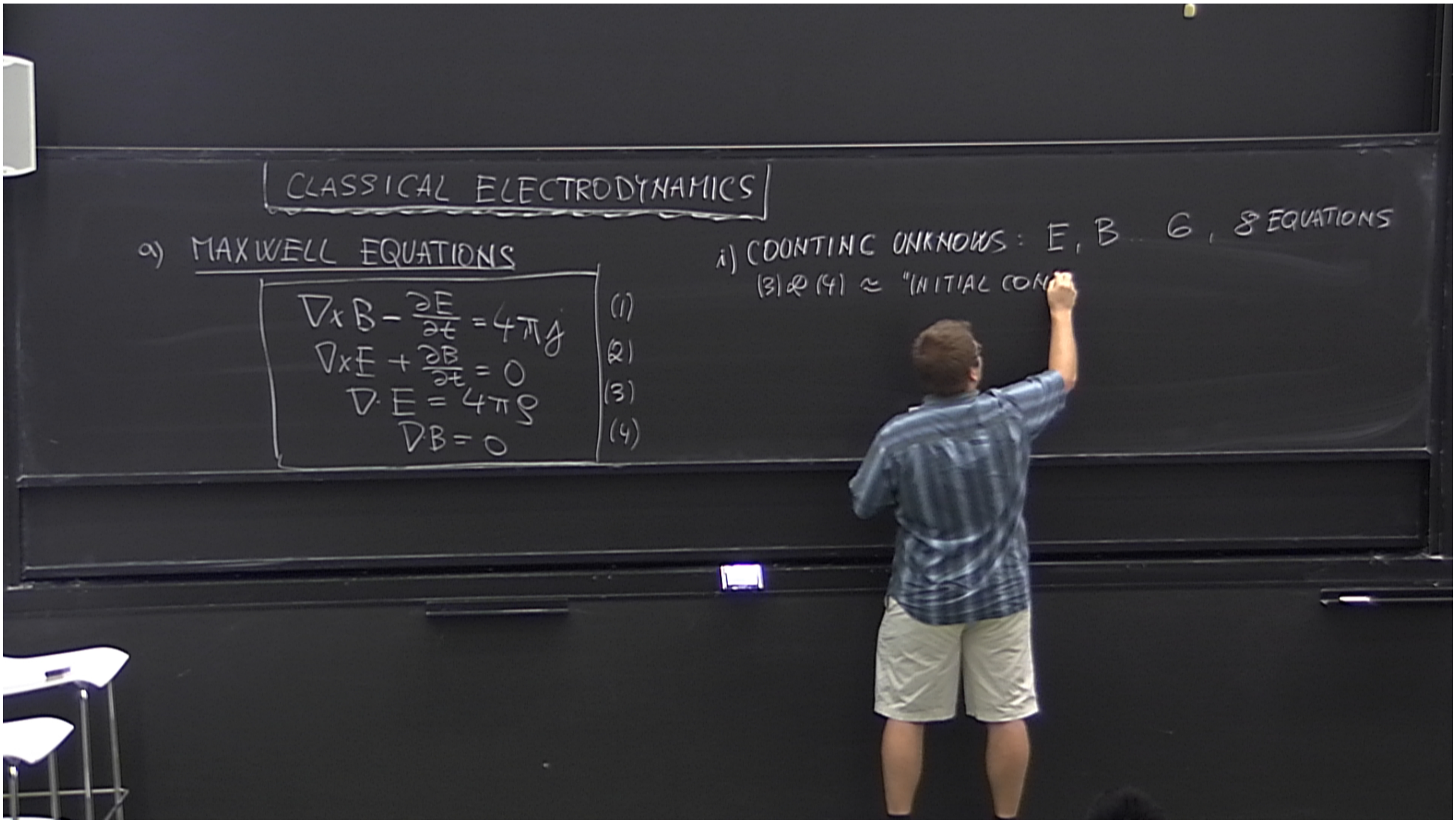
i) COUNTING UNKNOWNS: E, B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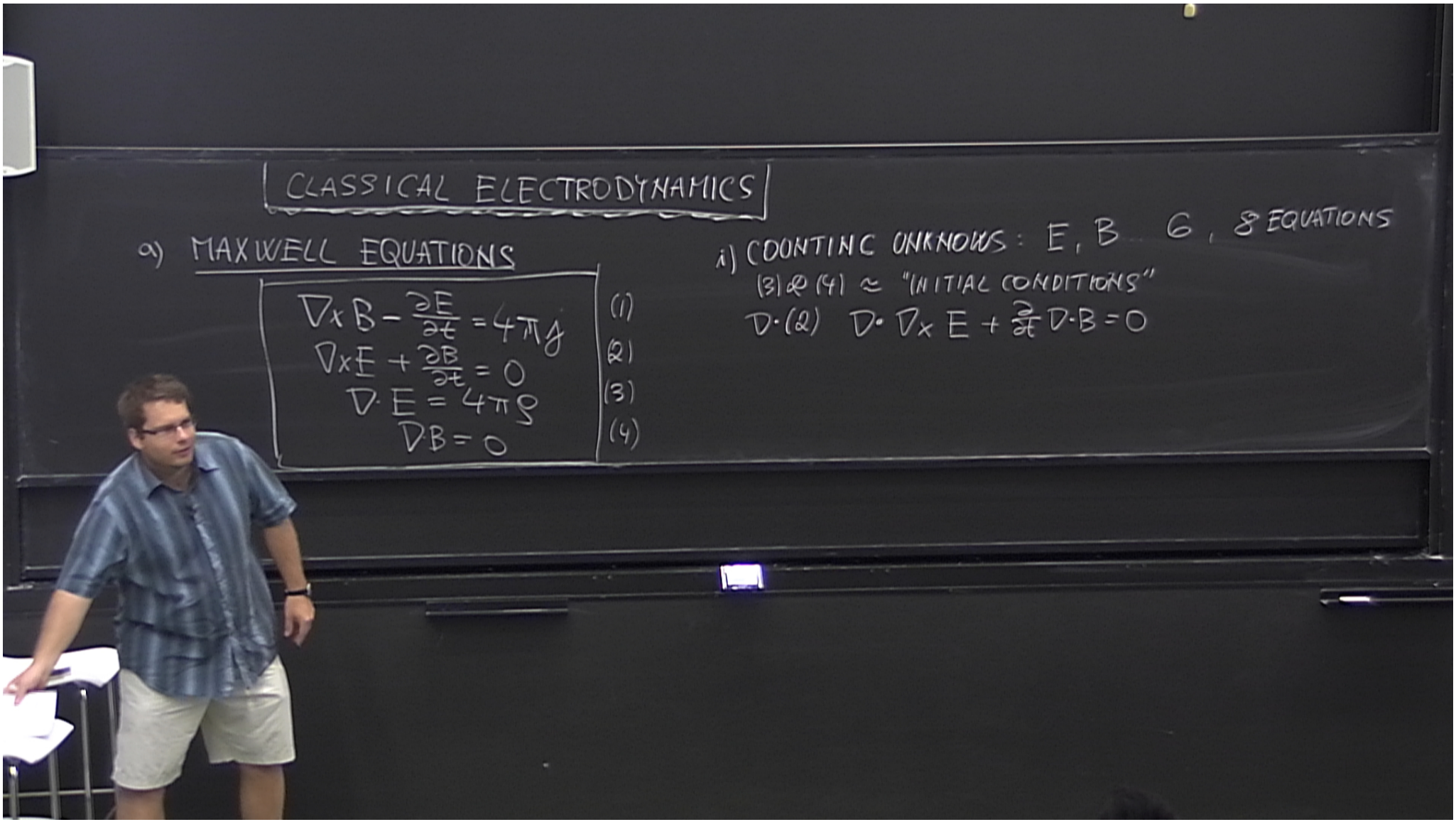
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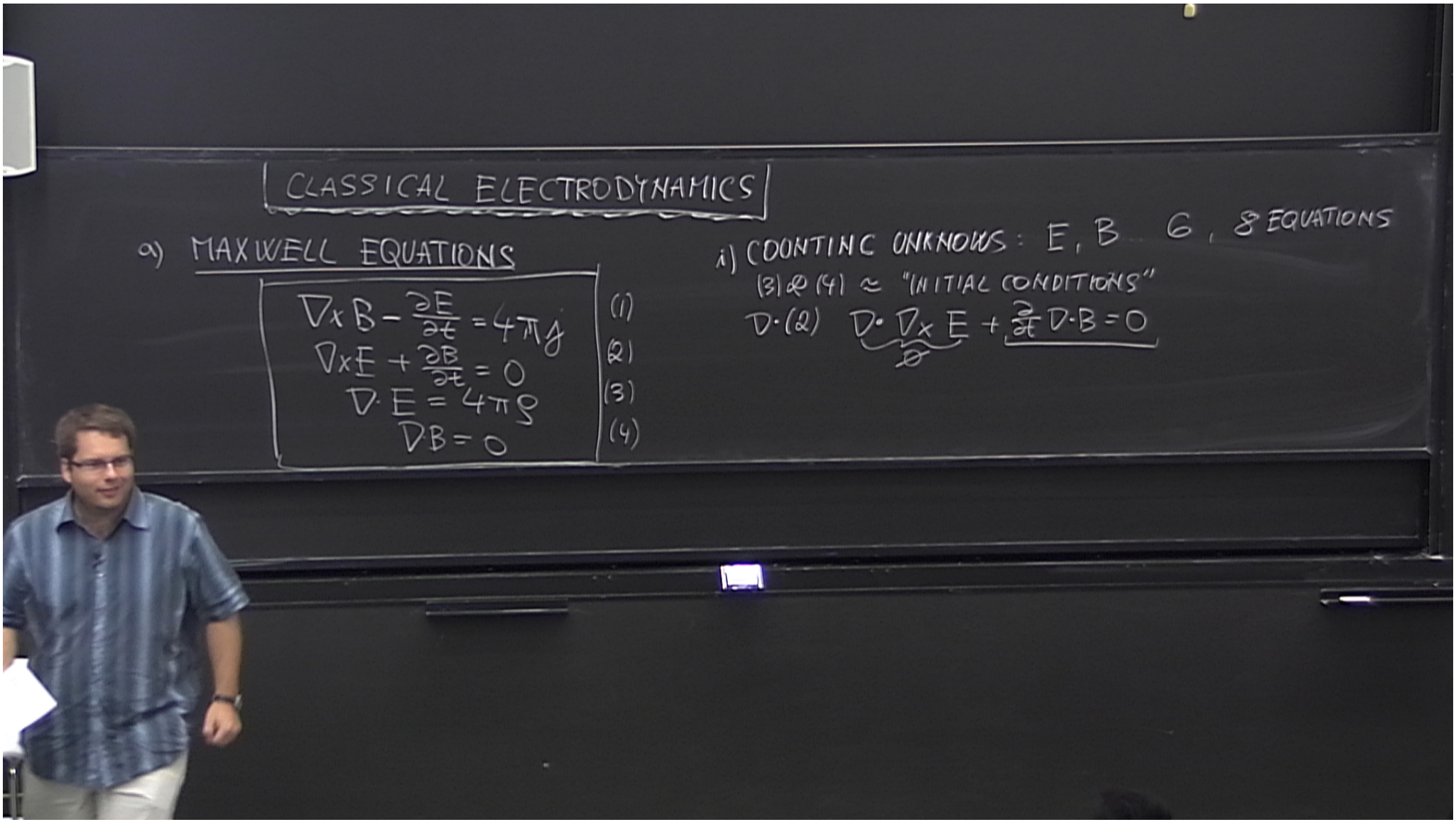
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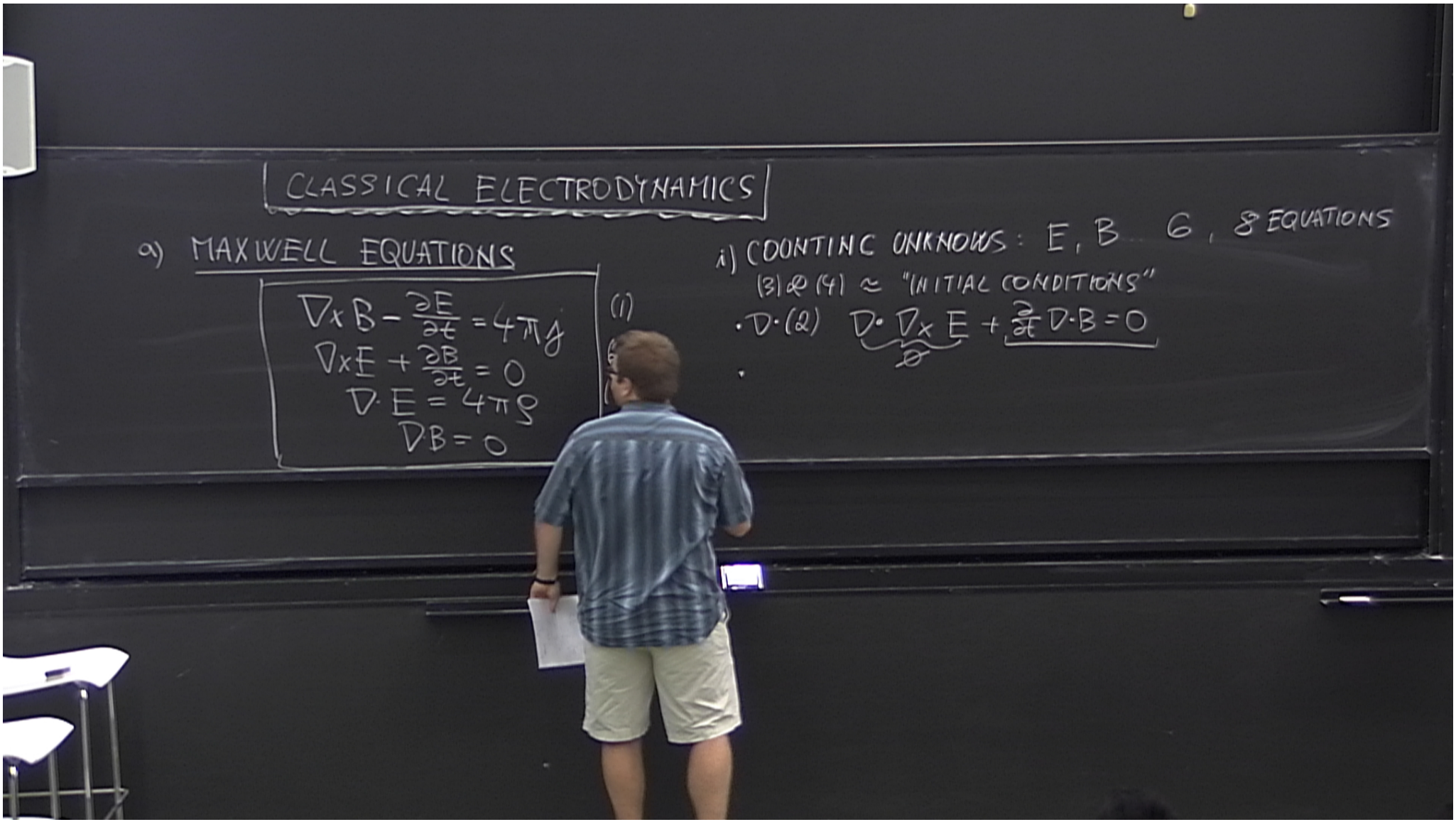
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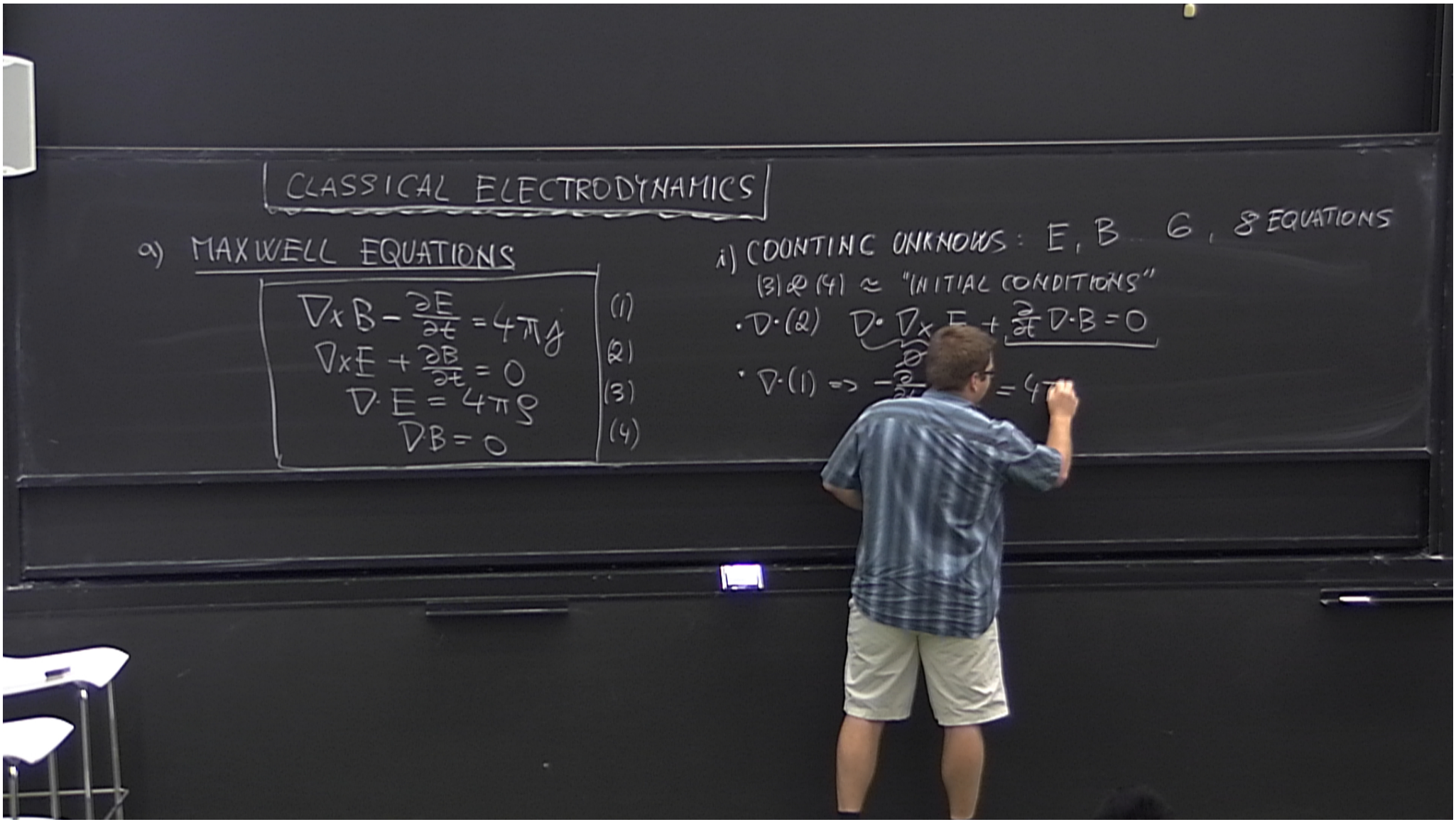
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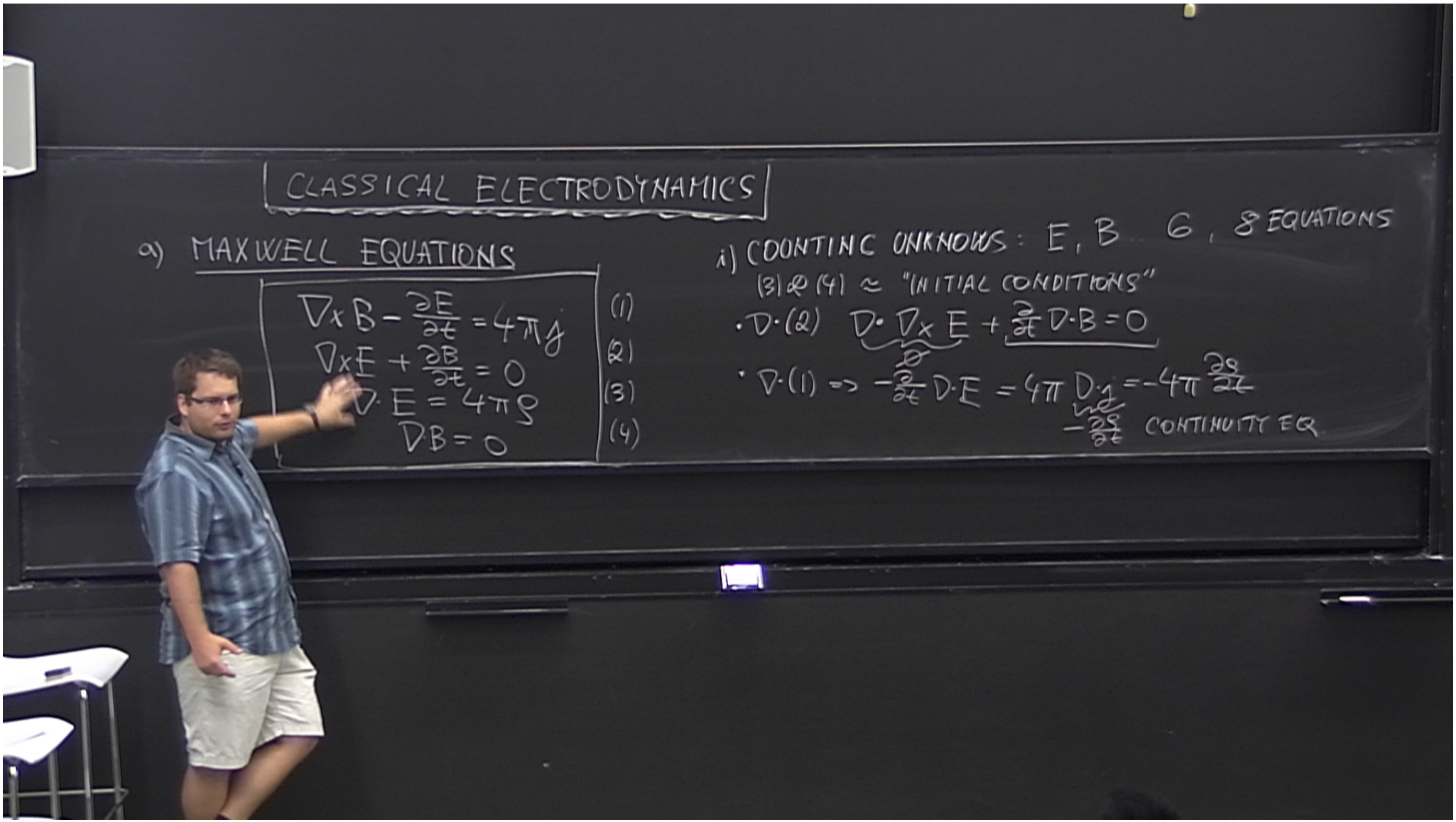
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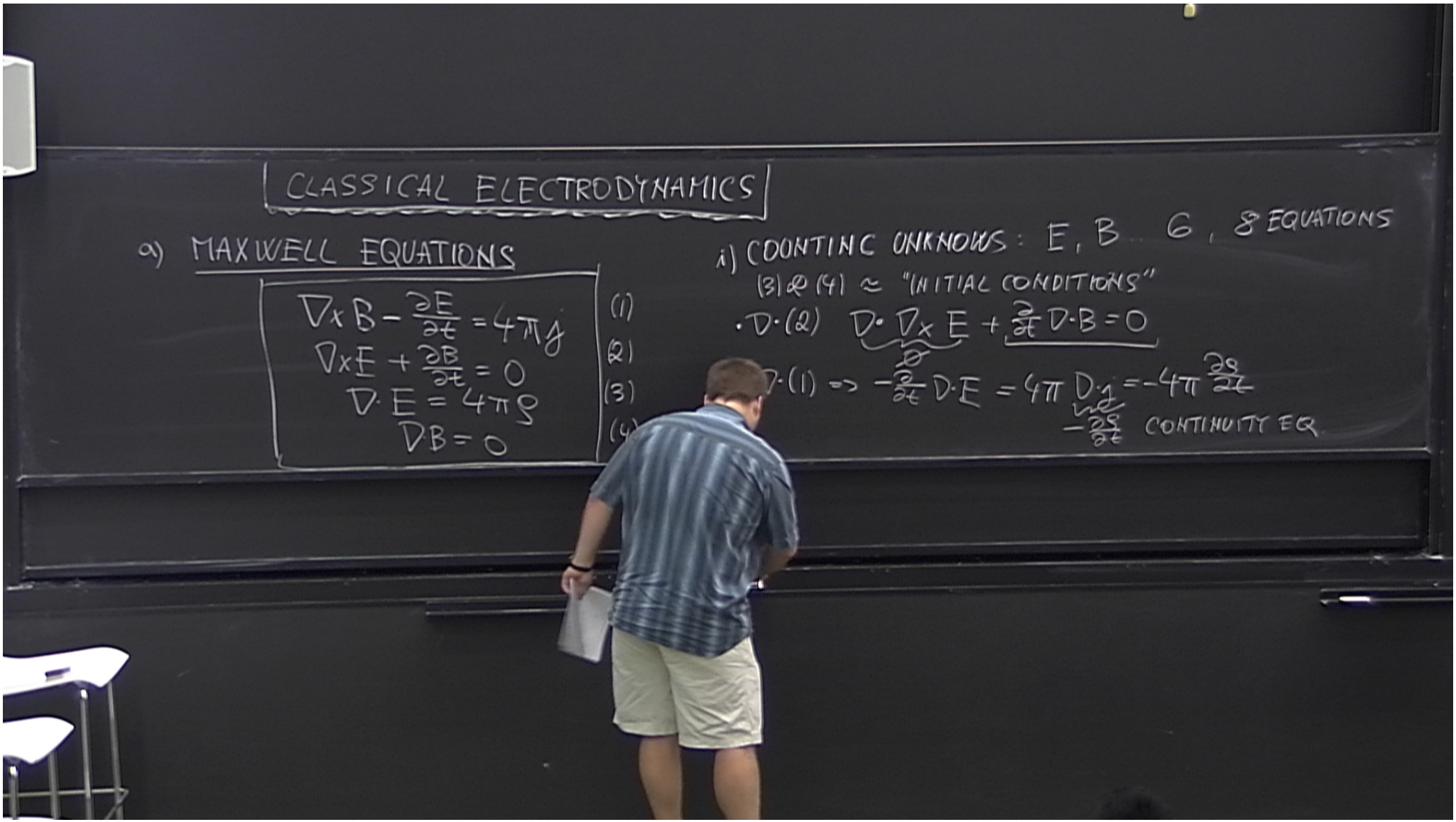
$-\frac{\partial \rho}{\partial t}$ CONTINUITY EQ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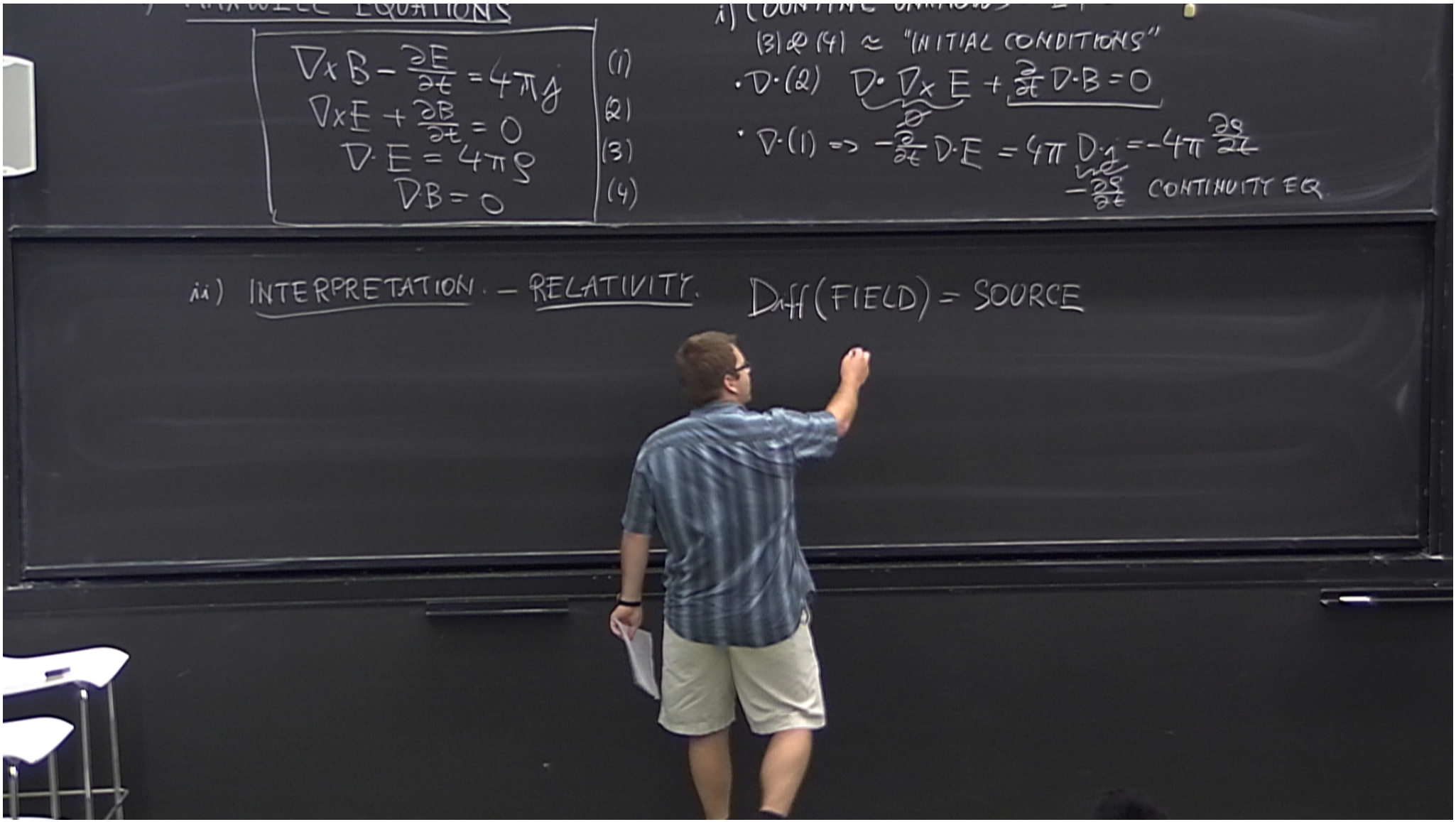
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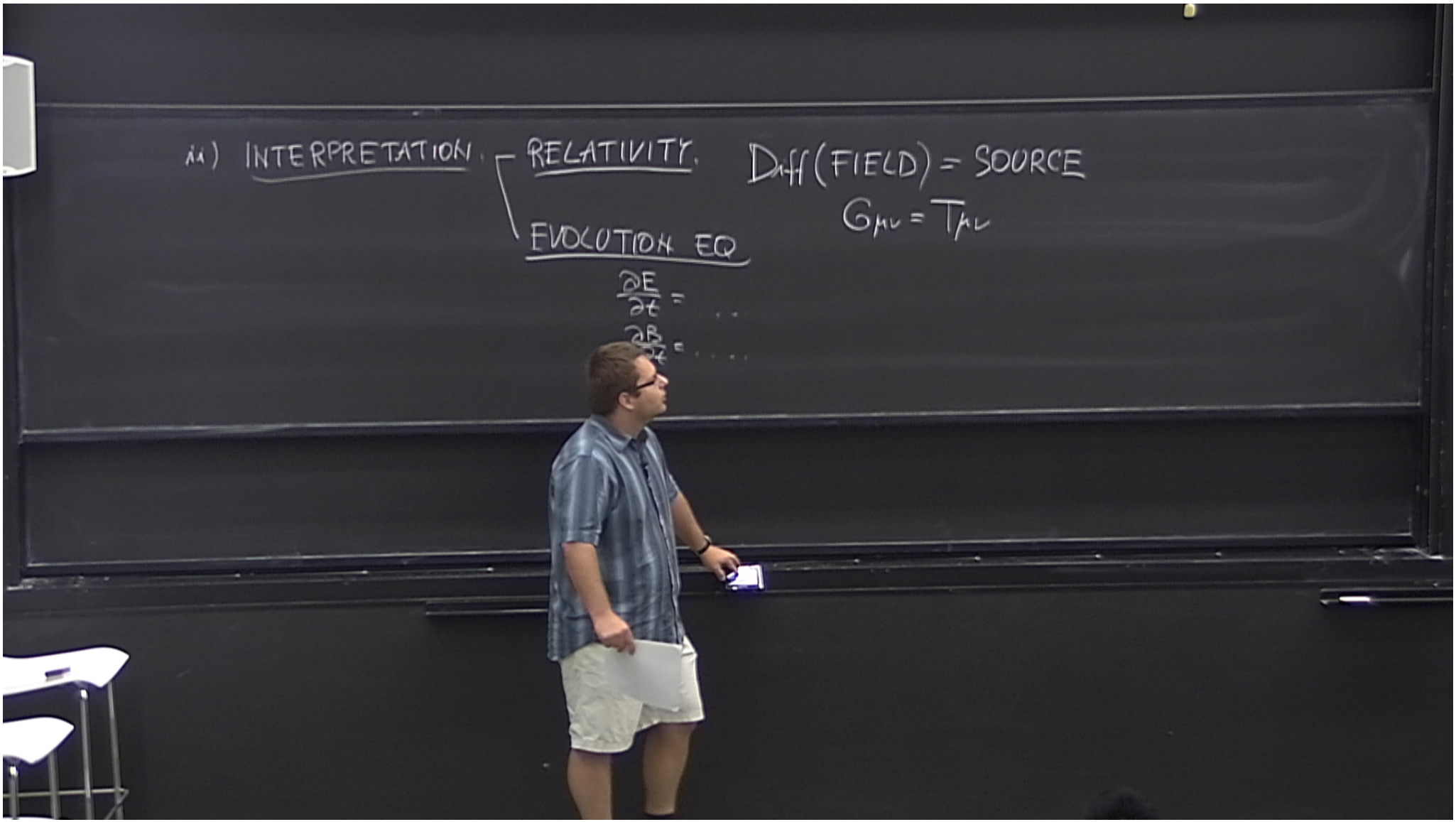
ii) INTERPRETATION. – RELATIVITY.
Diff(FIELD) = SOURCE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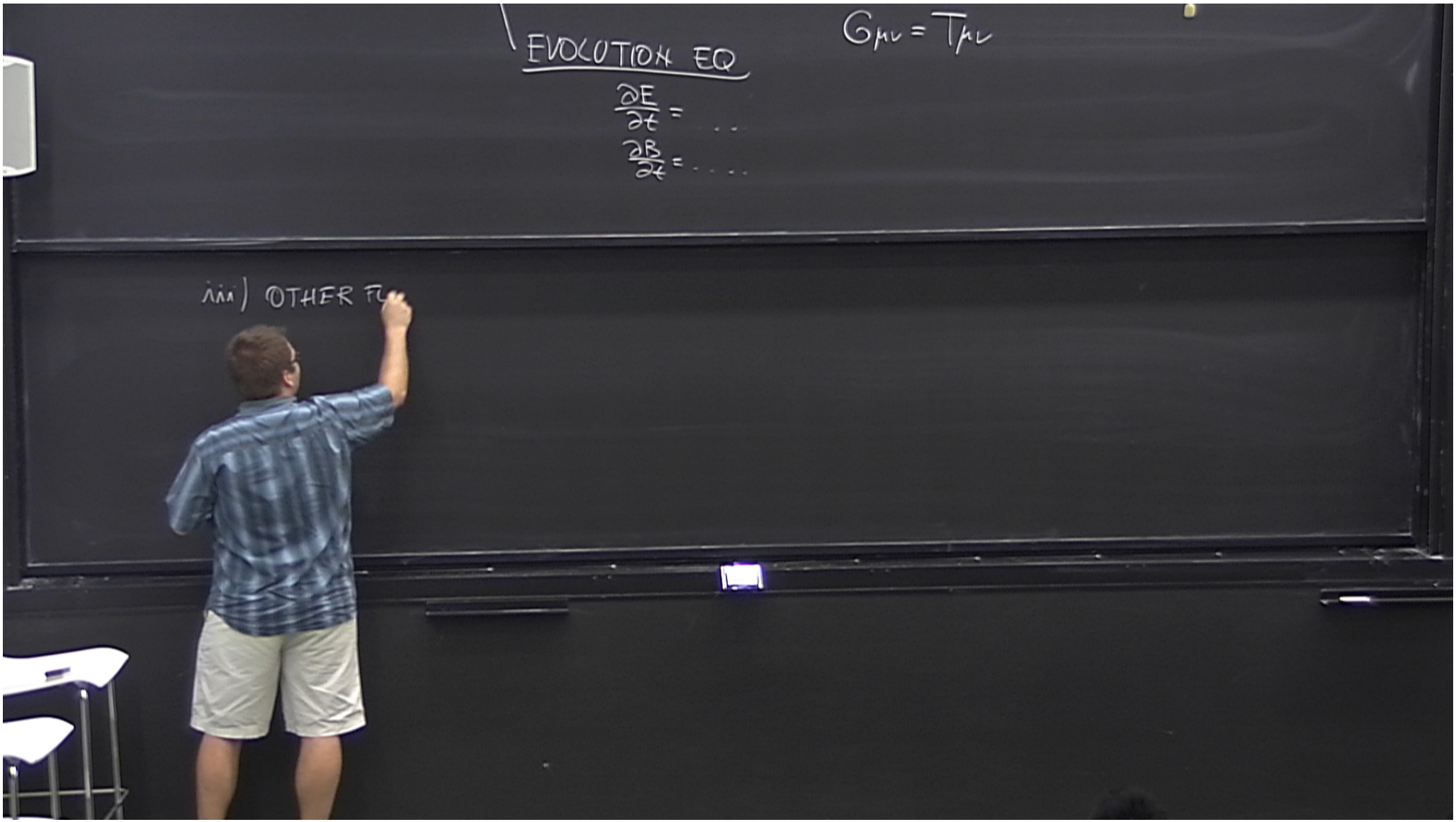
Diff (FIELD) = SOURCE
$G_{\mu\nu} = T_{\mu\nu}$
EVOLUTION EQ
$\frac{\partial E}{\partial t} = \ldots$
$\frac{\partial B}{\partial t} = \ldots$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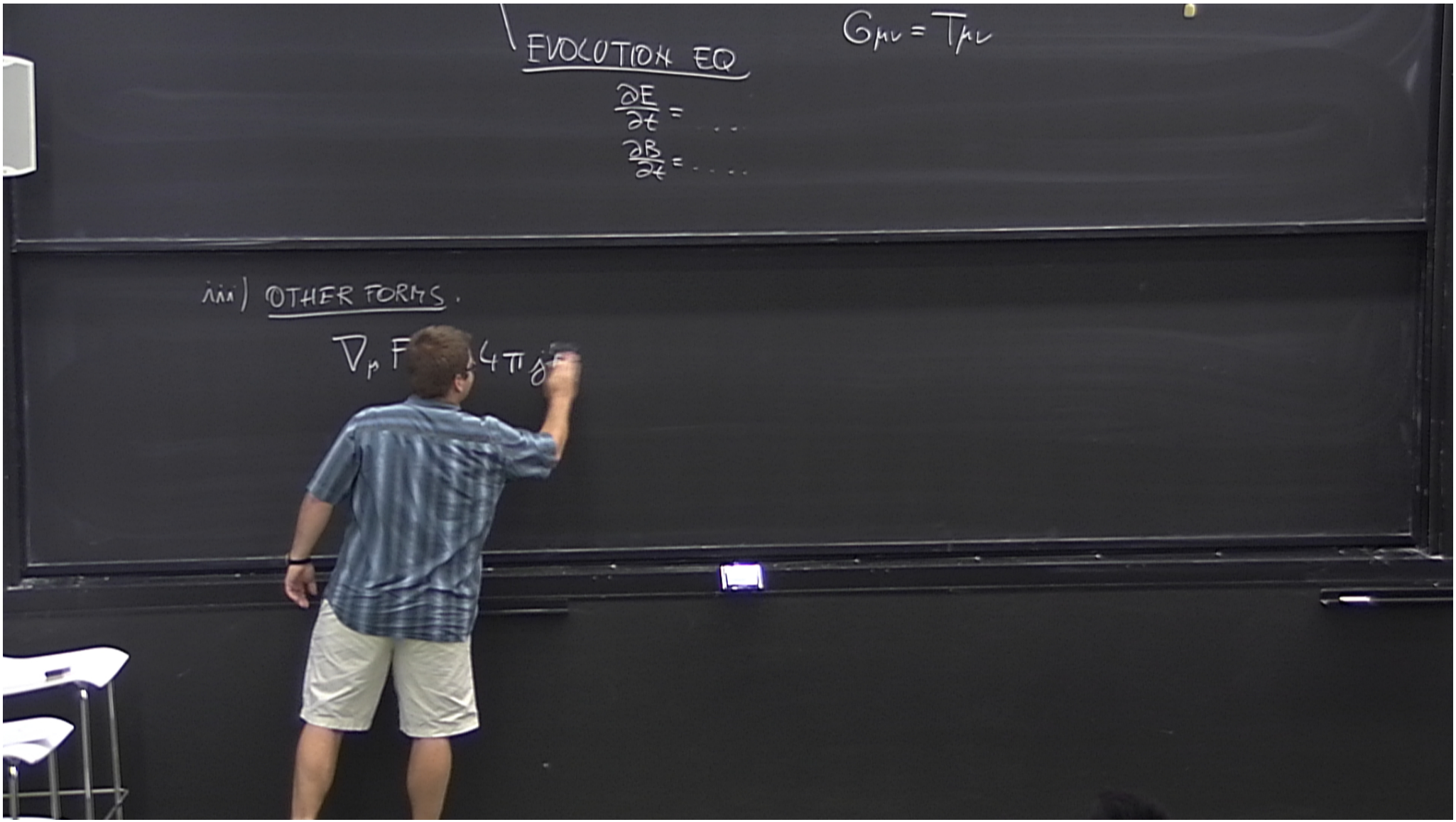
iii) OTHER FU


EVOLUTION EQ
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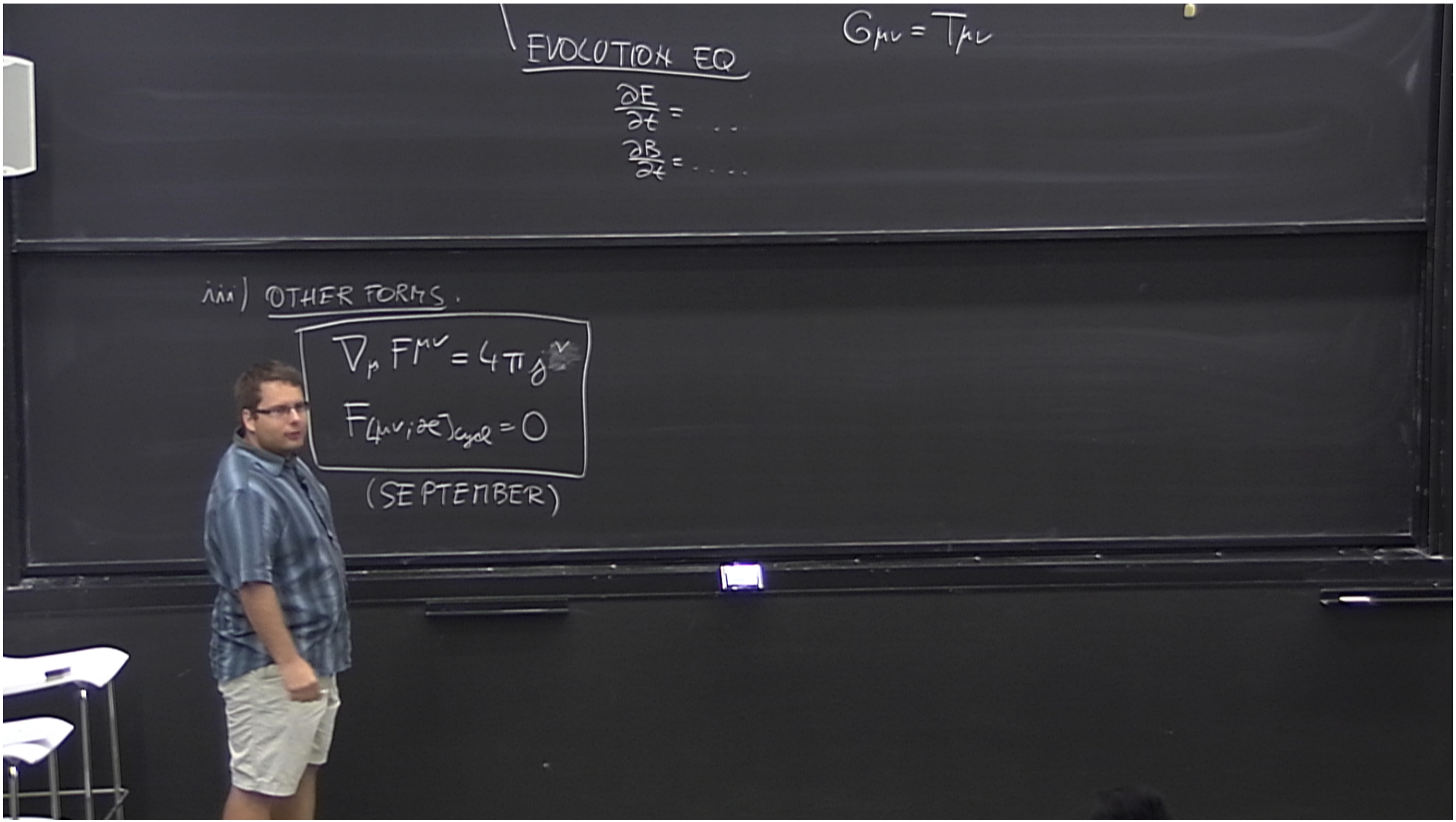
iii) OTHER FORMS.
$\nabla_\mu F$ $4\pi j$


EVOLUTION EQ
$G_{\mu\nu} = T_{\mu\nu}$
$\frac{\partial E}{\partial t} = \ldots$
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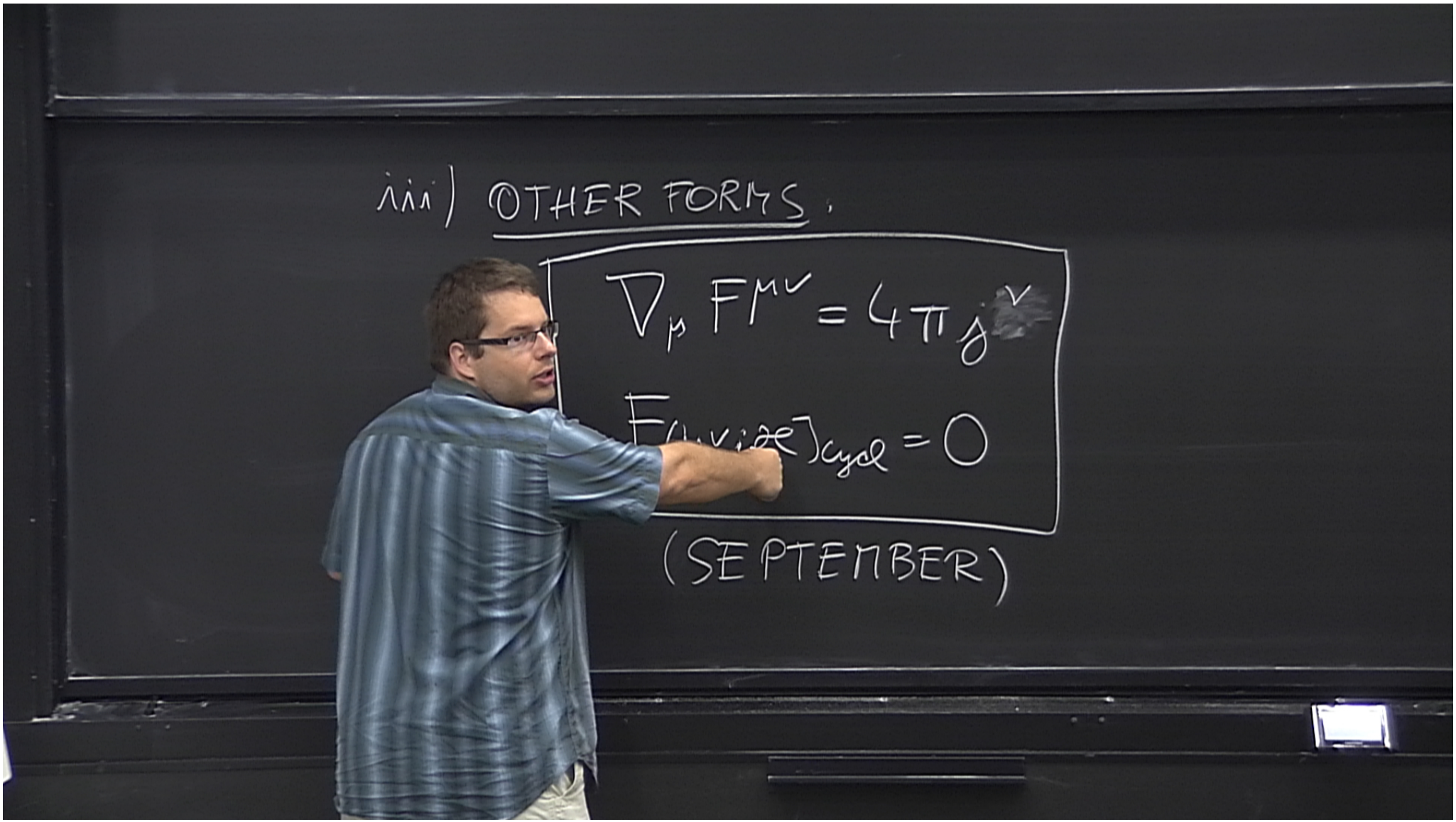
iii) OTHER FORMS.
$\nabla_\mu F^{\mu\nu} = 4\pi j^\nu$
$F_{[\mu\nu;\alpha]_{cycl}} = 0$
(SEPTEMBER)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(SEPTEMBER)

$$\boxed{\begin{aligned} d * F &= 4\pi j \\ dF &= 0 \end{aligned}}$$

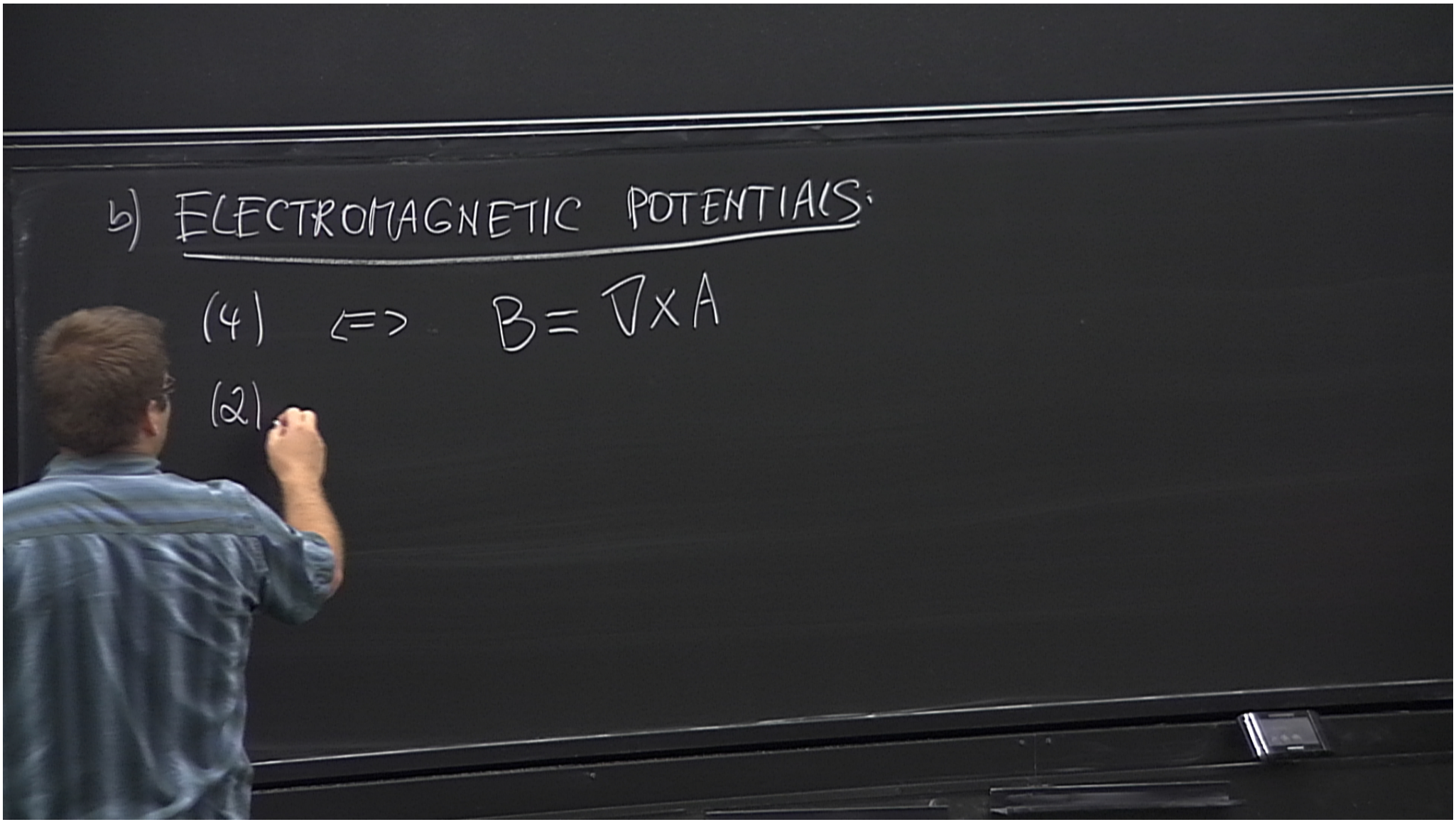
iii) OTHER FORMS.

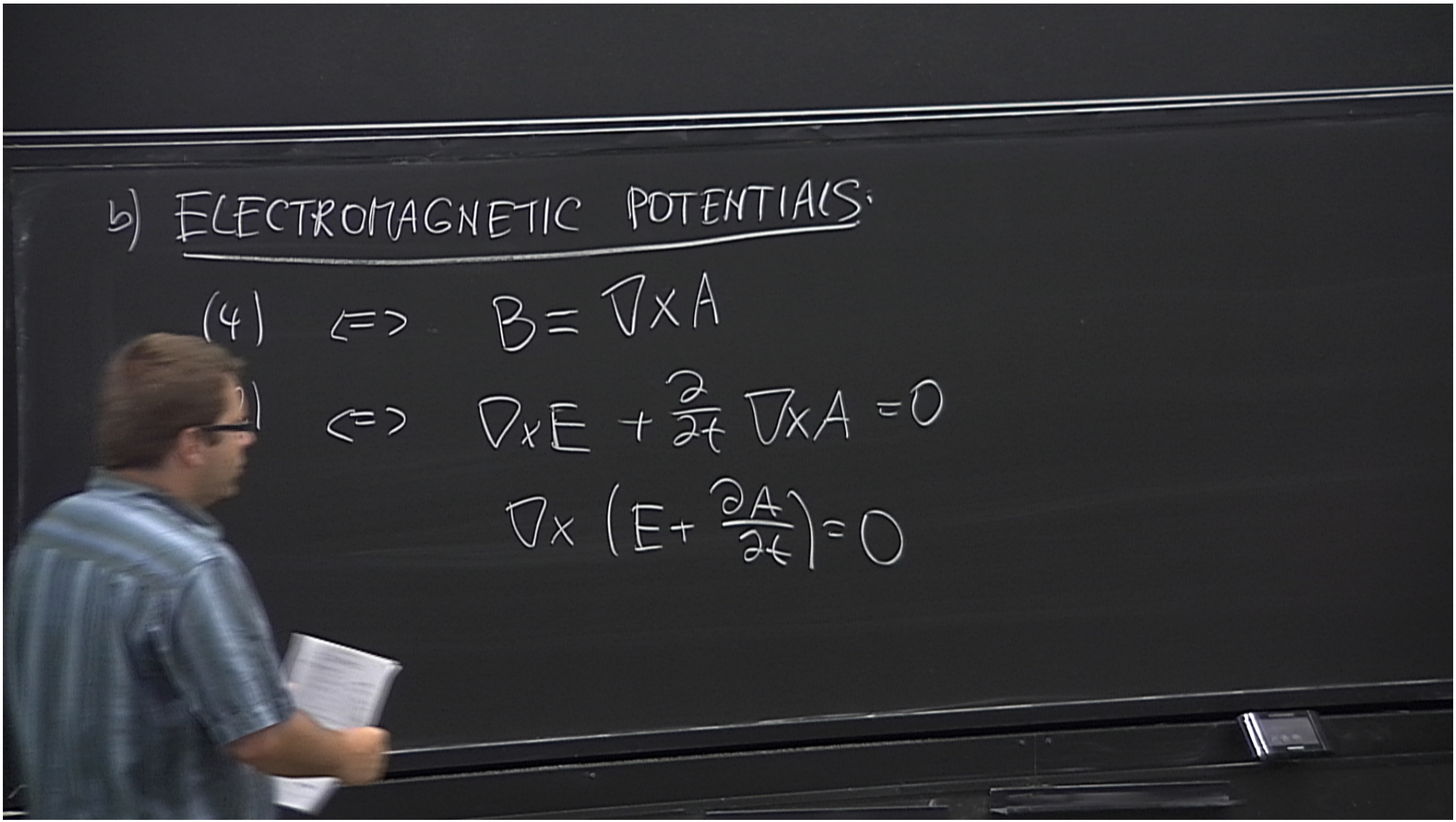
$$\boxed{\begin{aligned} \nabla_\mu F^{\mu\nu} &= 4\pi j^\nu \\ F_{[\mu\nu;\varkappa]\,\mathrm{cycl}} &= 0 \end{aligned}} \iff \boxed{\begin{aligned} d{*F} &= 4\pi j \\ dF &= 0 \end{aligned}}$$

(SEPTEMBER) (JANUARY)

b) ELECTROMAGNETIC POTENTIALS:

(4)


b) ELECTROMAGNETIC POTENTIALS:
(4) <=> B = ∇ x A
(2)

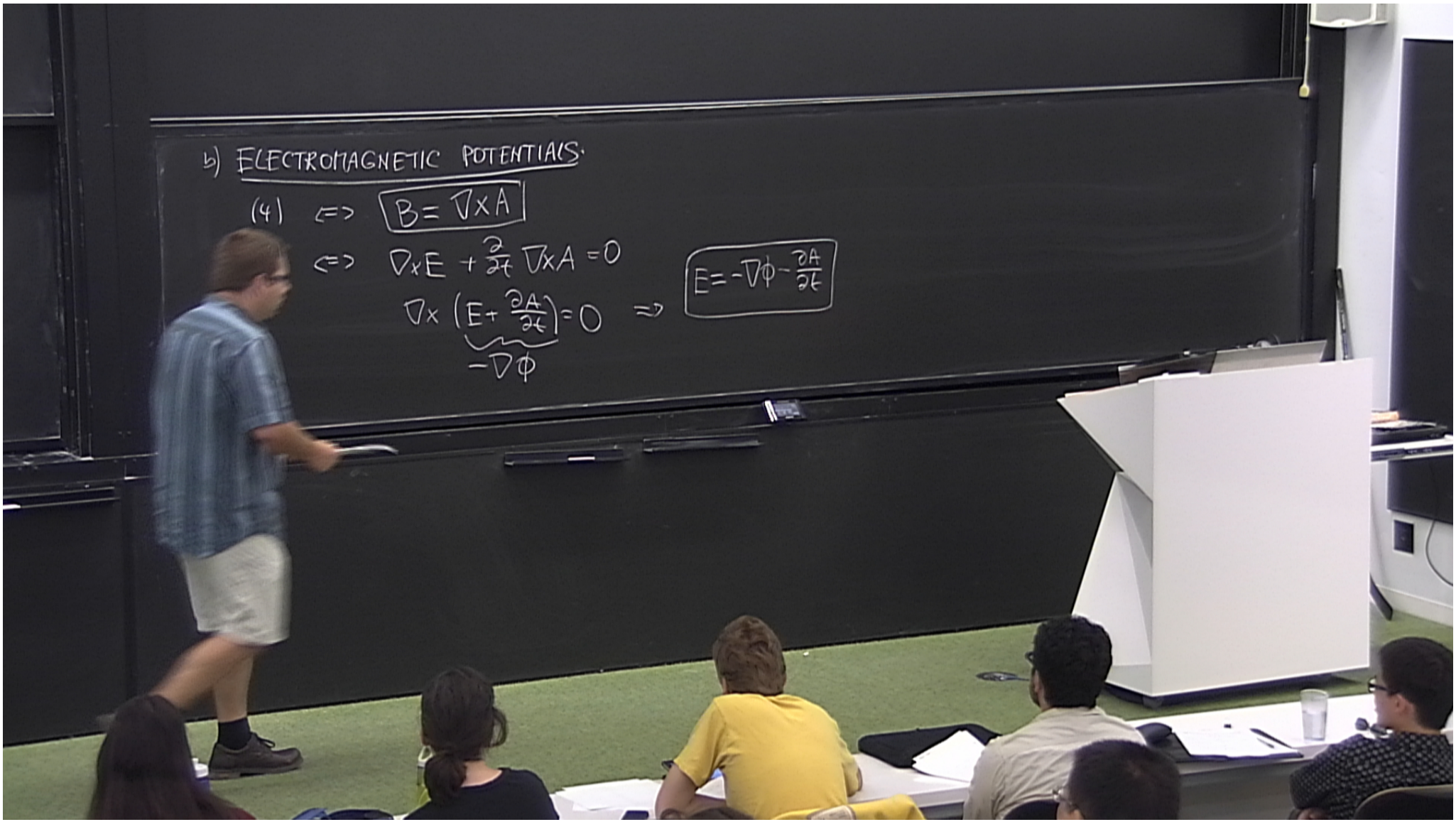

b) ELECTROMAGNETIC POTENTIALS:
(4) <=> B = ∇×A
<=> ∇×E + ∂/∂t ∇×A = 0
∇×(E + ∂A/∂t) = 0

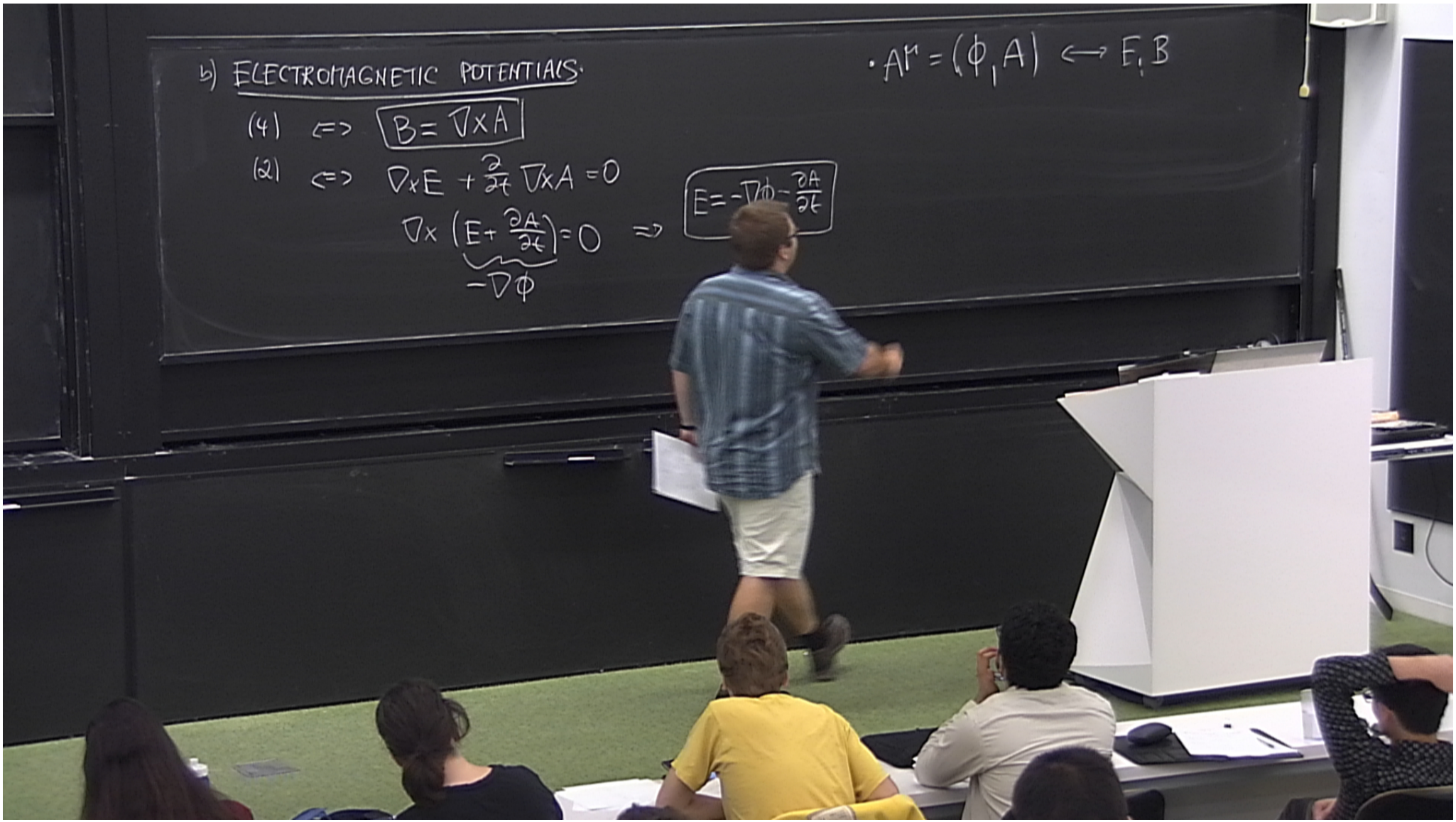
b) ELECTROMAGNETIC POTENTIALS:

$$(4) \iff B = \nabla \times A$$

$$(2) \iff \nabla \times E + \frac{\partial}{\partial t} \nabla \times A = 0$$

$$\nabla \times \underbrace{\left(E + \frac{\partial A}{\partial t}\right)}_{-\nabla \phi} = 0 \implies E = -\nabla \phi - \frac{\partial A}{\partial t}$$


b) ELECTROMAGNETIC POTENTIALS.
(4) <=> B = ∇xA
<=> ∇xE + ∂/∂t ∇xA = 0
∇x (E + ∂A/∂t) = 0 => E = -∇φ - ∂A/∂t
-∇φ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(4) <=> B = ∇×A
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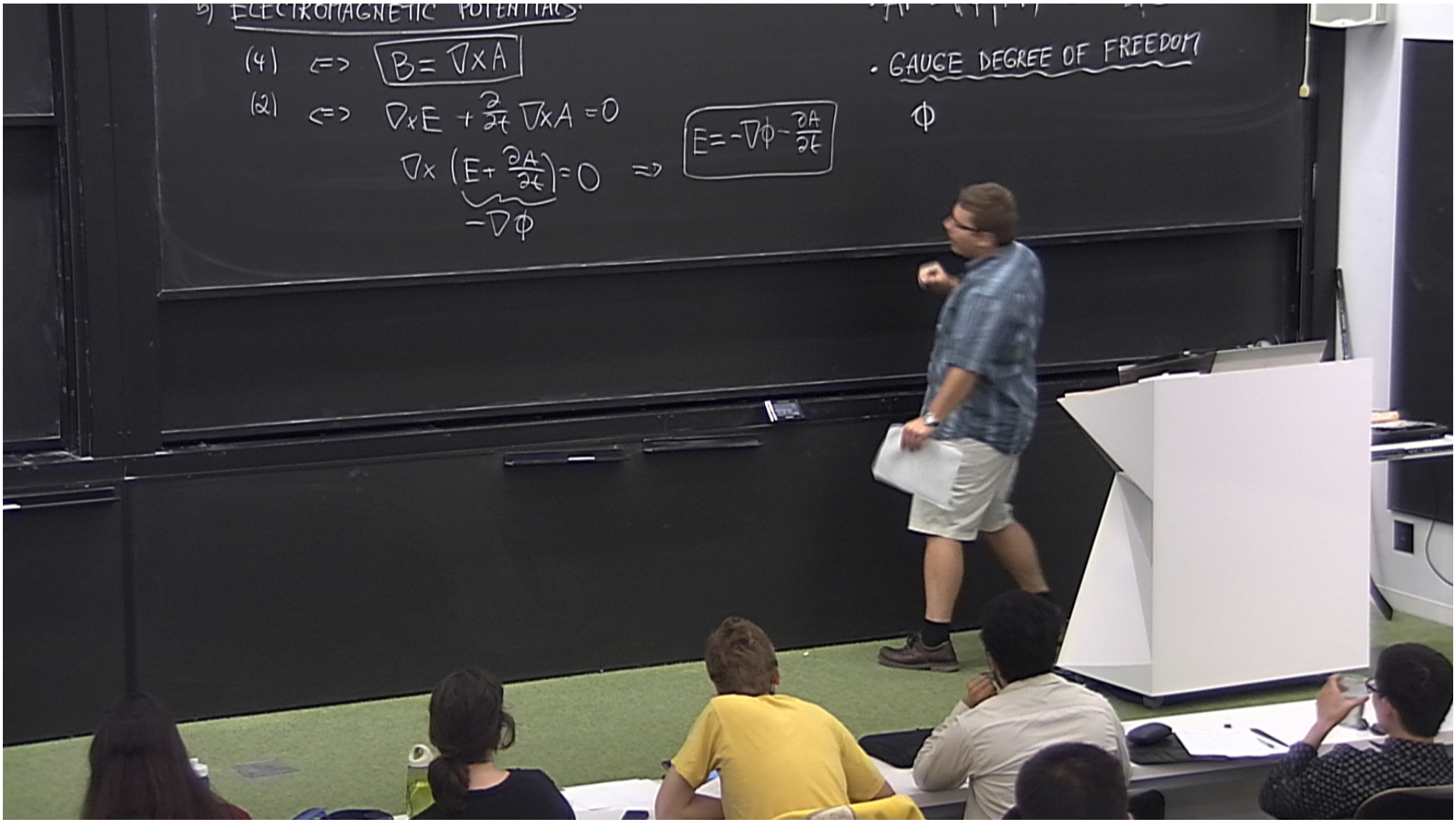
∇× (E + ∂A/∂t) = 0 => E = −∇φ − ∂A/∂t
−∇φ
• A^μ = (φ, A) ⟷ E, B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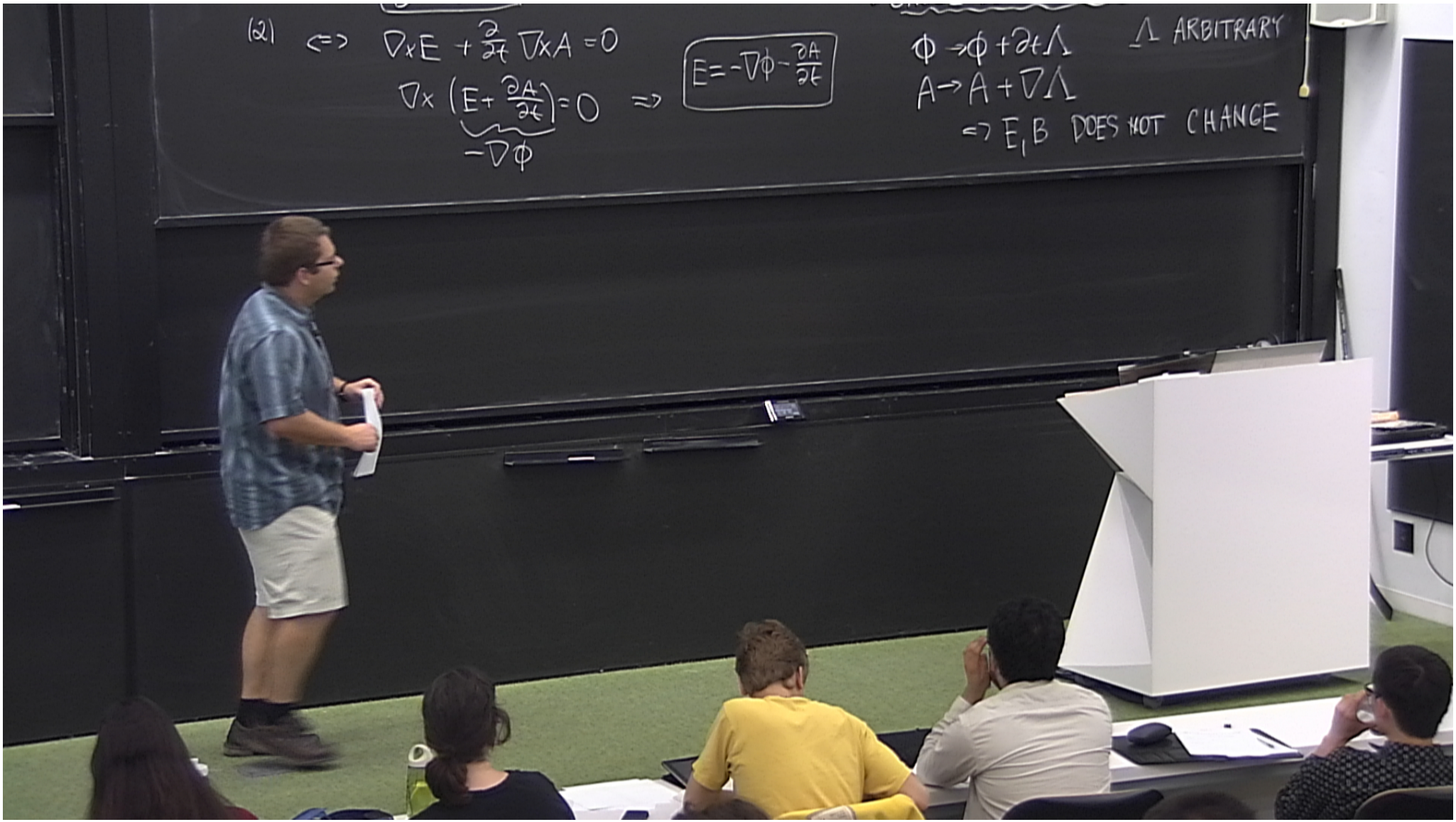
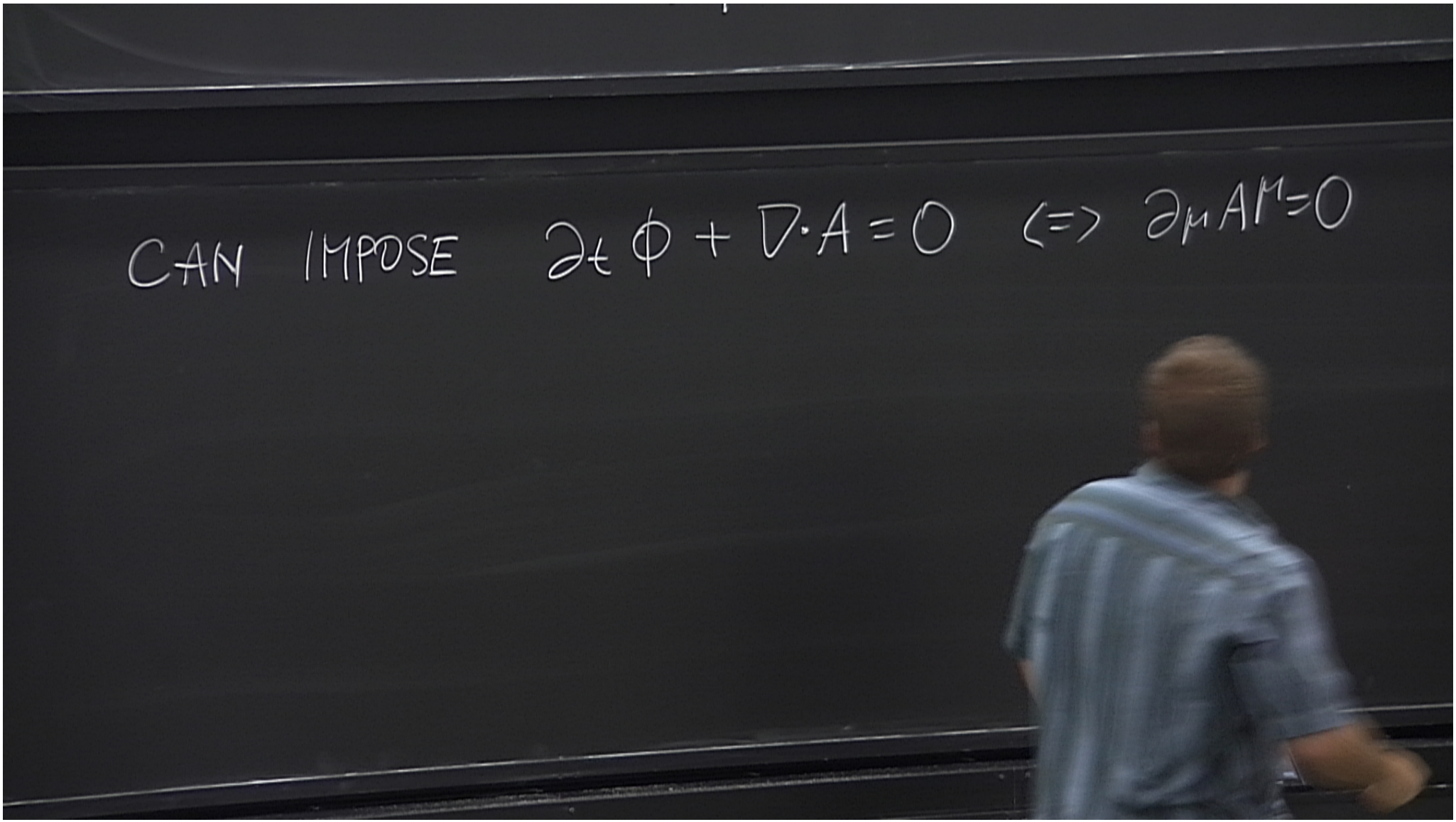
-∇φ
• GAUGE DEGREE OF FREEDOM
φ


(2) <=> ∇×E + ∂/∂t ∇×A = 0
∇× (E + ∂A/∂t) = 0 => E = -∇φ - ∂A/∂t
-∇φ
φ → φ + ∂t Λ
A → A + ∇Λ
Λ ARBITRARY
=> E, B DOES NOT CHANGE


CAN IMPOSE $\partial_t \phi + \nabla \cdot A = 0 \iff \partial_\mu A^\mu = 0$

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LORENTZ GAUGE COND.

CAN IMPOSE $\boxed{\partial_t \phi + \nabla \cdot A = 0} \iff \partial_\mu A^\mu = 0$

LORENTZ GAUGE COND.

c) <u>WAVE EQ.</u> (4) & (2) SOLVED BY A, ϕ

(3)

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LORENTZ GAUGE COND.

c) <u>WAVE EQ.</u> (4) & (2) SOLVED BY A, ϕ

(3) $\nabla \cdot \left(-\nabla\phi - \frac{\partial A}{\partial t}\right) = 4\pi\rho$

$-\Delta\phi - \frac{\partial}{\partial t}\nabla \cdot A = 4\pi\rho$

CAN IMPOSE $\boxed{\partial_t \phi + \nabla \cdot A = 0} \iff \partial_\mu A^\mu = 0$

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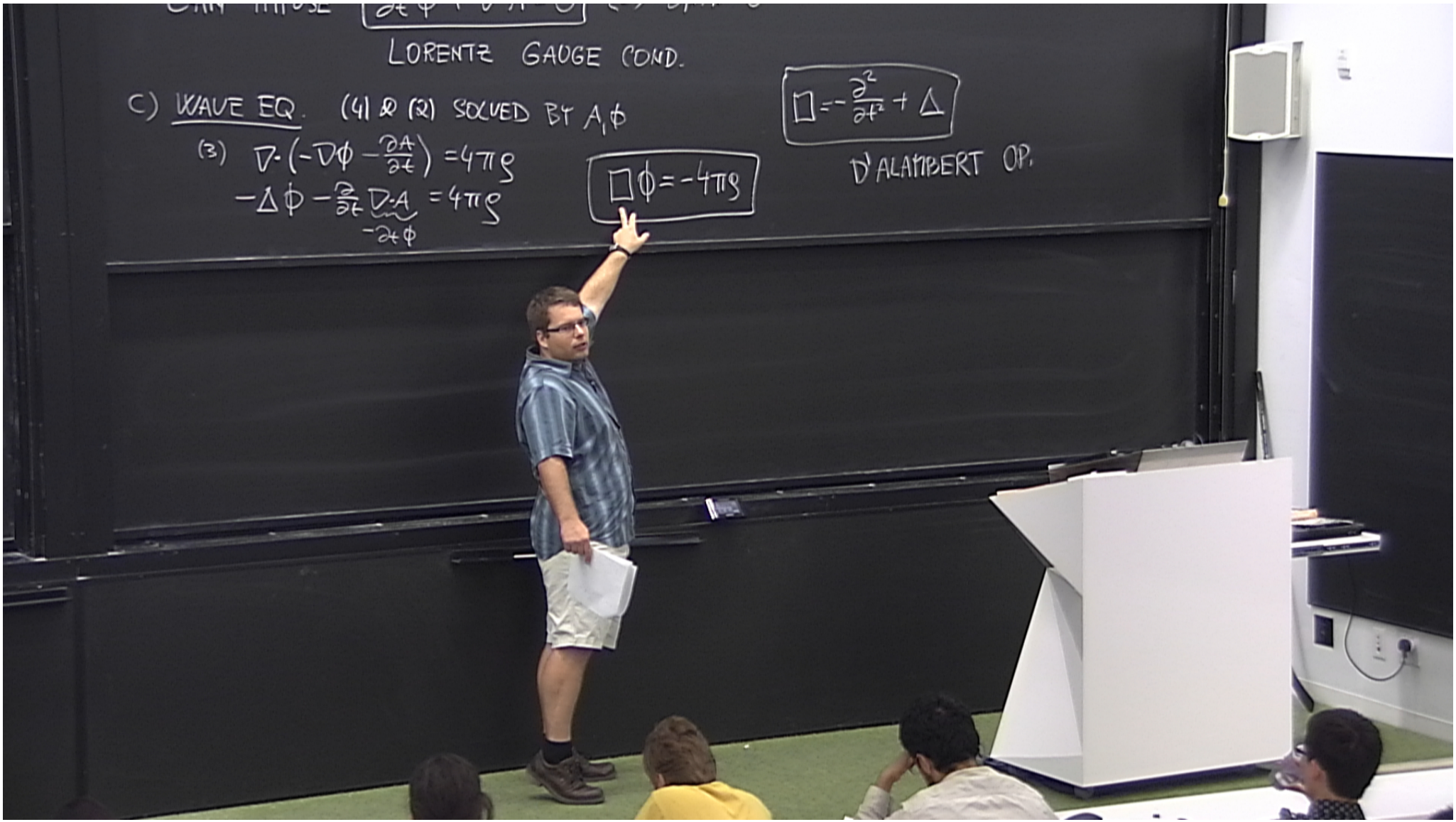
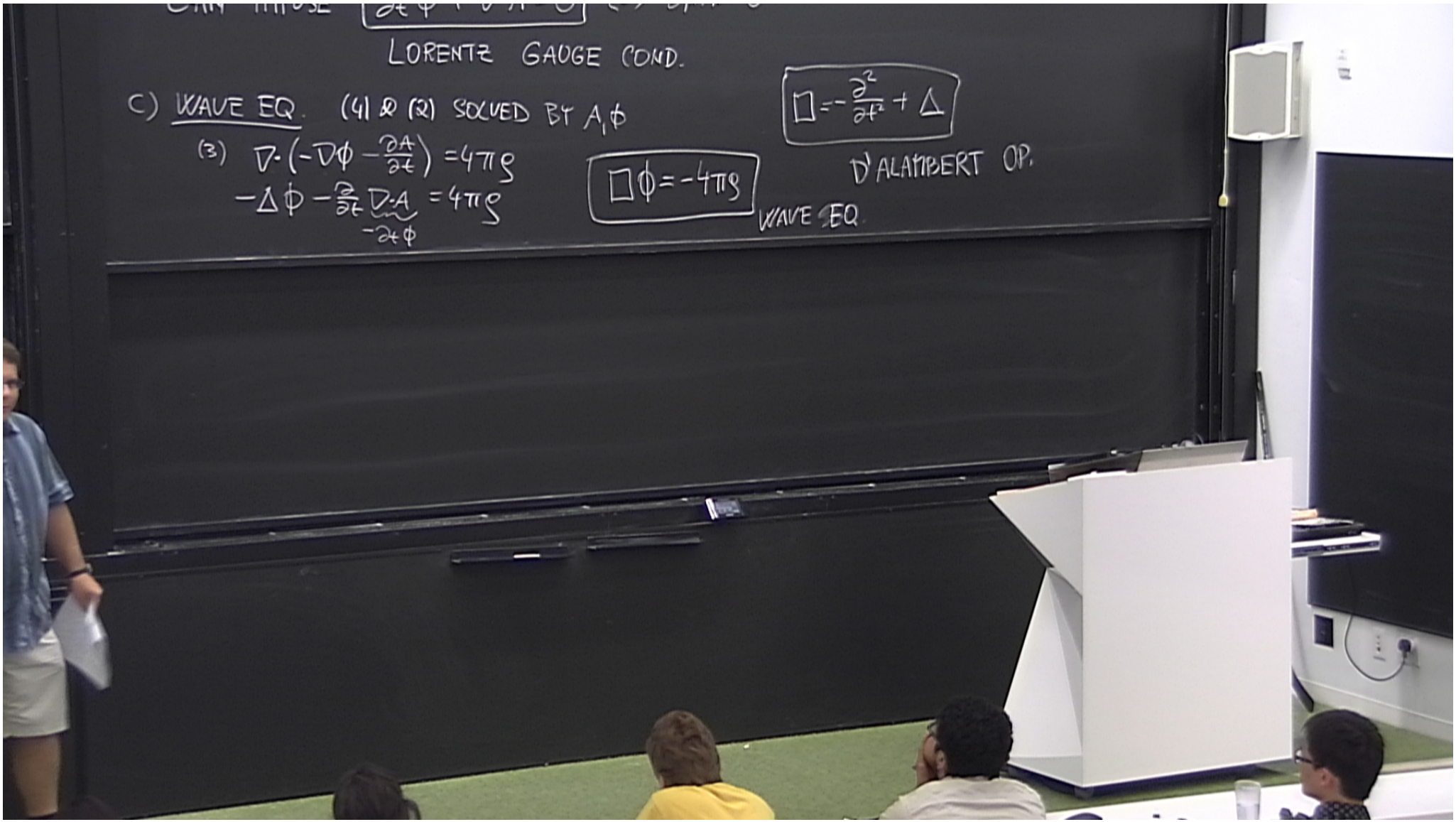
$$-\Delta\phi - \frac{\partial}{\partial t}\underbrace{\nabla \cdot A}_{-\partial_t \phi} = 4\pi\rho$$

$$\boxed{\Box\phi = -4\pi\rho}$$


LORENTZ GAUGE COND.
C) WAVE EQ. (4) & (2) SOLVED BY A, φ
(3) ∇·(−∇φ − ∂A/∂t) = 4πρ
−Δφ − ∂/∂t ∇·A = 4πρ
−∂tφ
□φ = −4πρ
□ = −∂²/∂t² + Δ
D'ALAMBERT OP.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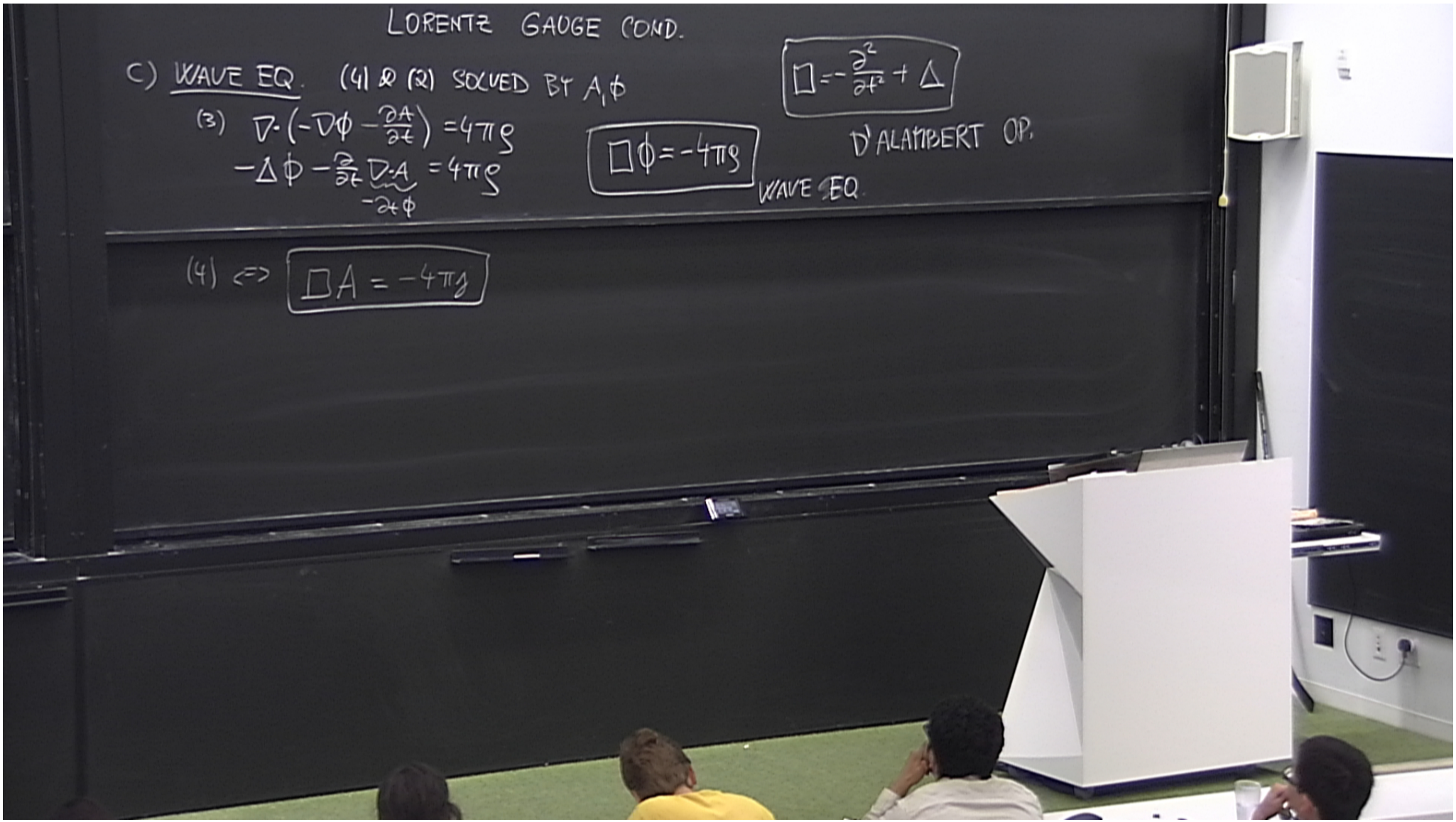
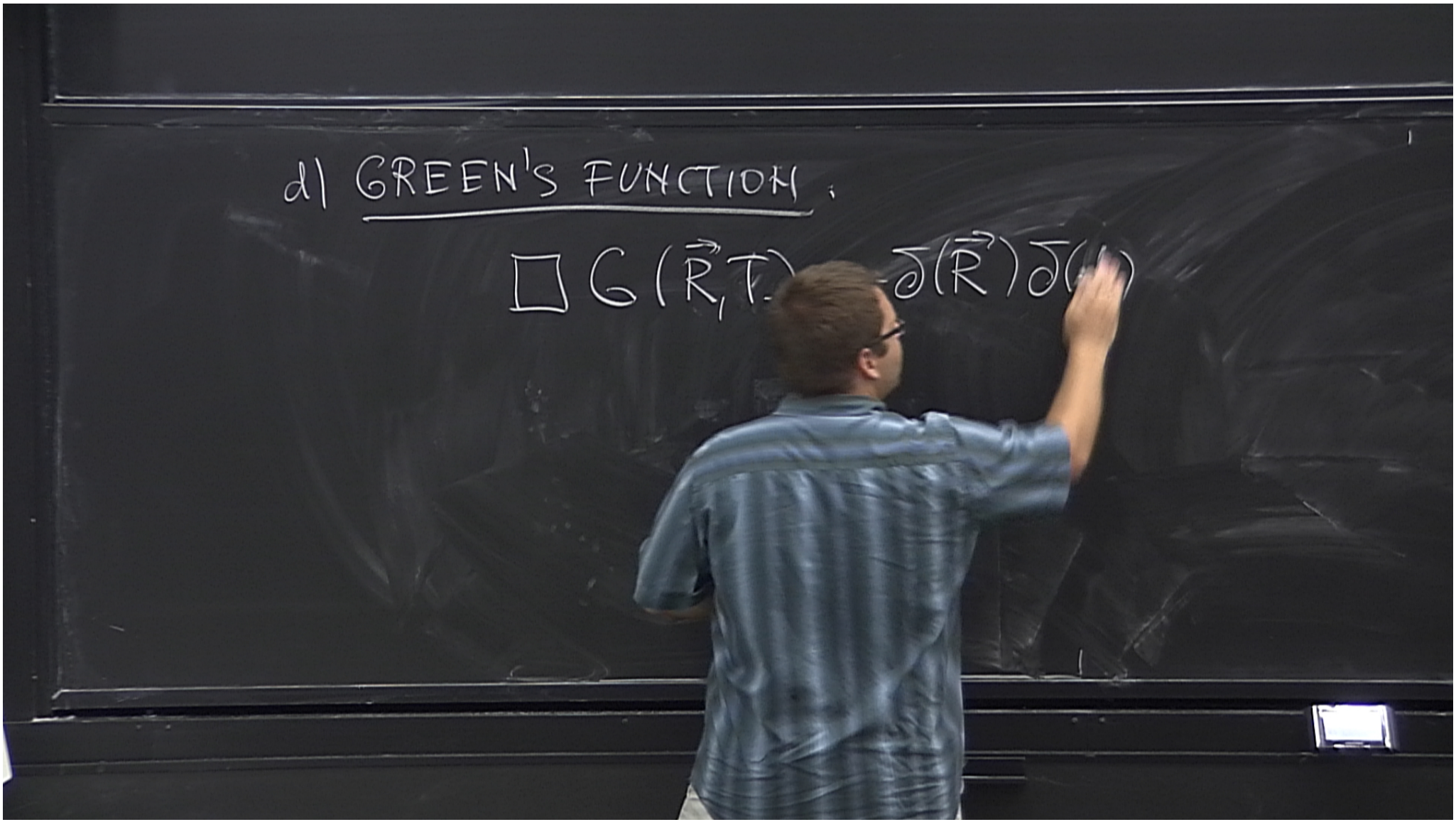
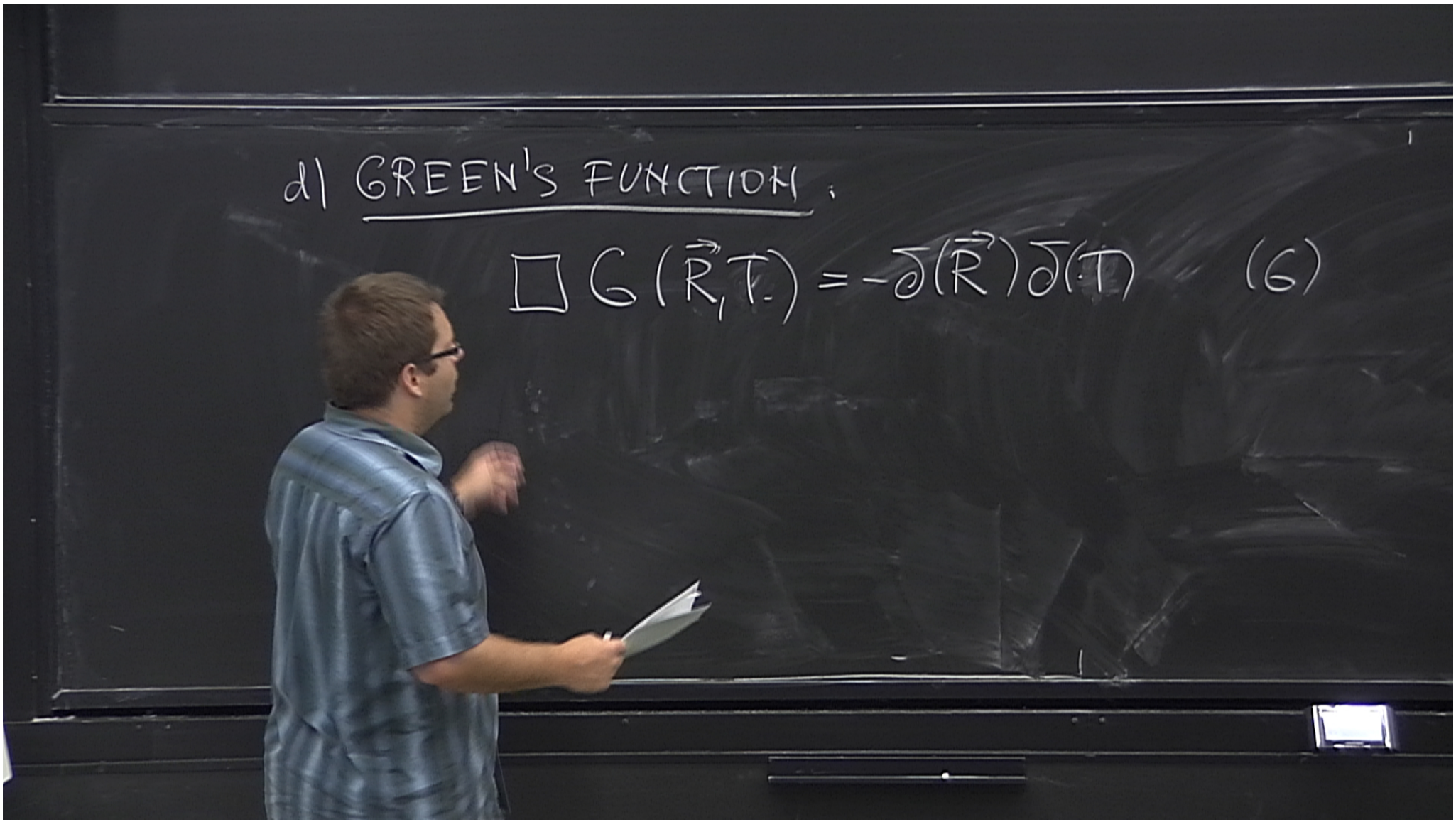
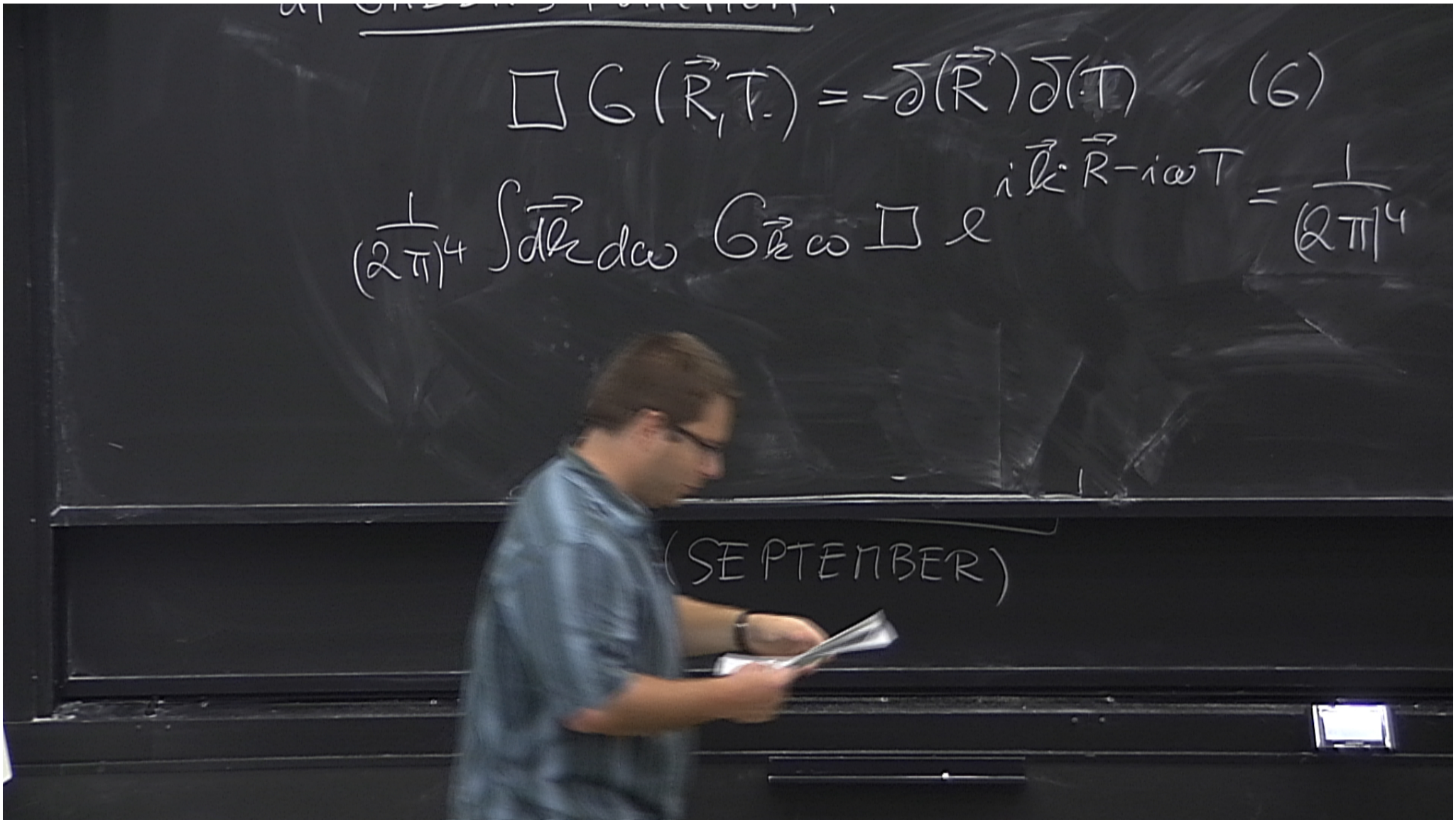
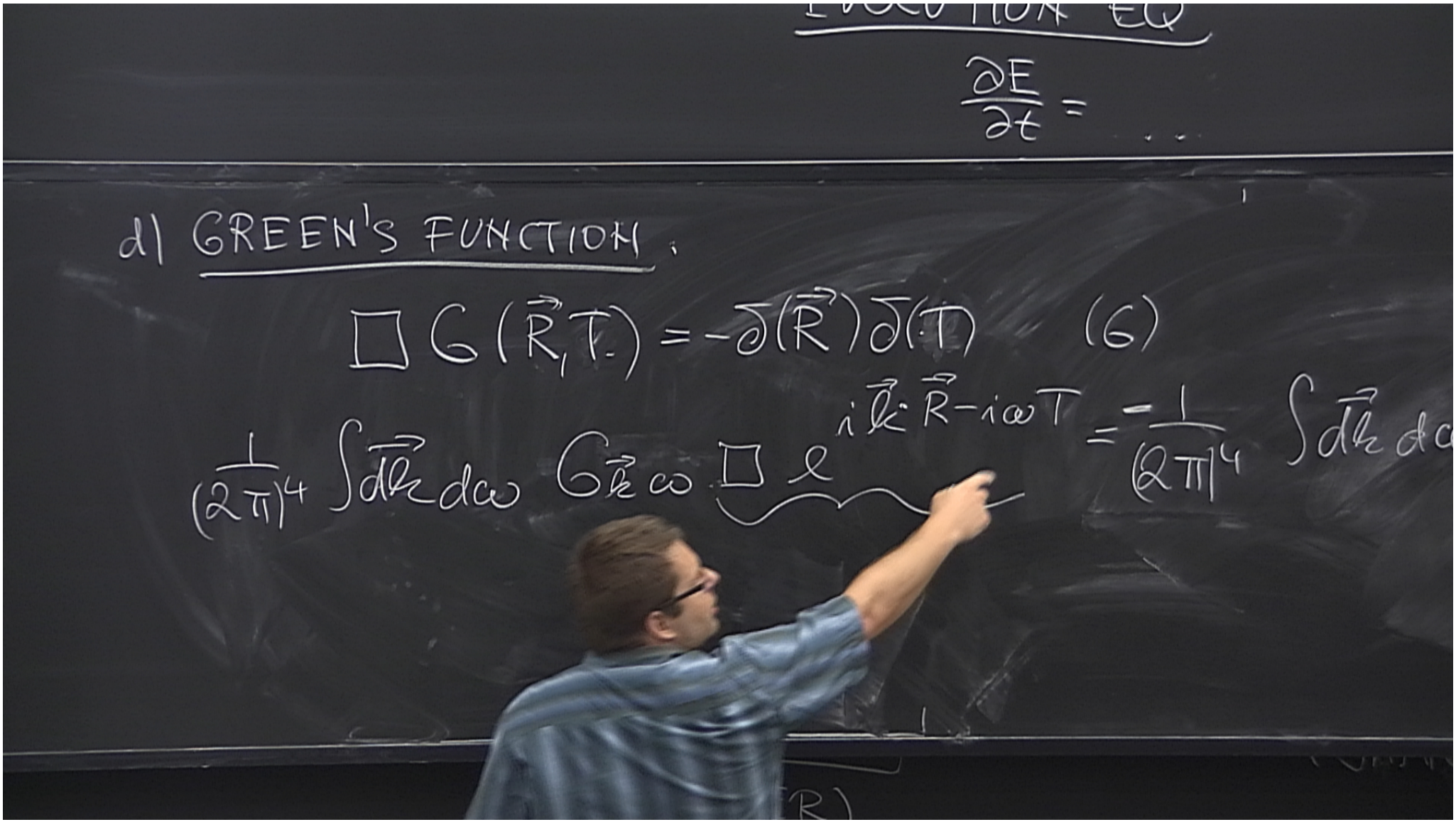
WAVE EQ.
□ = −∂²/∂t² + Δ
D'ALAMBERT OP.

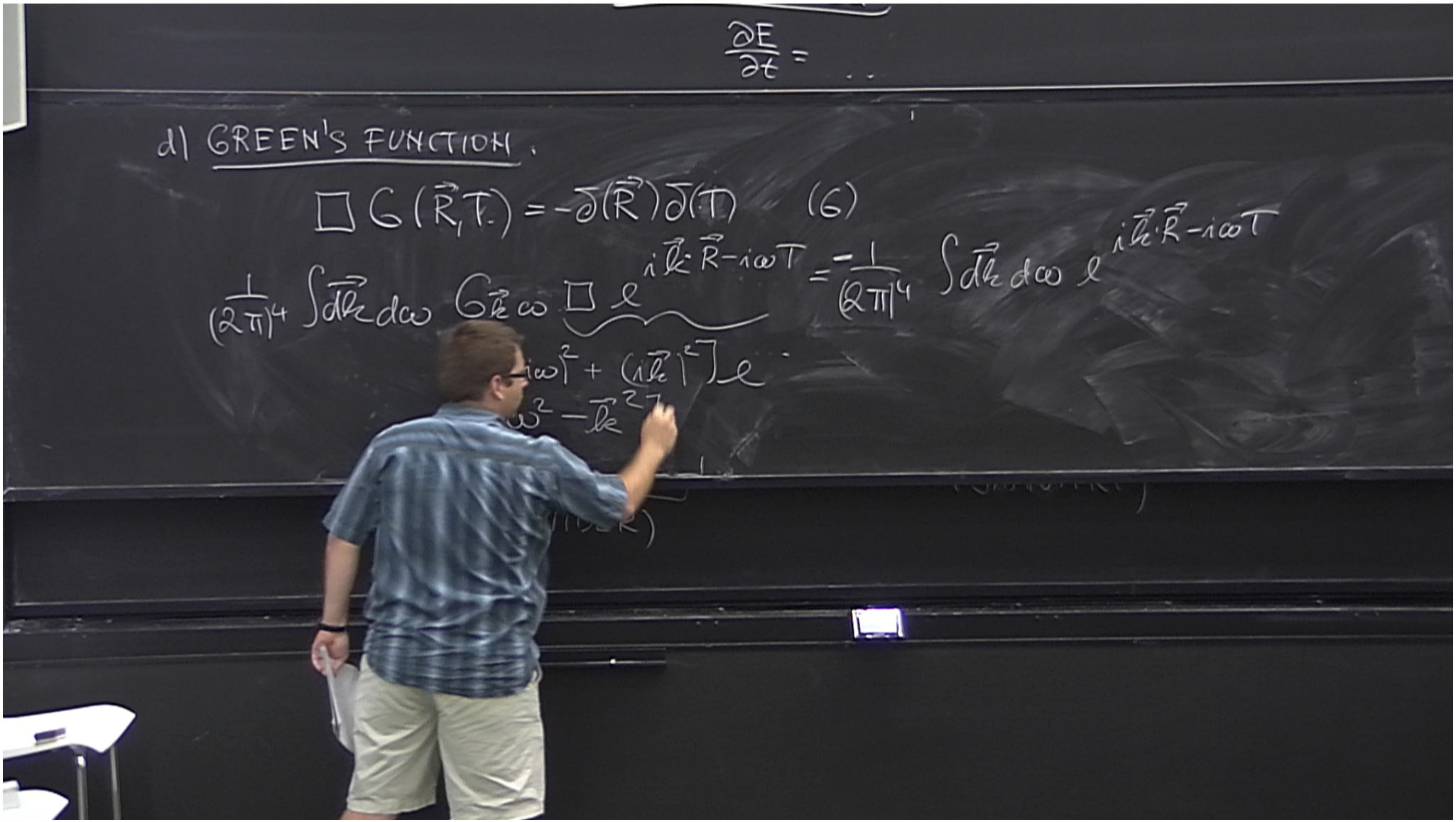

LORENTZ GAUGE COND.
C) WAVE EQ. (4) & (2) SOLVED BY A, φ
(3) ∇·(−∇φ − ∂A/∂t) = 4πρ
−Δφ − ∂/∂t ∇·A = 4πρ
−∂tφ
□φ = −4πρ
WAVE EQ.
□ = −∂²/∂t² + Δ
D'ALAMBERT OP.
(4) ⟺ □A = −4πj

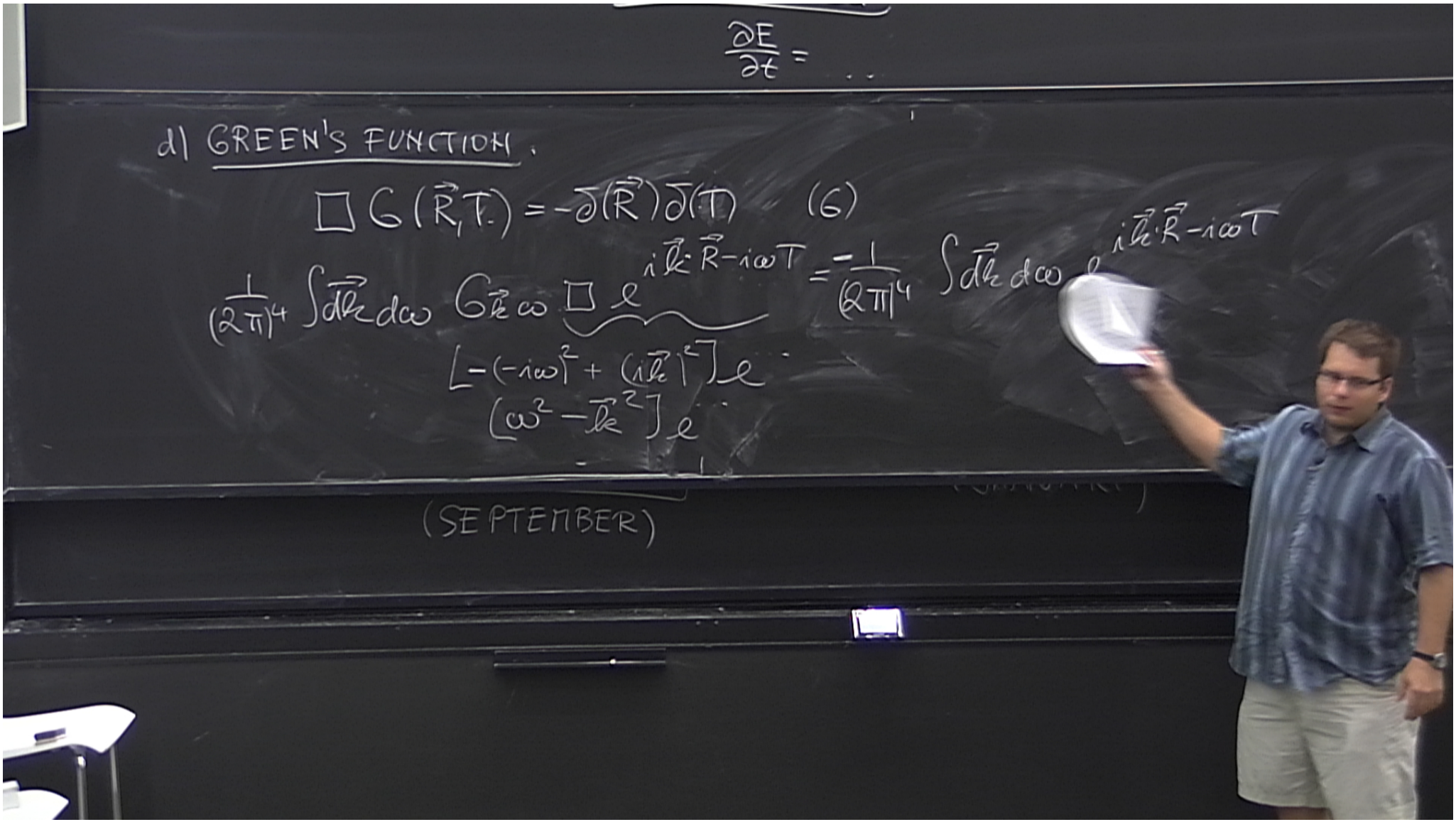

d) GREEN'S FUNCTION :
$\Box G(\vec{R}, T$
$\delta(\vec{R})\delta($


d) GREEN'S FUNCTION:
$\Box G(\vec{R}, T) = -\delta(\vec{R})\delta(T)$ (6)


$\Box G(\vec{R}, T) = -\delta(\vec{R})\delta(T)$ (6)
$\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega\, G_{\vec{k}\omega}\, \Box\, e^{i\vec{k}\cdot\vec{R} - i\omega T} = \frac{1}{(2\pi)^4}$
(SEPTEMBER)


$\frac{\partial E}{\partial t} = \ldots$
d) GREEN'S FUNCTION:
$\Box G(\vec{R}, T) = -\delta(\vec{R})\delta(T) \quad (G)$
$\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega\, G_{\vec{k}\omega}\, \Box\, e^{i\vec{k}\cdot\vec{R} - i\omega T} = -\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega$


∂E/∂t = ..
d) GREEN'S FUNCTION.
□ G(R, T) = −δ(R) δ(T) (6)
1/(2π)⁴ ∫ dk dω G_{k ω} □ e^{ik·R − iωT} = −1/(2π)⁴ ∫ dk dω e^{ik·R − iωT}
−iω)² + (ik)²] e
ω² − k²


$\frac{\partial E}{\partial t} = \ldots$
d) GREEN'S FUNCTION.
$\Box G(\vec{R}, T) = -\delta(\vec{R})\delta(T)$ (6)
$\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega\, G_{\vec{k}\omega}\, \Box\, e^{i\vec{k}\cdot\vec{R} - i\omega T} = -\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega\, e^{i\vec{k}\cdot\vec{R} - i\omega T}$
$[-(-i\omega)^2 + (i\vec{k})^2]\, e$
$[\omega^2 - \vec{k}^2]\, e$
(SEPTEMBER)

$$\frac{\partial E}{\partial t} = \ldots$$

d) GREEN'S FUNCTION.

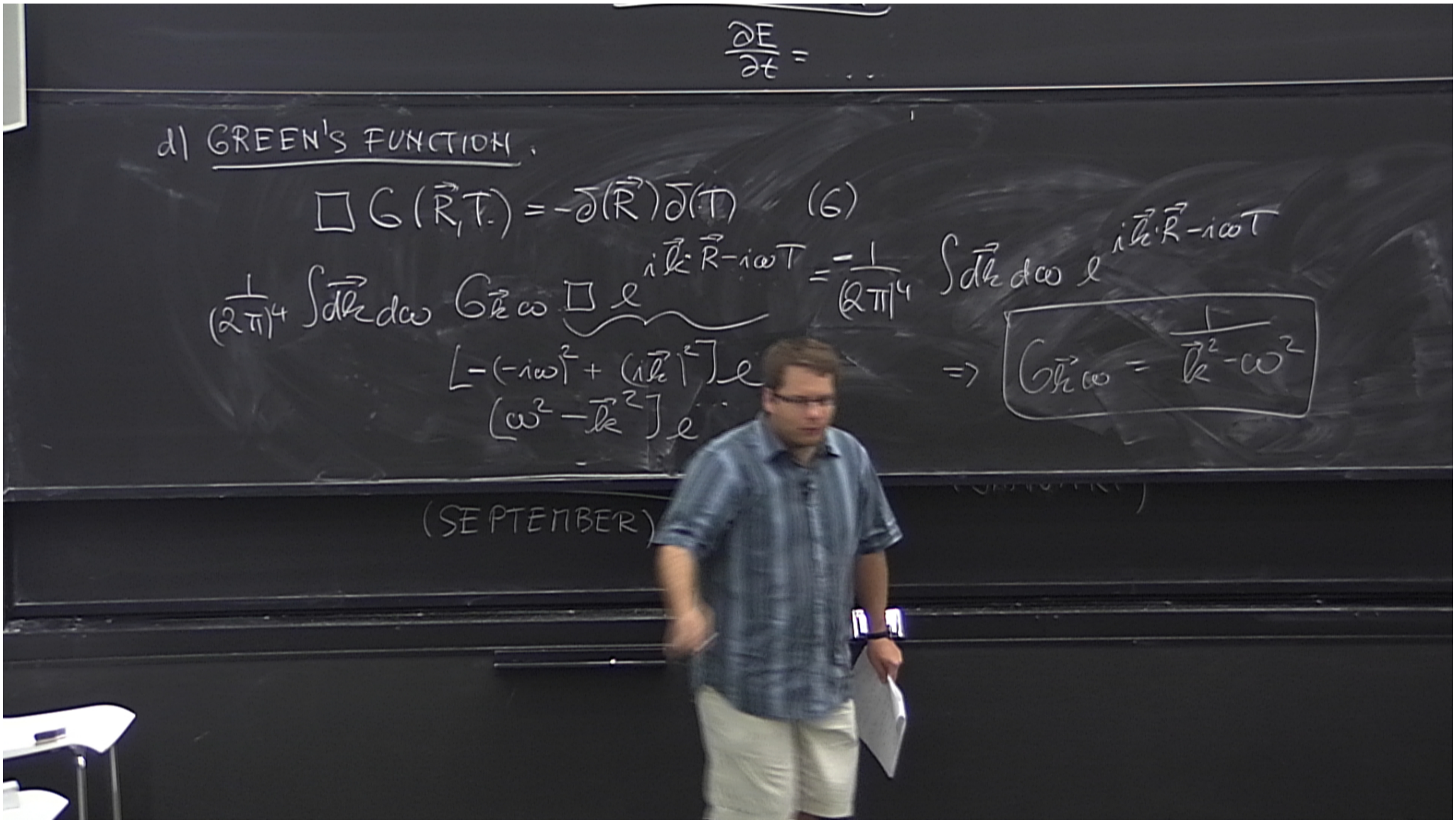
$$\Box G(\vec{R}, T) = -\delta(\vec{R})\,\delta(T) \qquad (6)$$

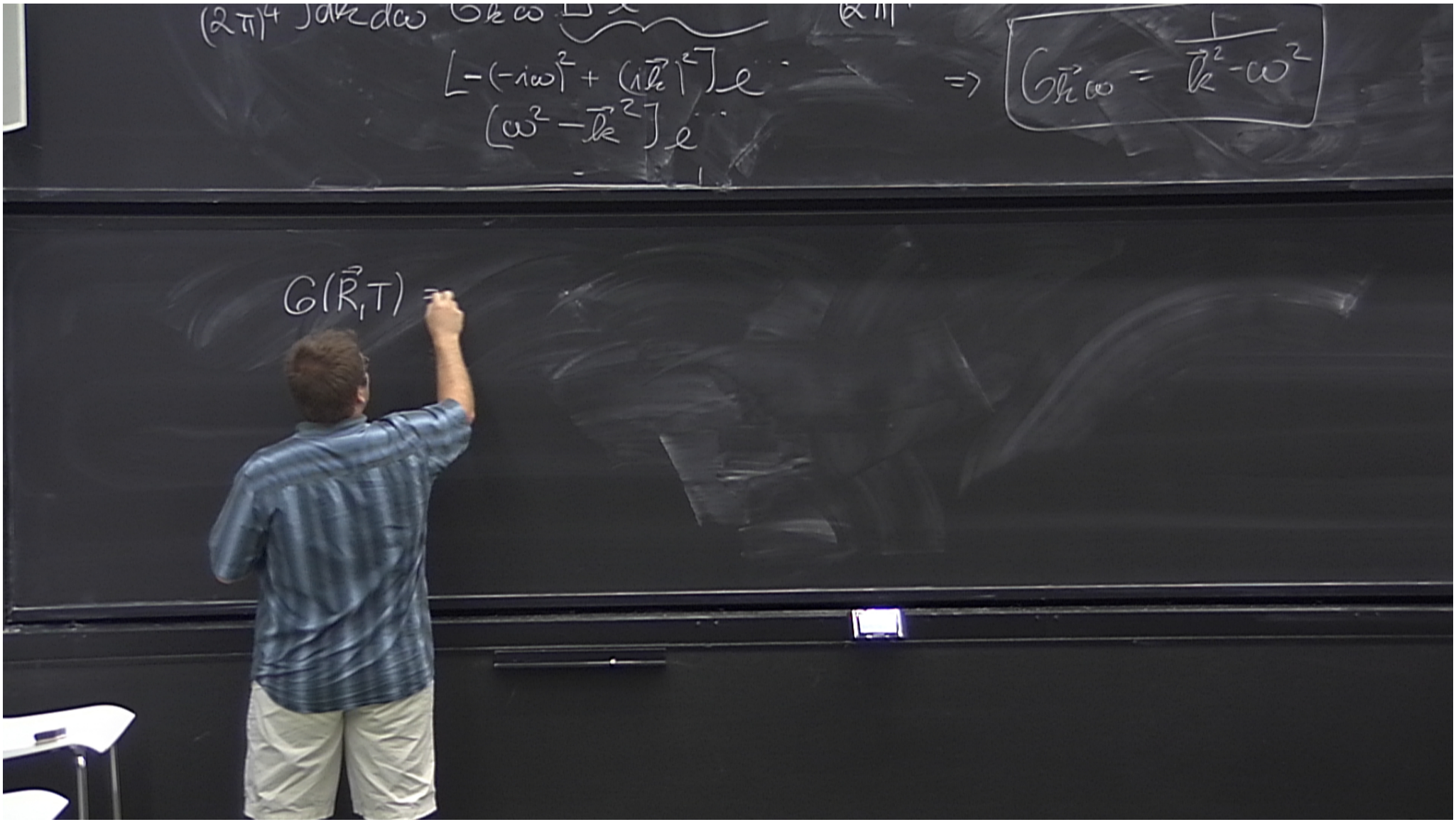
$$\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega\, G_{\vec{k}\omega}\, \underbrace{\Box\, e^{i\vec{k}\cdot\vec{R} - i\omega T}}_{} = -\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega\, e^{i\vec{k}\cdot\vec{R} - i\omega T}$$

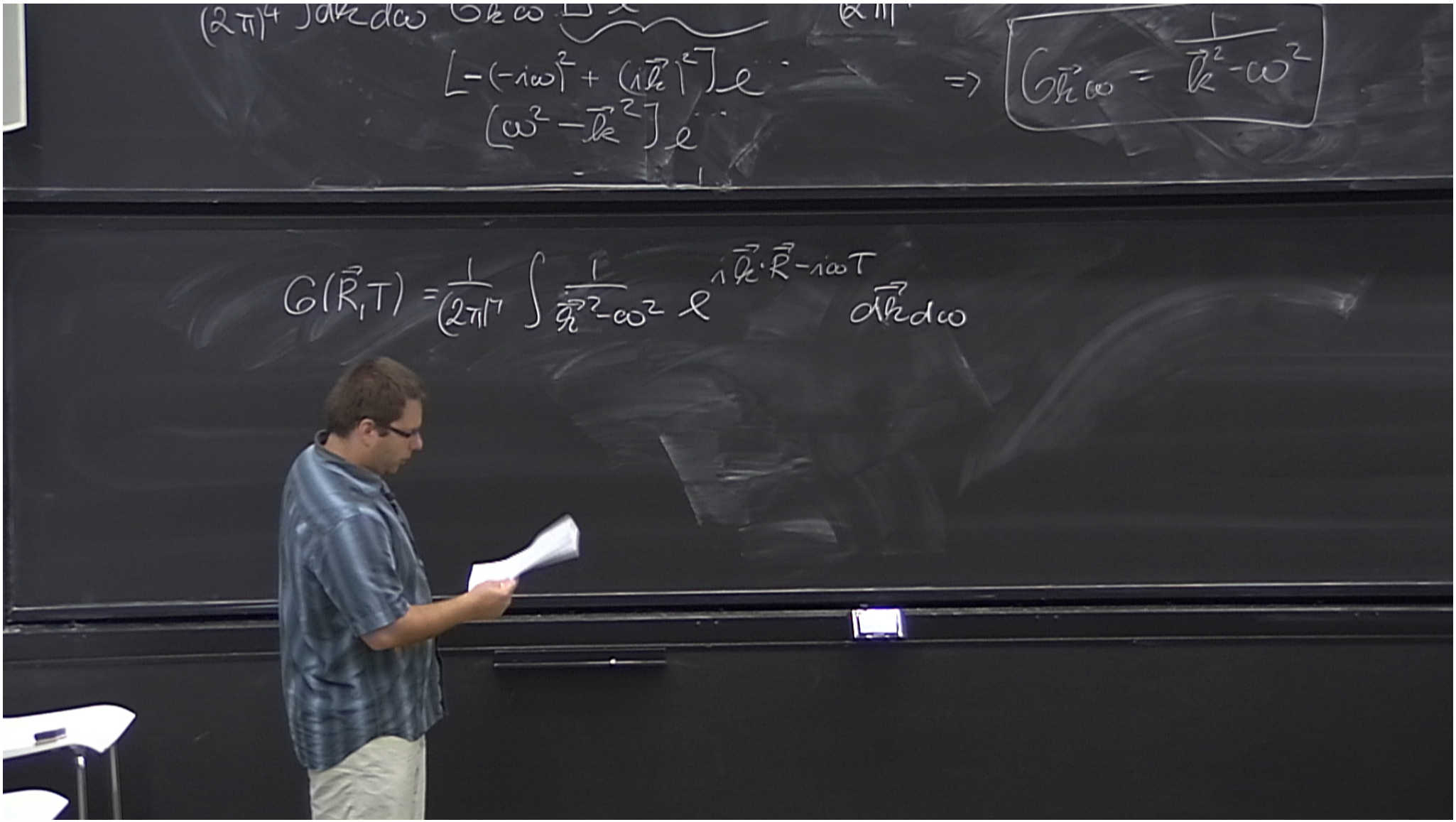
$$\left[-(-i\omega)^2 + (i\vec{k})^2\right] e \qquad \Rightarrow \quad G_{\vec{k}\omega} =$$

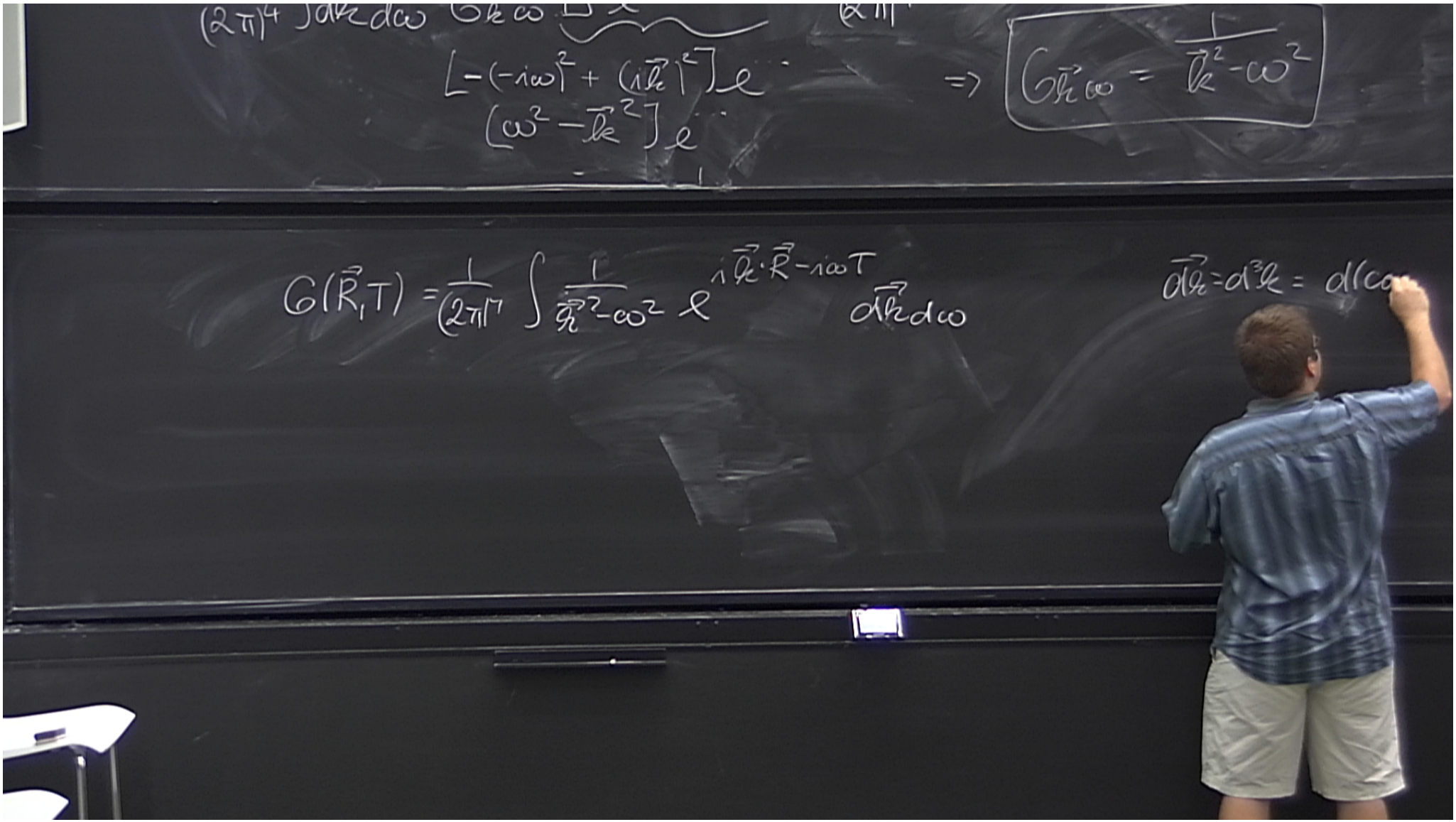
$$\left[\omega^2 - \vec{k}^2\right] e$$

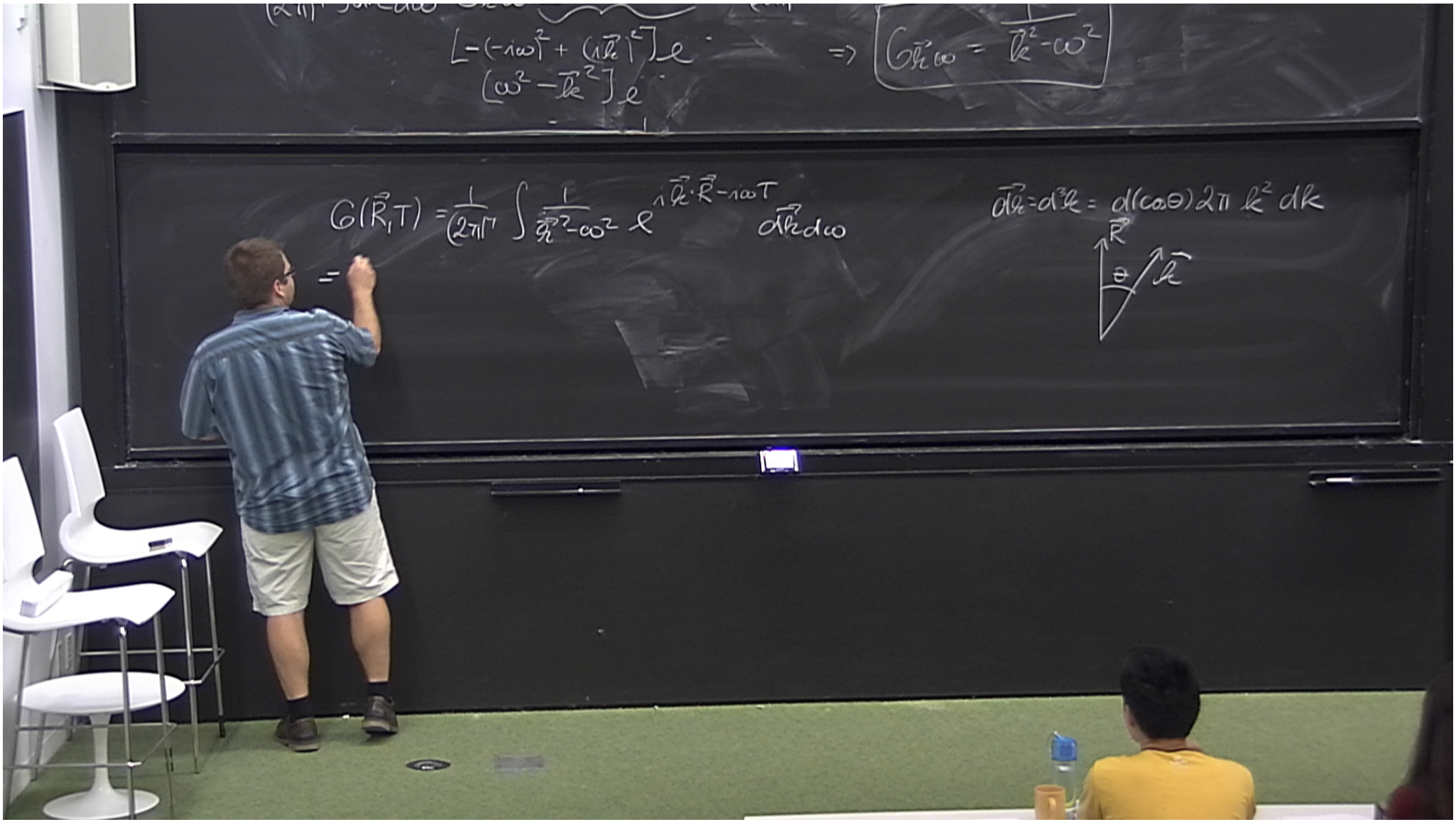
(SEPTEMBER)

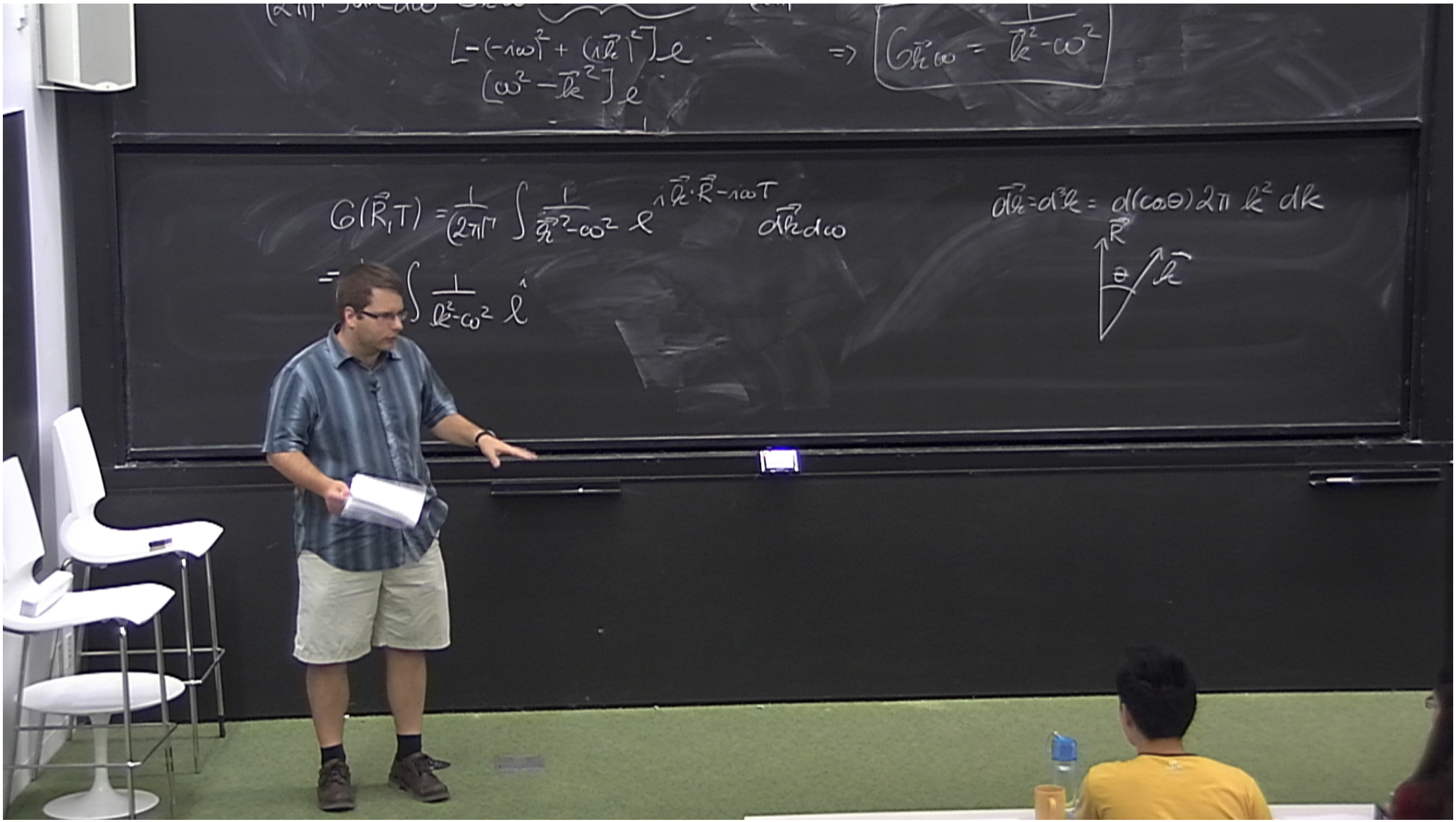

$\frac{\partial E}{\partial t} = \ldots$
d) GREEN'S FUNCTION.
$\Box G(\vec{R}, T) = -\delta(\vec{R})\delta(T) \quad (6)$
$\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega\, G_{\vec{k}\omega}\, \Box\, e^{i\vec{k}\cdot\vec{R} - i\omega T} = -\frac{1}{(2\pi)^4}\int d\vec{k}\, d\omega\, e^{i\vec{k}\cdot\vec{R} - i\omega T}$
$[-(-i\omega)^2 + (i\vec{k})^2]\, e$
$[\omega^2 - \vec{k}^2]\, e$
$\Rightarrow \boxed{G_{\vec{k}\omega} = \frac{1}{\vec{k}^2 - \omega^2}}$
(SEPTEMBER)

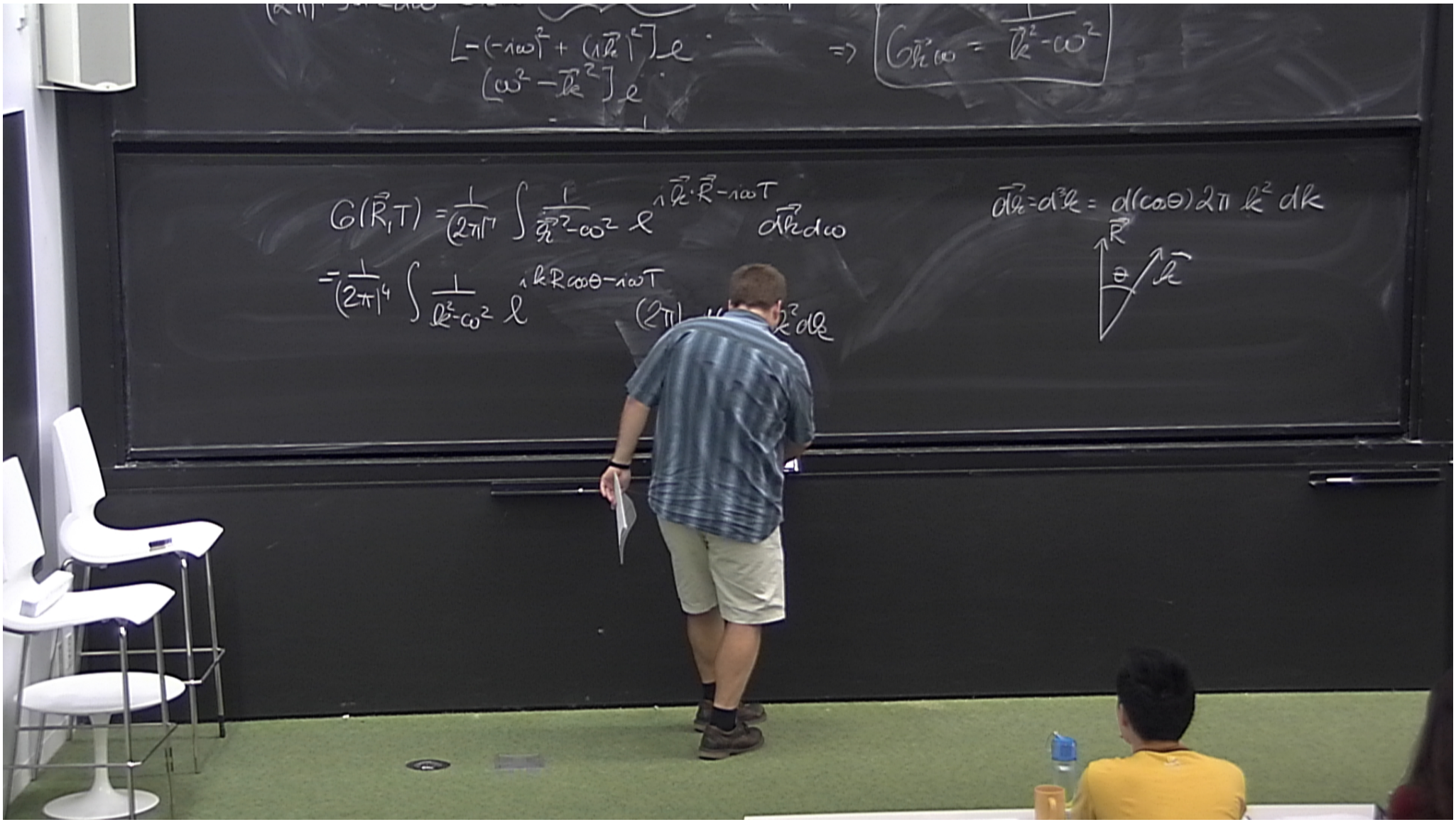

$(2\pi)^4 \int d^3k\, d\omega\, G_{\vec{k}\omega}$
$[-(-i\omega)^2 + (i\vec{k})^2]$
$[\omega^2 - \vec{k}^2]$
$\Rightarrow G_{\vec{k}\omega} = \frac{1}{\vec{k}^2 - \omega^2}$
$G(\vec{R}, T) =$

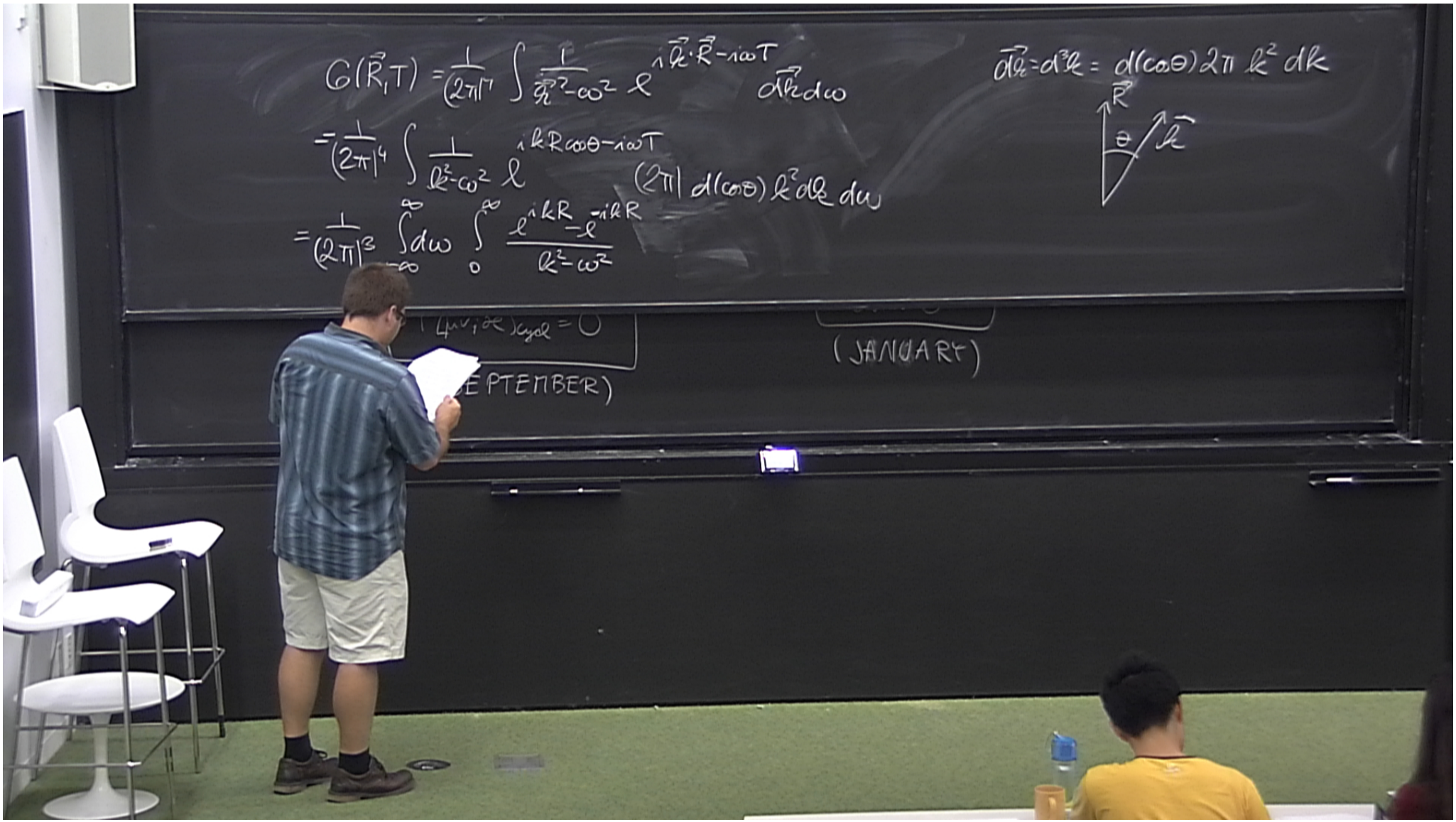

$(2\pi)^4 \int d\vec{k}\, d\omega\, G_{\vec{k}\omega}$
$[-(-i\omega)^2 + (i\vec{k})^2]\, e$
$[\omega^2 - \vec{k}^2]\, e$
$\Rightarrow \boxed{G_{\vec{k}\omega} = \frac{1}{\vec{k}^2 - \omega^2}}$
$G(\vec{R}, T) = \frac{1}{(2\pi)^4} \int \frac{1}{\vec{k}^2 - \omega^2}\, e^{i\vec{k}\cdot\vec{R} - i\omega T}\, d\vec{k}\, d\omega$

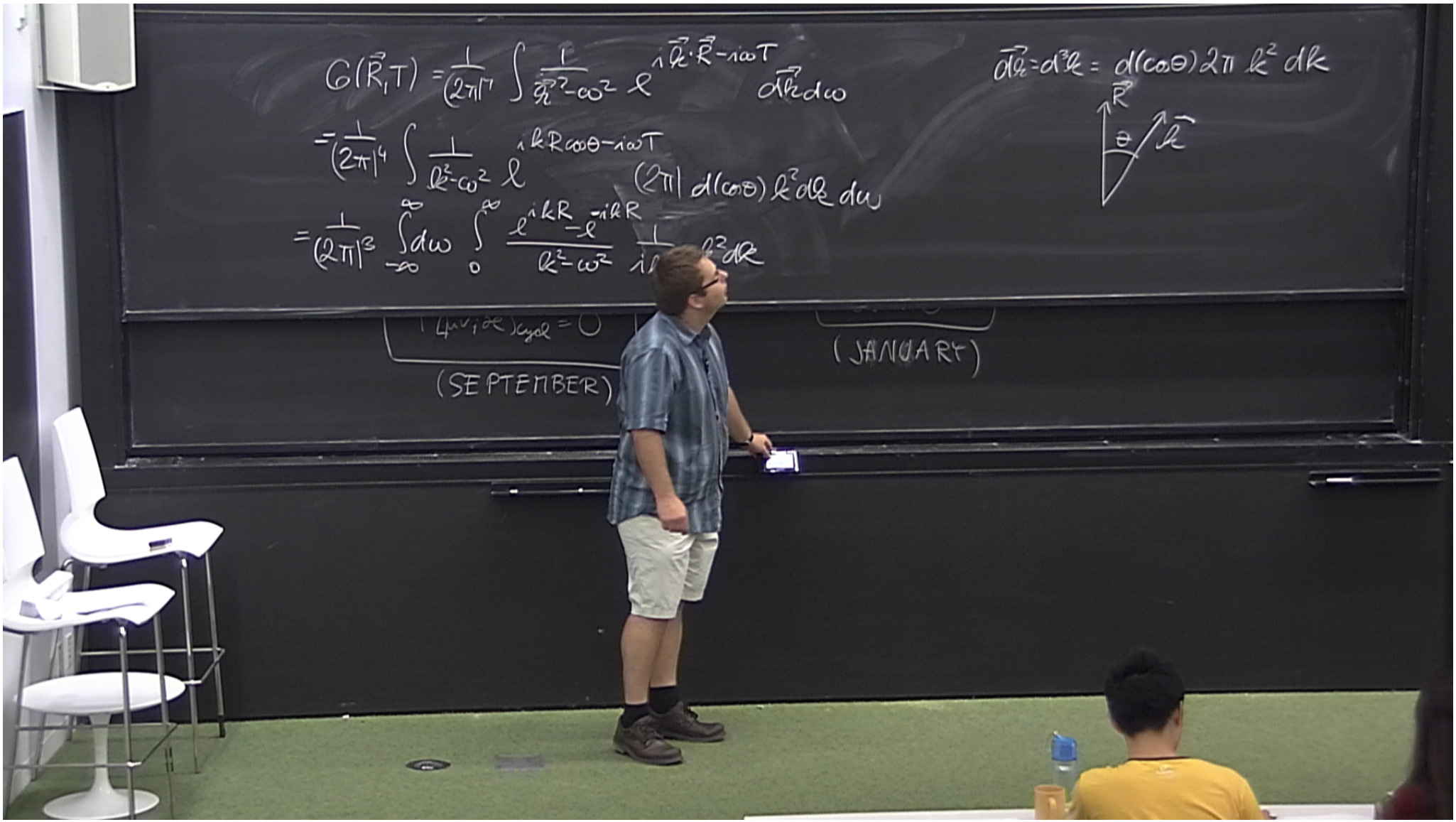

$(2\pi)^4 \int d\vec{k}\, d\omega\, G_{\vec{k}\omega}$
$[-(-i\omega)^2 + (i\vec{k})^2]\, e$
$[\omega^2 - \vec{k}^2]\, e$
$\Rightarrow \boxed{G_{\vec{k}\omega} = \frac{1}{\vec{k}^2 - \omega^2}}$
$G(\vec{R}, T) = \frac{1}{(2\pi)^4} \int \frac{1}{\vec{k}^2 - \omega^2}\, e^{i\vec{k}\cdot\vec{R} - i\omega T}\, d\vec{k}\, d\omega$
$d\vec{k} = d^3k =$

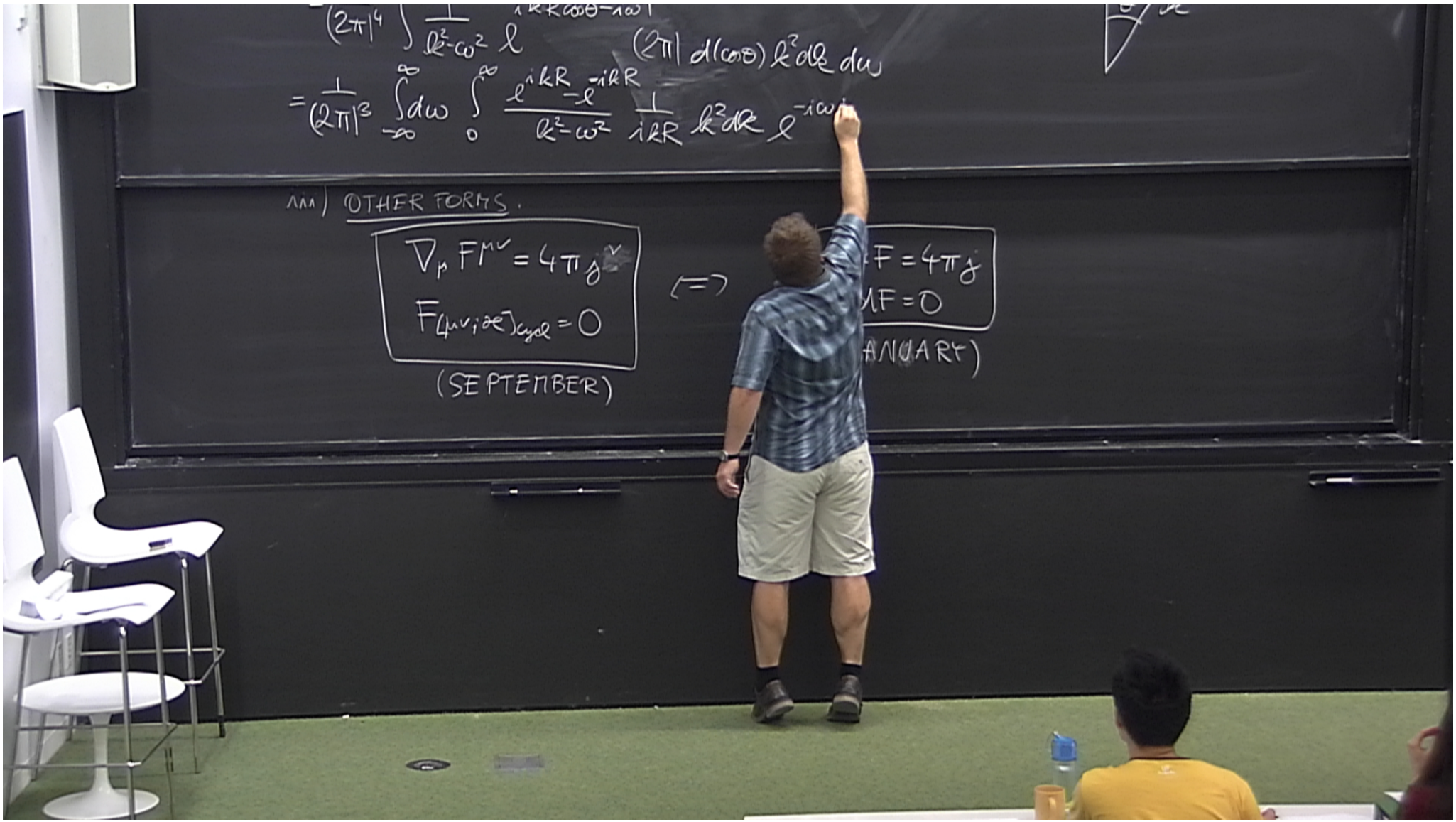

$[-(-i\omega)^2 + (i\vec{k})^2]\, e$
$[\omega^2 - \vec{k}^2]\, e$
$\Rightarrow \boxed{G_{\vec{k}\omega} = \frac{1}{\vec{k}^2 - \omega^2}}$
$G(\vec{R},T) = \frac{1}{(2\pi)^4} \int \frac{1}{\vec{k}^2-\omega^2}\, e^{i\vec{k}\cdot\vec{R} - i\omega T}\, d\vec{k}\, d\omega$
$=$
$d\vec{k} = d^3k = d(\cos\theta)\, 2\pi\, k^2\, dk$
$\vec{R}$
θ
$\vec{k}$

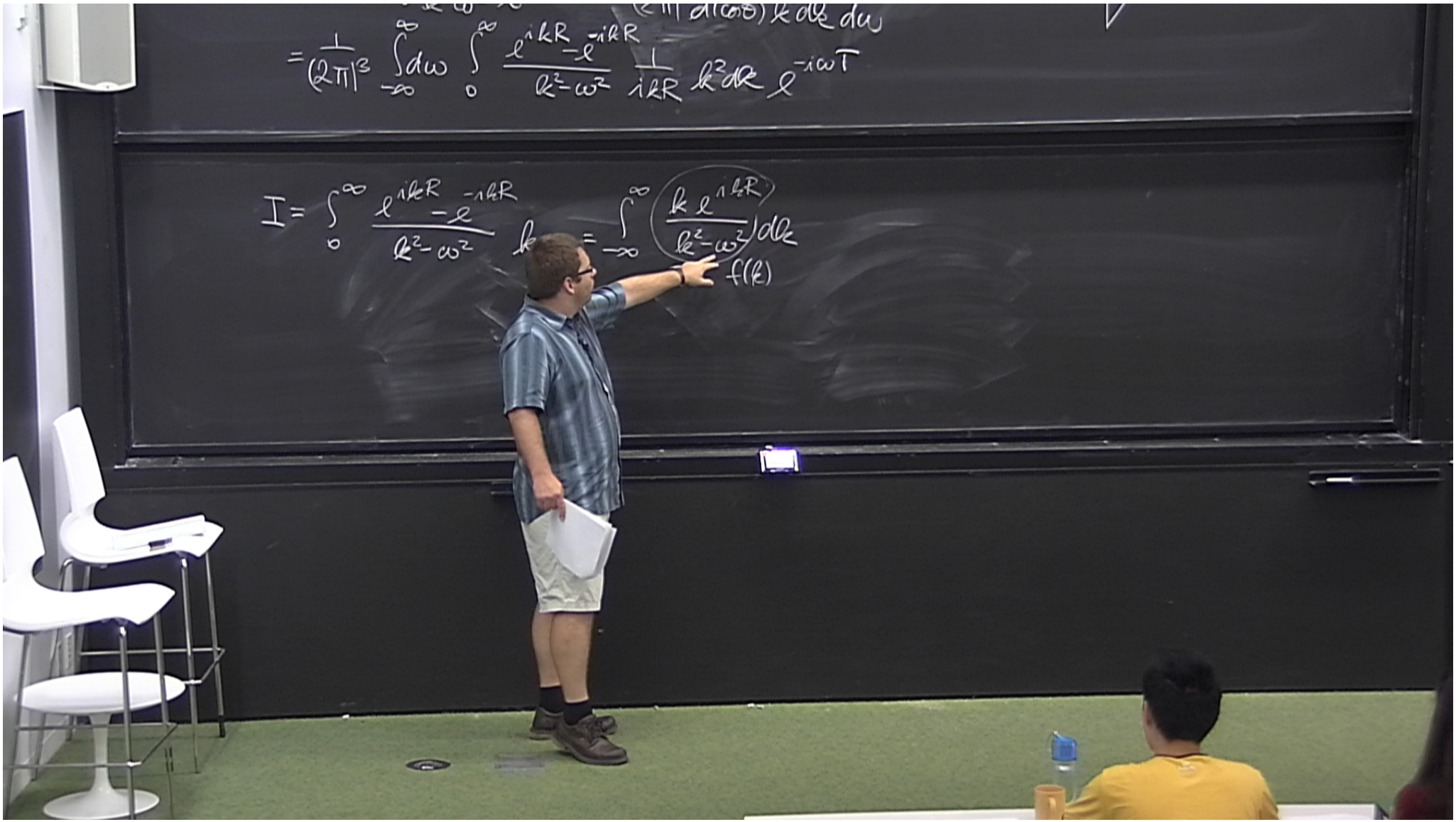

$[-(-i\omega)^2 + (i\vec{k})^2]e$
$[\omega^2 - \vec{k}^2]e$
$\Rightarrow \boxed{G_{\vec{k}\omega} = \frac{1}{\vec{k}^2-\omega^2}}$
$G(\vec{R},T) = \frac{1}{(2\pi)^4}\int \frac{1}{\vec{k}^2-\omega^2} e^{i\vec{k}\cdot\vec{R}-i\omega T} d\vec{k}d\omega$
$= \int \frac{1}{k^2-\omega^2} e^{i}$
$d\vec{k} = d^3k = d(\cos\theta)\, 2\pi\, k^2\, dk$
$\vec{R}$
θ
$\vec{k}$


$[-(-i\omega)^2 + (i\vec{k})^2]e$
$[\omega^2 - \vec{k}^2]e$
$\Rightarrow \boxed{G_{\vec{k},\omega} = \frac{1}{\vec{k}^2-\omega^2}}$
$G(\vec{R},T) = \frac{1}{(2\pi)^4}\int \frac{1}{\vec{k}^2-\omega^2} e^{i\vec{k}\cdot\vec{R}-i\omega T} d\vec{k}\,d\omega$
$= \frac{1}{(2\pi)^4}\int \frac{1}{k^2-\omega^2} e^{ikR\cos\theta - i\omega T}$
$d\vec{k} = d^3k = d(\cos\theta)\,2\pi\,k^2\,dk$
$\vec{R}$
θ
$\vec{k}$


$G(\vec{R},T) = \frac{1}{(2\pi)^4} \int \frac{1}{\vec{k}^2-\omega^2} e^{i\vec{k}\cdot\vec{R}-i\omega T} d\vec{k}\, d\omega$
$= \frac{1}{(2\pi)^4} \int \frac{1}{k^2-\omega^2} e^{ikR\cos\theta - i\omega T} (2\pi)\, d(\cos\theta)\, k^2 dk\, d\omega$
$= \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} d\omega \int_0^{\infty} \frac{e^{ikR} - e^{-ikR}}{k^2-\omega^2}$
$d\vec{k} = d^3k = d(\cos\theta)\, 2\pi\, k^2\, dk$
$\vec{R}$
θ
$\vec{k}$
(JANUARY)
EPTEMBER)

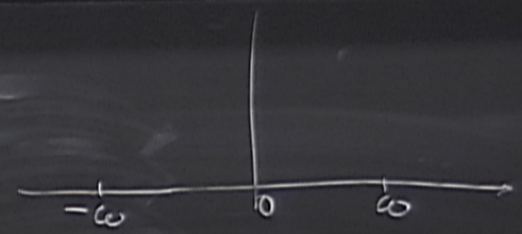

$G(\vec{R},T) = \frac{1}{(2\pi)^4} \int \frac{1}{\vec{k}^2-\omega^2} e^{i\vec{k}\cdot\vec{R}-i\omega T} d\vec{k}\, d\omega$
$= \frac{1}{(2\pi)^4} \int \frac{1}{k^2-\omega^2} e^{ikR\cos\theta - i\omega T} (2\pi)\, d(\cos\theta)\, k^2 dk\, d\omega$
$= \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} d\omega \int_0^{\infty} \frac{e^{ikR}-e^{-ikR}}{k^2-\omega^2} \frac{1}{iR} k^2 dk$
$d\vec{k} = d^3k = d(\cos\theta)\, 2\pi\, k^2 dk$
$\vec{R}$
θ
$\vec{k}$
(SEPTEMBER)
(JANUARY)

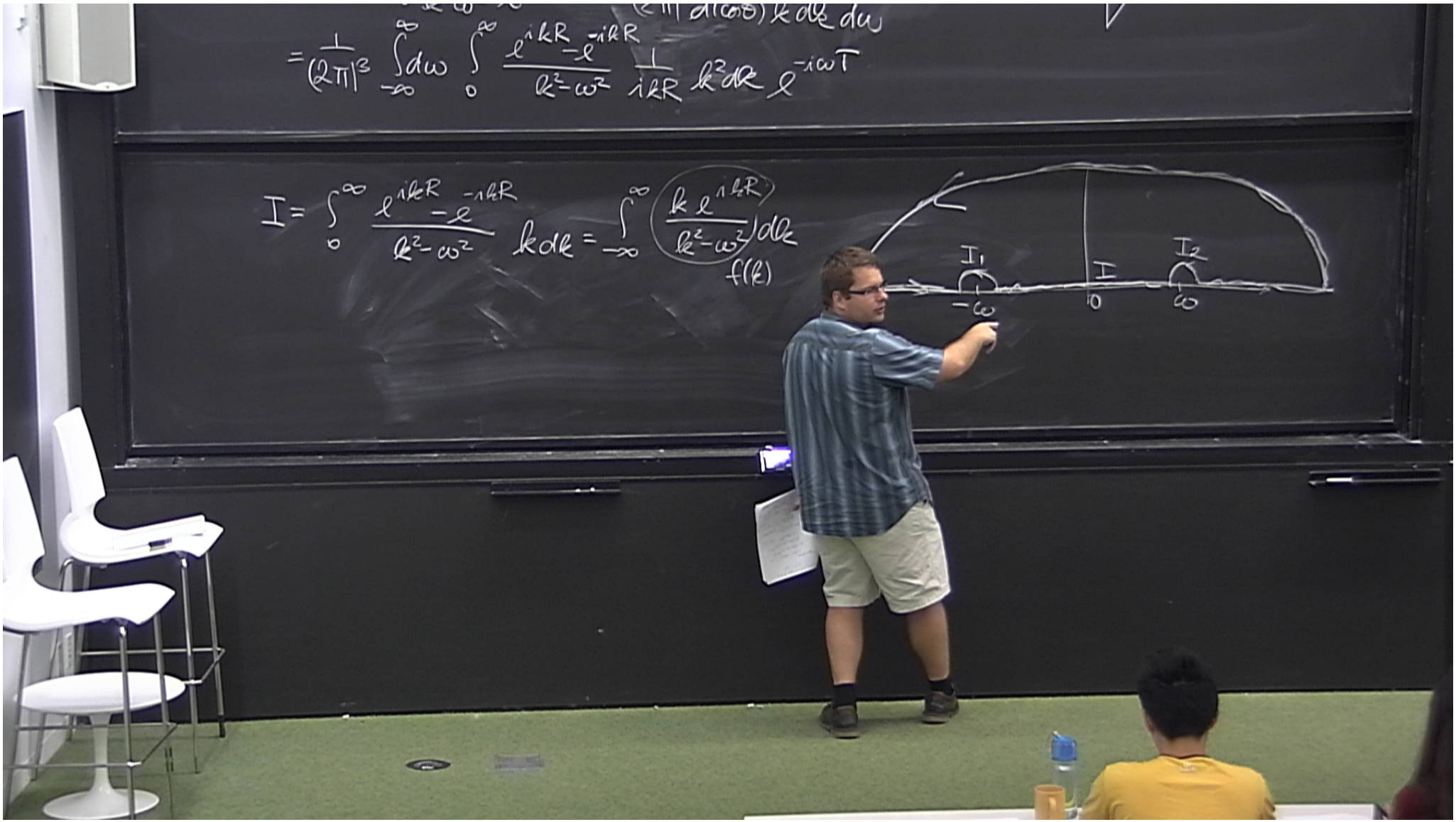

(2π)^4 ∫ 1/(k²-ω²) e^{ikR cosθ - iωt} (2π) d(cosθ) k² dk dω
= 1/(2π)³ ∫_{-∞}^{∞} dω ∫_0^{∞} (e^{ikR} - e^{-ikR})/(k²-ω²) 1/(ikR) k² dk e^{-iωt}
III) OTHER FORMS.
∇_μ F^{μν} = 4π j^ν
F_{[μν;σ]} = 0
(SEPTEMBER)
⟺
F = 4π j
F = 0
(JANUARY)

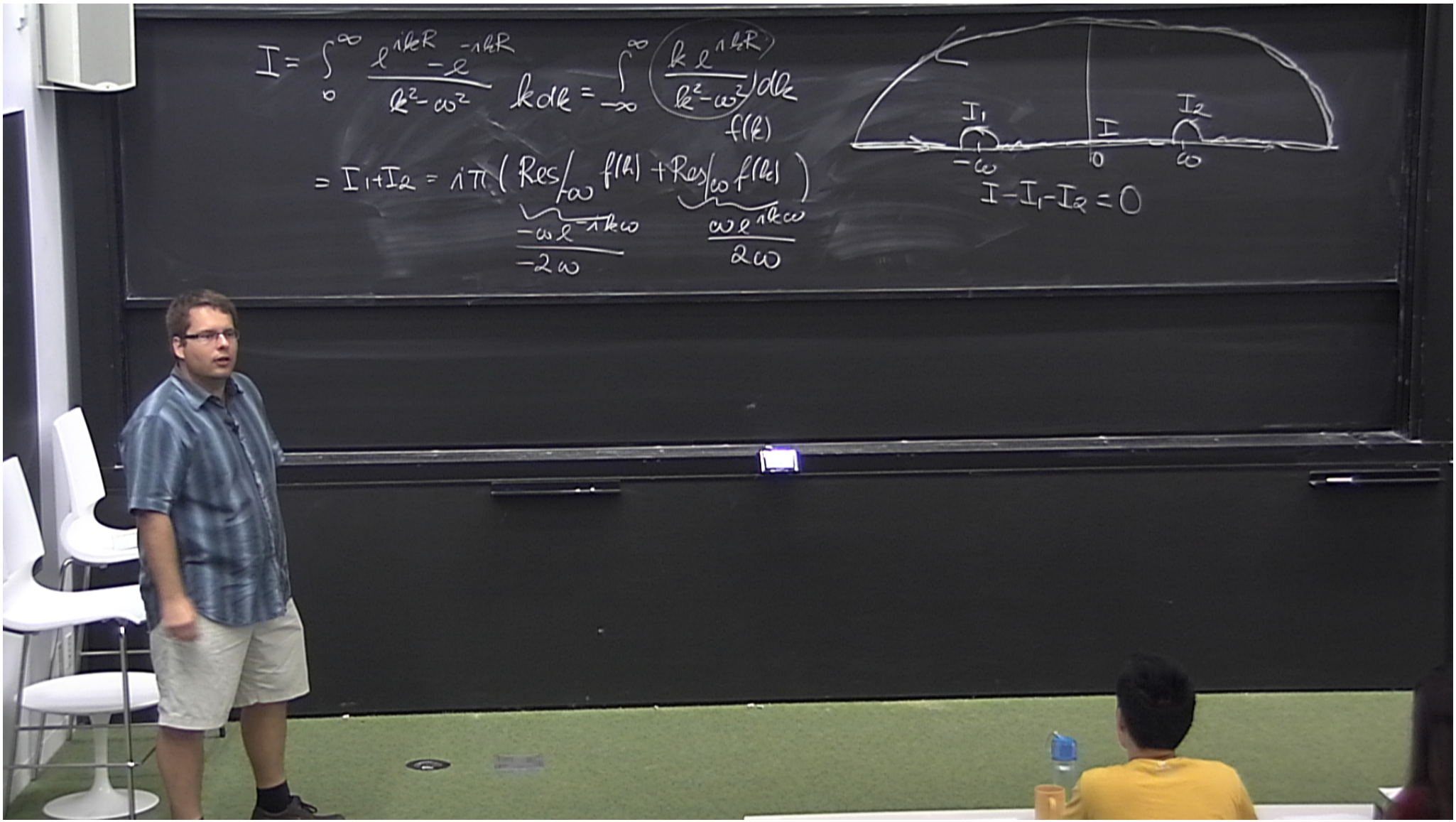

$= \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} d\omega \int_0^{\infty} \frac{e^{ikR} - e^{-ikR}}{k^2 - \omega^2} \frac{1}{ikR} k^2 dk \, e^{-i\omega T}$
$I = \int_0^{\infty} \frac{e^{ikR} - e^{-ikR}}{k^2 - \omega^2} k = \int_{-\infty}^{\infty} \frac{k e^{ikR}}{k^2 - \omega^2} dk$
$f(k)$

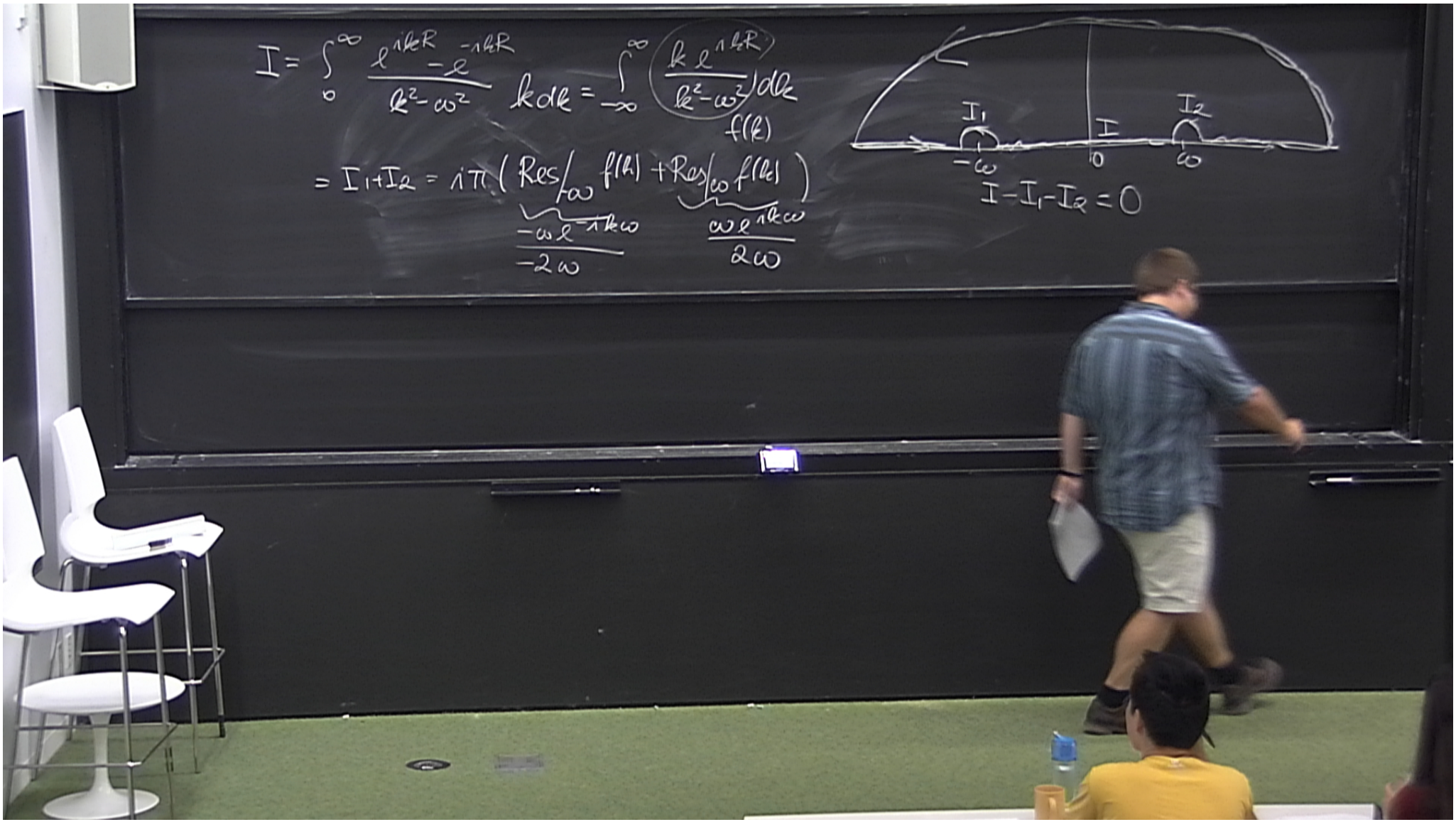
$$= \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} d\omega \int_0^{\infty} \frac{e^{ikR} - e^{-ikR}}{k^2 - \omega^2} \frac{1}{ikR} k^2 dk \, e^{-i\omega T}$$

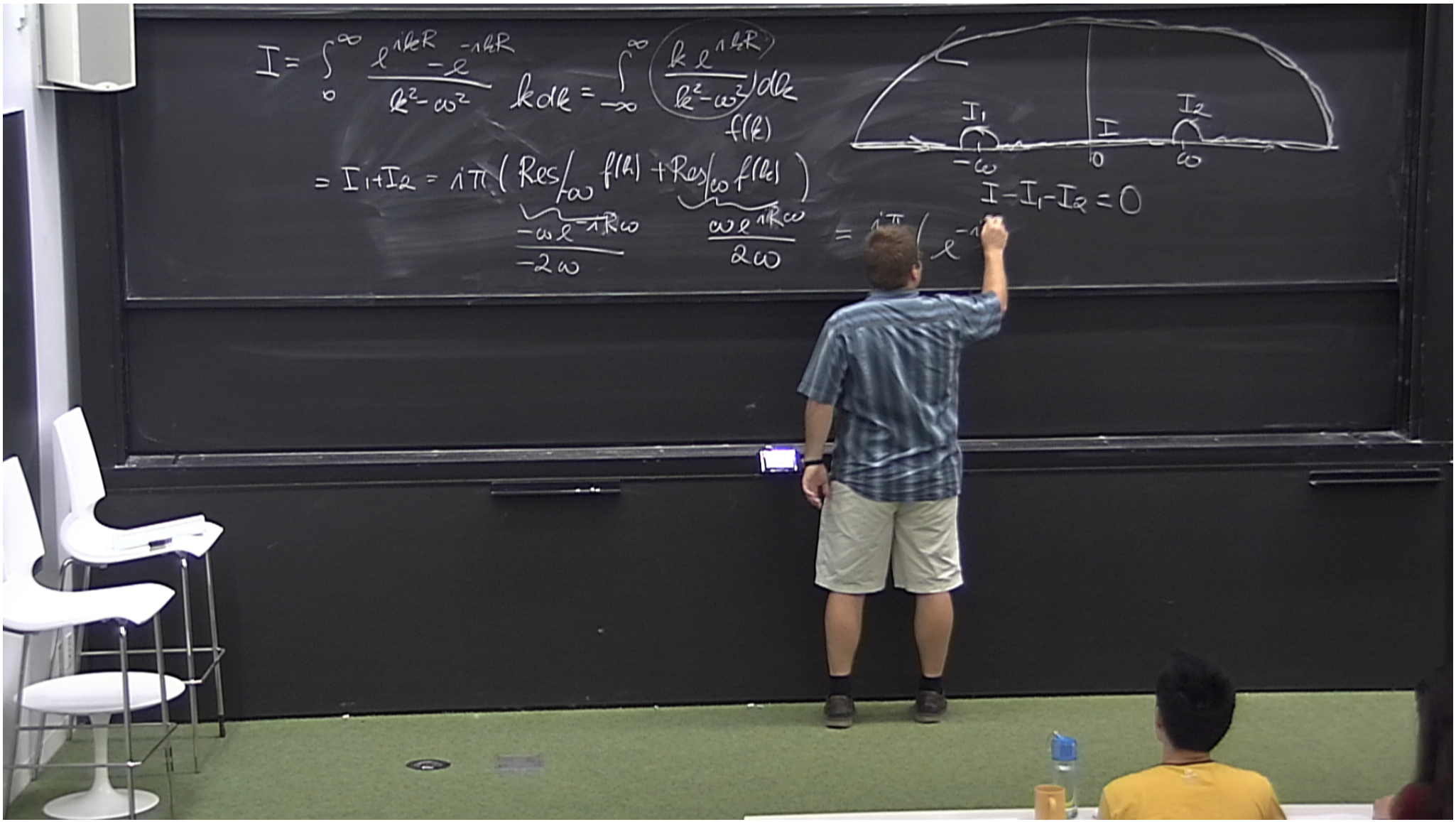
$$I = \int_0^{\infty} \frac{e^{ikR} - e^{-ikR}}{k^2 - \omega^2} k \, dk = \int_{-\infty}^{\infty} \underbrace{\left(\frac{k e^{ikR}}{k^2 - \omega^2} \right)}_{f(k)} dk$$

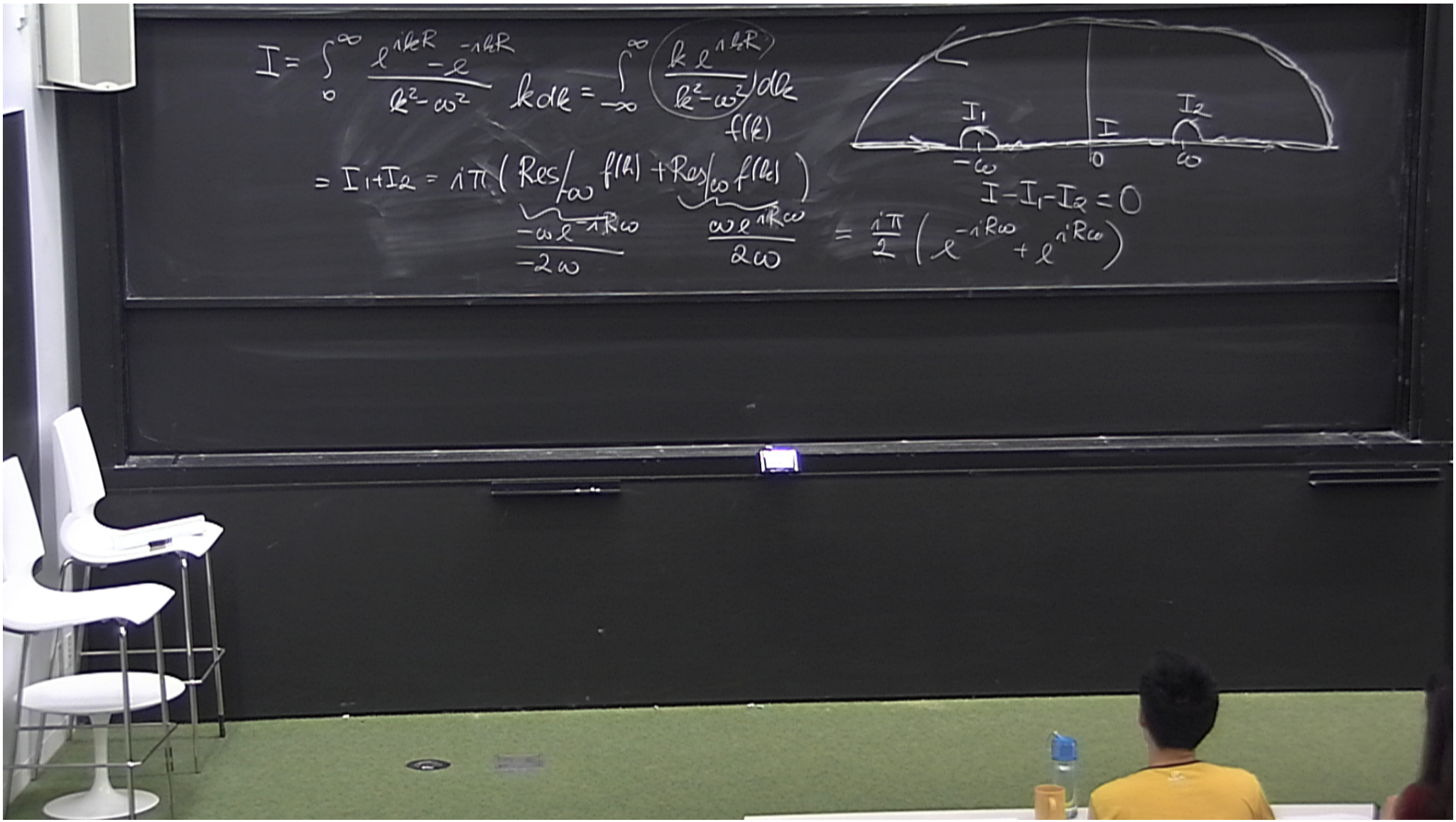


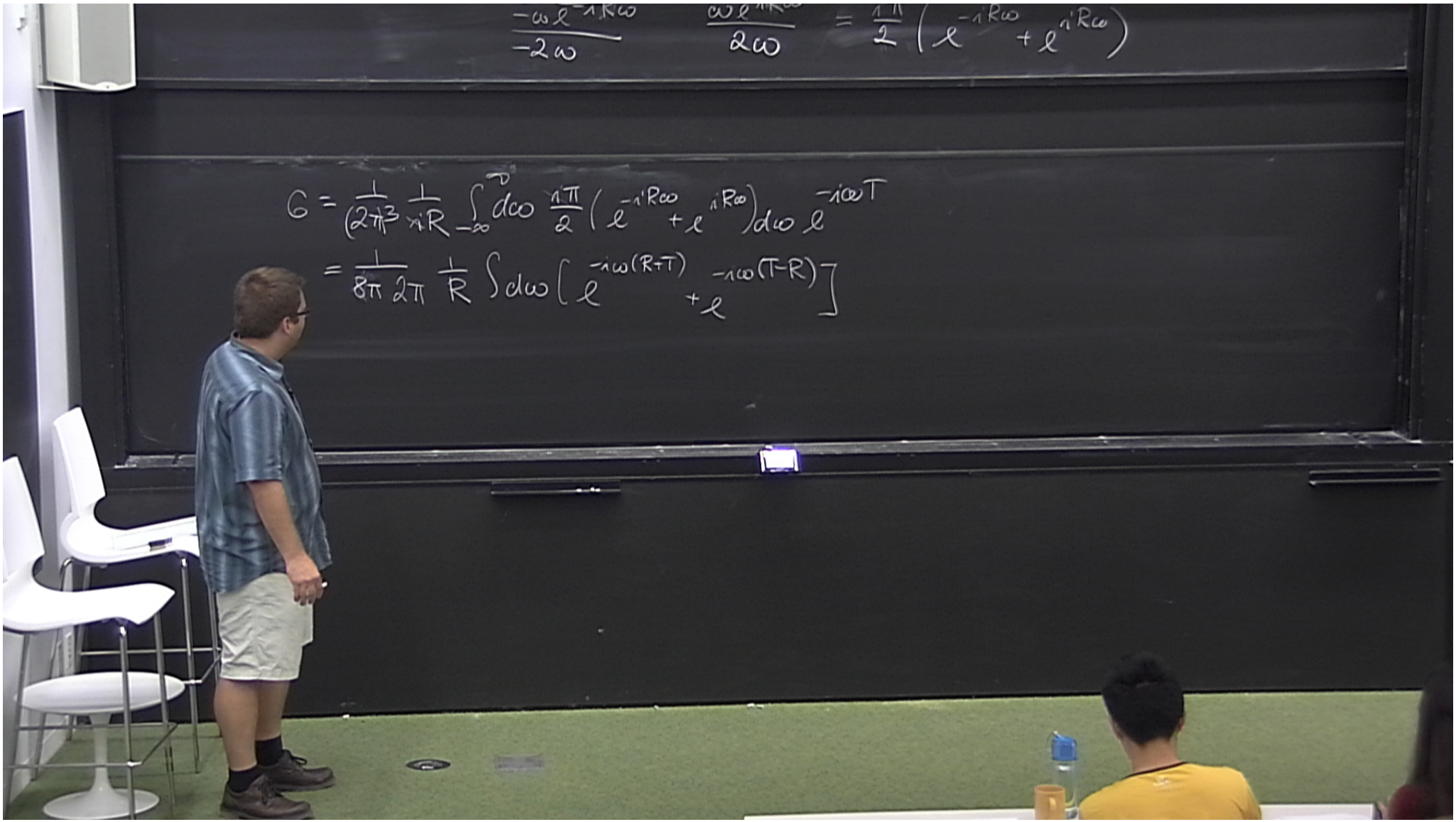

$= \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} d\omega \int_0^{\infty} \frac{e^{ikR} - e^{-ikR}}{k^2-\omega^2} \frac{1}{ikR} k^2 dk \, e^{-i\omega T}$
$I = \int_0^{\infty} \frac{e^{ikR} - e^{-ikR}}{k^2-\omega^2} k dk = \int_{-\infty}^{\infty} \frac{k e^{ikR}}{k^2-\omega^2} dk$
$f(k)$
I_1
I
I_2
$-\omega$
0
ω

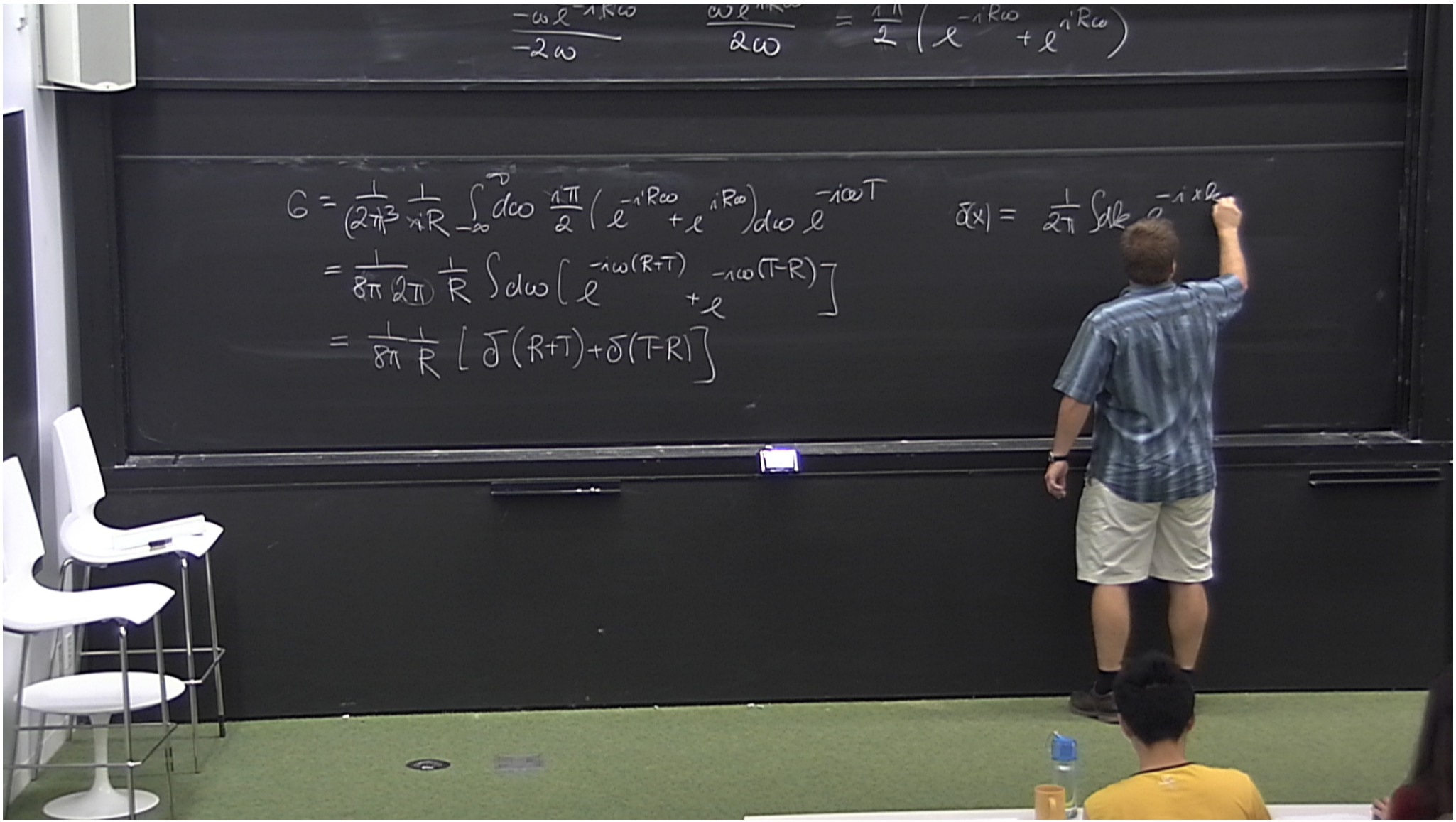

$I = \int_0^\infty \frac{e^{ikR} - e^{-ikR}}{k^2-\omega^2} k\,dk = \int_{-\infty}^{\infty} \frac{k e^{ikR}}{k^2-\omega^2} dk$
$f(k)$
$= I_1 + I_2 = i\pi \left(\mathrm{Res}_{-\omega} f(k) + \mathrm{Res}_{\omega} f(k) \right)$
$\frac{-\omega e^{-ik\omega}}{-2\omega}$
$\frac{\omega e^{ik\omega}}{2\omega}$
I_1
I_2
I
$-\omega$
0
ω
$I - I_1 - I_2 = 0$

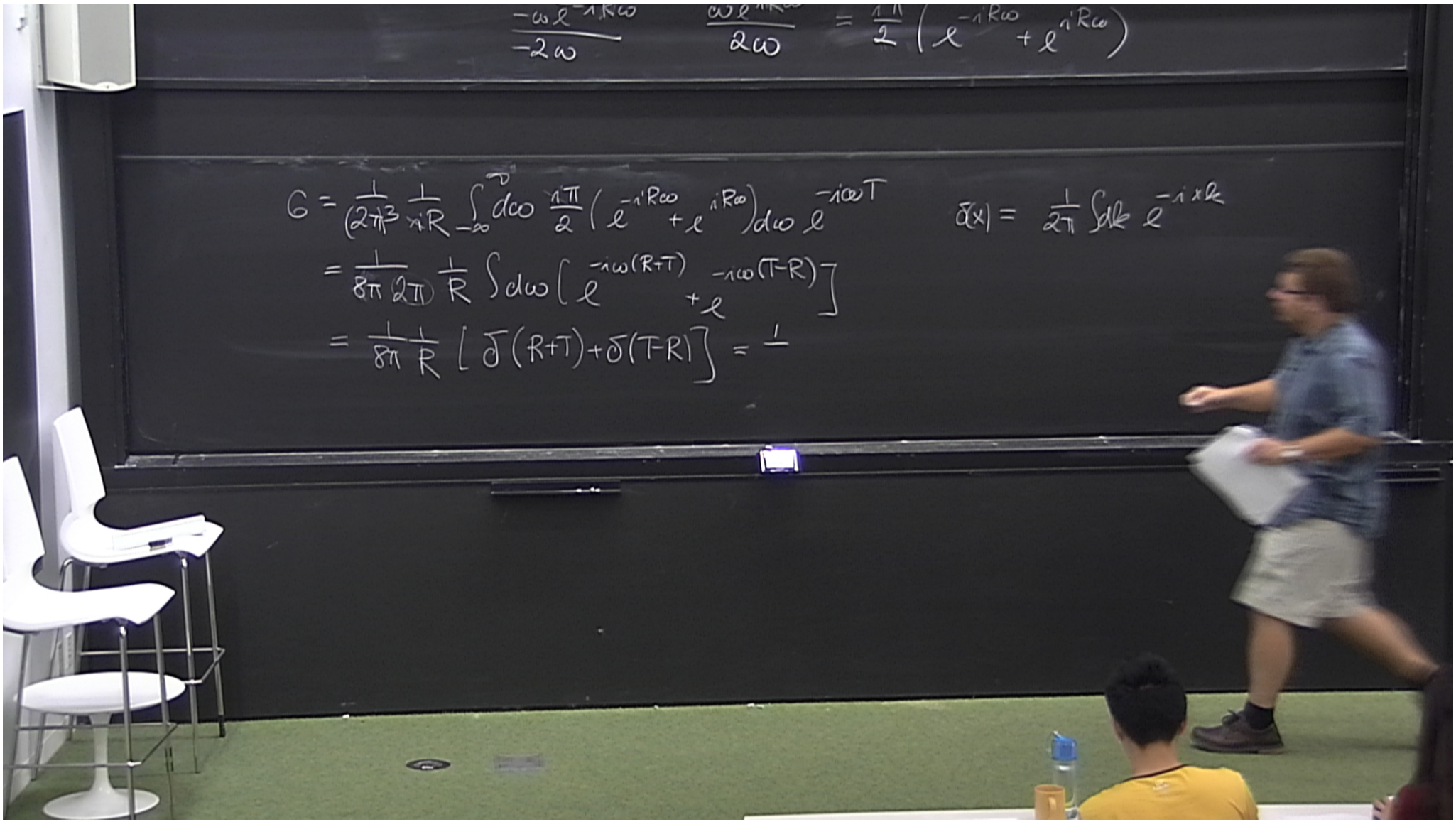

$I = \int_0^\infty \frac{e^{ikR} - e^{-ikR}}{k^2-\omega^2} k\,dk = \int_{-\infty}^{\infty} \frac{k e^{ikR}}{k^2-\omega^2} dk$
$f(k)$
$= I_1 + I_2 = i\pi \left(\mathrm{Res}_{-\omega} f(k) + \mathrm{Res}_{\omega} f(k) \right)$
$\frac{-\omega e^{-ik\omega}}{-2\omega}$
$\frac{\omega e^{ik\omega}}{2\omega}$
I_1
I
I_2
$-\omega$
0
ω
$I - I_1 - I_2 = 0$

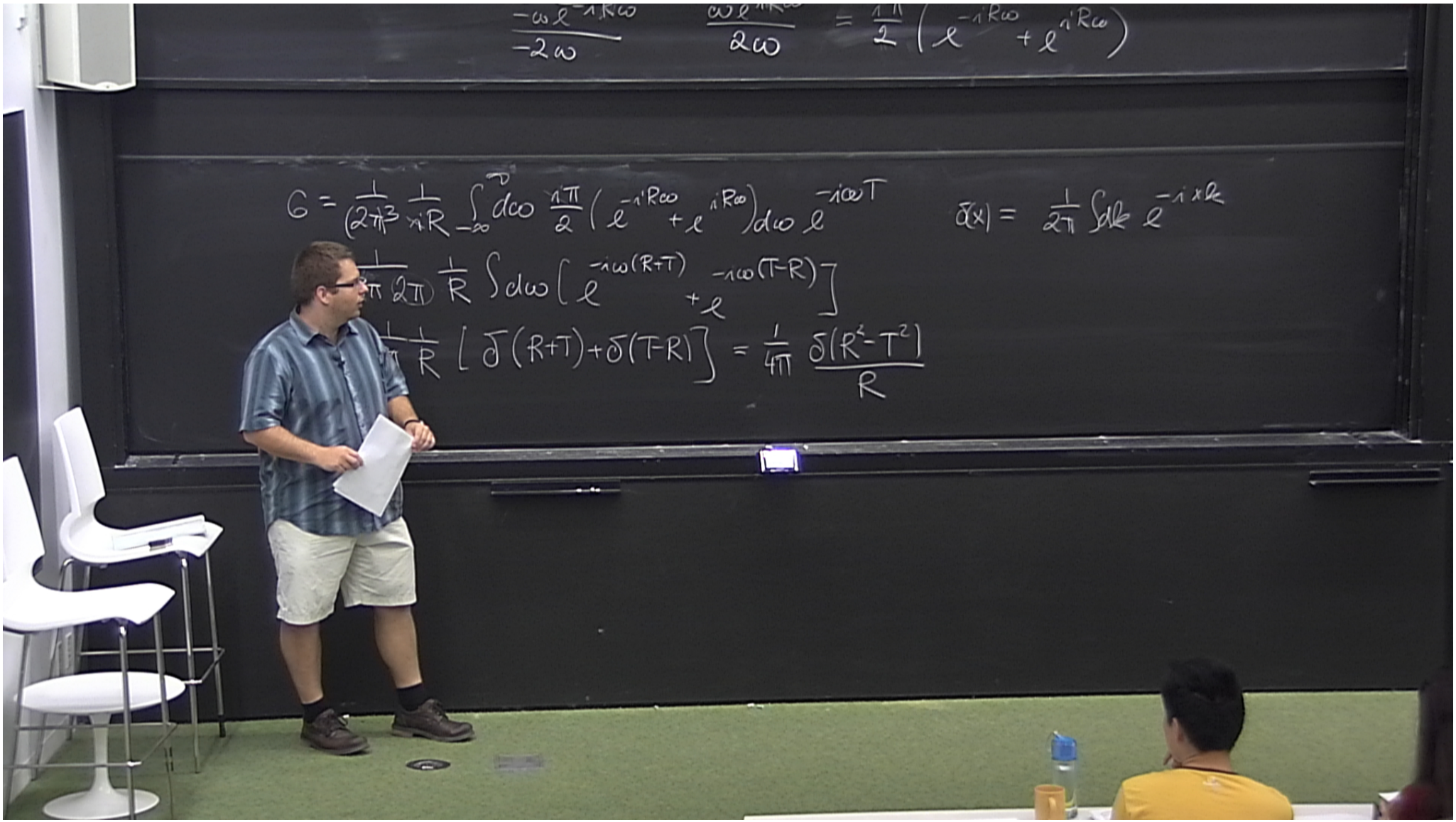

$I = \int_0^\infty \frac{e^{ikR} - e^{-ikR}}{k^2-\omega^2} k\,dk = \int_{-\infty}^{\infty} \frac{k e^{ikR}}{k^2-\omega^2} dk$
$f(k)$
$= I_1 + I_2 = i\pi \left(\mathrm{Res}_{-\omega} f(k) + \mathrm{Res}_{\omega} f(k) \right)$
$\frac{-\omega e^{-iR\omega}}{-2\omega}$
$\frac{\omega e^{iR\omega}}{2\omega}$
$= i\pi \left(e^{-i}\right.$
I_1
I
I_2
$-\omega$
0
ω
$I - I_1 - I_2 = 0$

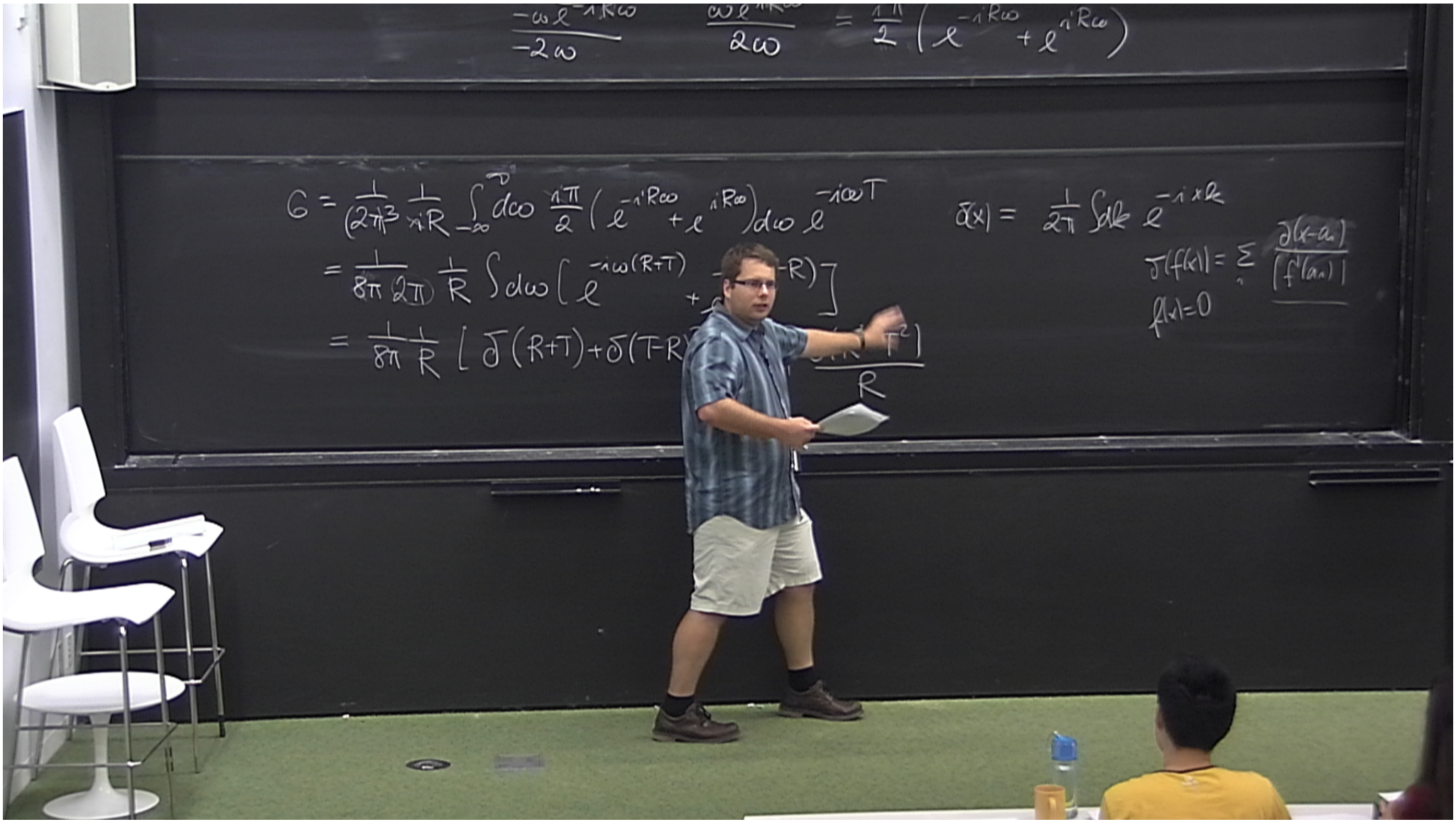

$I = \int_0^\infty \frac{e^{ikR} - e^{-ikR}}{k^2-\omega^2} k\,dk = \int_{-\infty}^{\infty} \frac{k e^{ikR}}{k^2-\omega^2} dk$
$f(k)$
$= I_1 + I_2 = i\pi \left(\underbrace{\mathrm{Res}_{-\omega} f(k)}_{\frac{-\omega e^{-iR\omega}}{-2\omega}} + \underbrace{\mathrm{Res}_{\omega} f(k)}_{\frac{\omega e^{iR\omega}}{2\omega}} \right) = \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right)$
I_1
I
I_2
$-\omega$
0
ω
$I - I_1 - I_2 = 0$

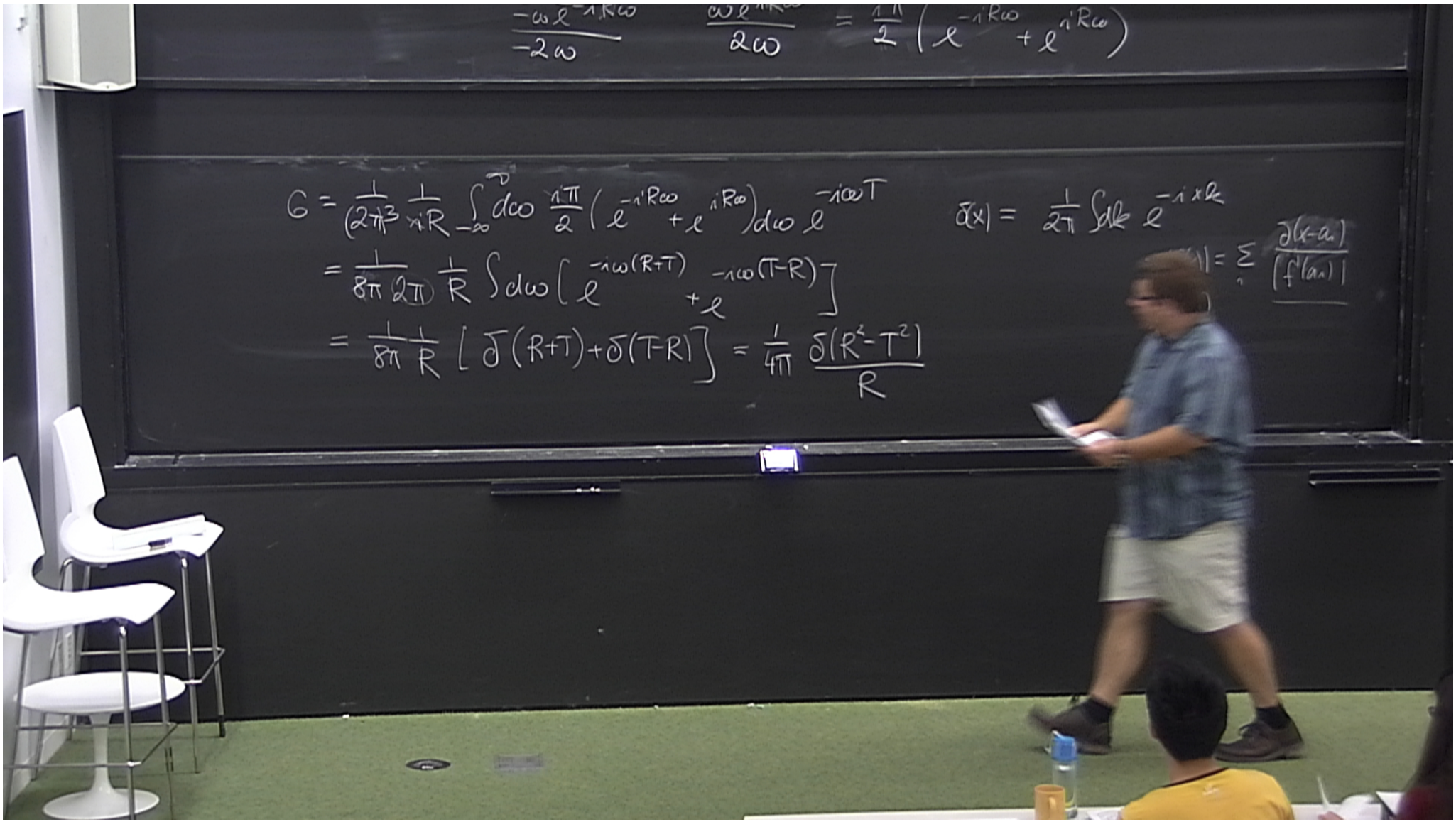

$\frac{-\omega e^{-iR\omega}}{-2\omega} \quad \frac{\omega e^{iR\omega}}{2\omega} = \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right)$
$G = \frac{1}{(2\pi)^3}\frac{1}{iR}\int_{-\infty}^{\infty} d\omega \, \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right) d\omega \, e^{-i\omega T}$
$= \frac{1}{8\pi}\frac{1}{2\pi}\frac{1}{R}\int d\omega \left[e^{-i\omega(R+T)} + e^{-i\omega(T-R)}\right]$


$\frac{-\omega e^{-iR\omega}}{-2\omega}$ $\frac{\omega e^{iR\omega}}{2\omega} = \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right)$
$G = \frac{1}{(2\pi)^3}\frac{1}{iR}\int_{-\infty}^{\infty} d\omega \, \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right) d\omega \, e^{-i\omega T}$
$= \frac{1}{8\pi}\frac{1}{2\pi}\frac{1}{R}\int d\omega \left[e^{-i\omega(R+T)} + e^{-i\omega(T-R)}\right]$
$= \frac{1}{8\pi}\frac{1}{R}\left[\delta(R+T) + \delta(T-R)\right]$
$\delta(x) = \frac{1}{2\pi}\int dk \, e^{-ixk}$


$\frac{-\omega e^{-iR\omega}}{-2\omega}$ $\frac{\omega e^{iR\omega}}{2\omega} = \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right)$
$G = \frac{1}{(2\pi)^3}\frac{1}{iR}\int_{-\infty}^{\infty} d\omega \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right) d\omega\, e^{-i\omega T}$
$\delta(x) = \frac{1}{2\pi}\int dk\, e^{-ixk}$
$= \frac{1}{8\pi\, 2\pi}\frac{1}{R}\int d\omega \left[e^{-i\omega(R+T)} + e^{-i\omega(T-R)}\right]$
$= \frac{1}{8\pi}\frac{1}{R}\left[\delta(R+T) + \delta(T-R)\right] = \frac{1}{}$


$\frac{-\omega e^{-iR\omega}}{-2\omega}$ $\frac{\omega e^{iR\omega}}{2\omega} = \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right)$
$G = \frac{1}{(2\pi)^3}\frac{1}{iR}\int_{-\infty}^{\infty} d\omega\, \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right) d\omega\, e^{-i\omega T}$
$\delta(x) = \frac{1}{2\pi}\int dk\, e^{-ixk}$
$\frac{1}{\pi}\frac{1}{2\pi}\frac{1}{R}\int d\omega\left[e^{-i\omega(R+T)} + e^{-i\omega(T-R)}\right]$
$\frac{1}{\pi}\frac{1}{R}\left[\delta(R+T) + \delta(T-R)\right] = \frac{1}{4\pi}\frac{\delta(R^2-T^2)}{R}$


$\frac{-\omega e^{-iR\omega}}{-2\omega}$ $\frac{\omega e^{iR\omega}}{2\omega} = \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right)$
$G = \frac{1}{(2\pi)^3}\frac{1}{iR}\int_{-\infty}^{\infty} d\omega \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right) d\omega\, e^{-i\omega T}$
$= \frac{1}{8\pi\,(2\pi)}\frac{1}{R}\int d\omega \left[e^{-i\omega(R+T)} + e^{-i\omega(T-R)}\right]$
$= \frac{1}{8\pi}\frac{1}{R}\left[\delta(R+T) + \delta(T-R)\right]$
$\delta(x) = \frac{1}{2\pi}\int dk\, e^{-ixk}$
$\delta(f(x)) = \sum_i \frac{\delta(x-a_i)}{|f'(a_i)|}$
$f(x)=0$


$\frac{-\omega e^{-iR\omega}}{-2\omega} \quad \frac{\omega e^{iR\omega}}{2\omega} = \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right)$
$G = \frac{1}{(2\pi)^3}\frac{1}{iR}\int_{-\infty}^{\infty} d\omega \, \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right) d\omega \, e^{-i\omega T}$
$= \frac{1}{8\pi\, 2\pi}\frac{1}{R}\int d\omega \left[e^{-i\omega(R+T)} + e^{-i\omega(T-R)}\right]$
$= \frac{1}{8\pi}\frac{1}{R}\left[\delta(R+T) + \delta(T-R)\right] = \frac{1}{4\pi}\frac{\delta(R^2-T^2)}{R}$
$\delta(x) = \frac{1}{2\pi}\int dk \, e^{-ixk}$
$= \sum_n \frac{\delta(x-a_n)}{|f'(a_n)|}$

$$\frac{-\omega e^{-iR\omega}}{-2\omega} \qquad \frac{\omega e^{iR\omega}}{2\omega} = \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right)$$

$$G = \frac{1}{(2\pi)^3}\frac{1}{iR}\int_{-\infty}^{\infty} d\omega\, \frac{i\pi}{2}\left(e^{-iR\omega} + e^{iR\omega}\right) d\omega\, e^{-i\omega T}$$

$$= \frac{1}{8\pi\, 2\pi}\frac{1}{R}\int d\omega \left[e^{-i\omega(R+T)} + e^{-i\omega(T-R)}\right]$$

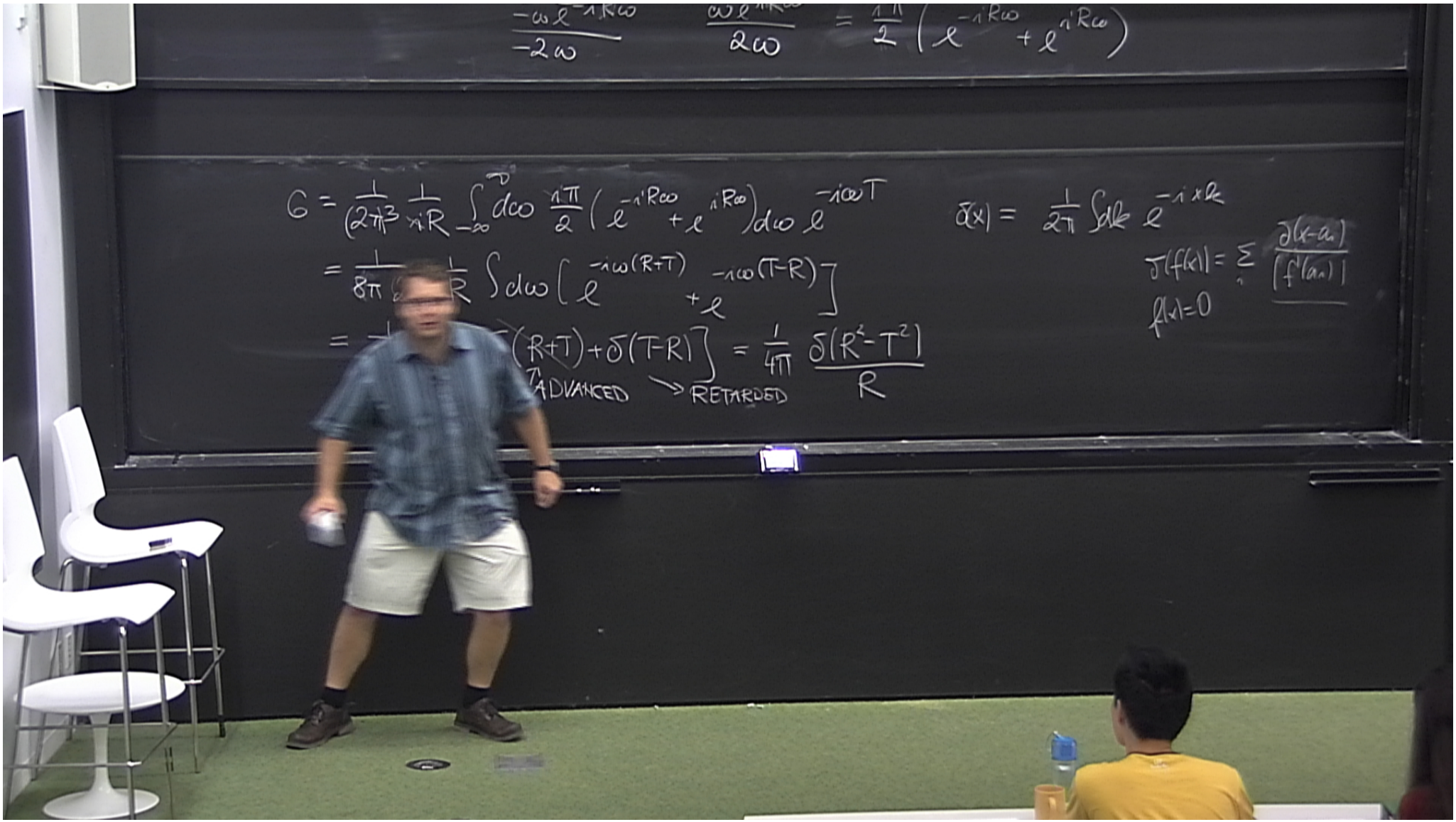
$$= \frac{1}{8\pi}\frac{1}{R}\left[\delta(R+T) + \delta(T-R)\right] = \frac{1}{4\pi}\frac{\delta(R^2-T^2)}{R}$$

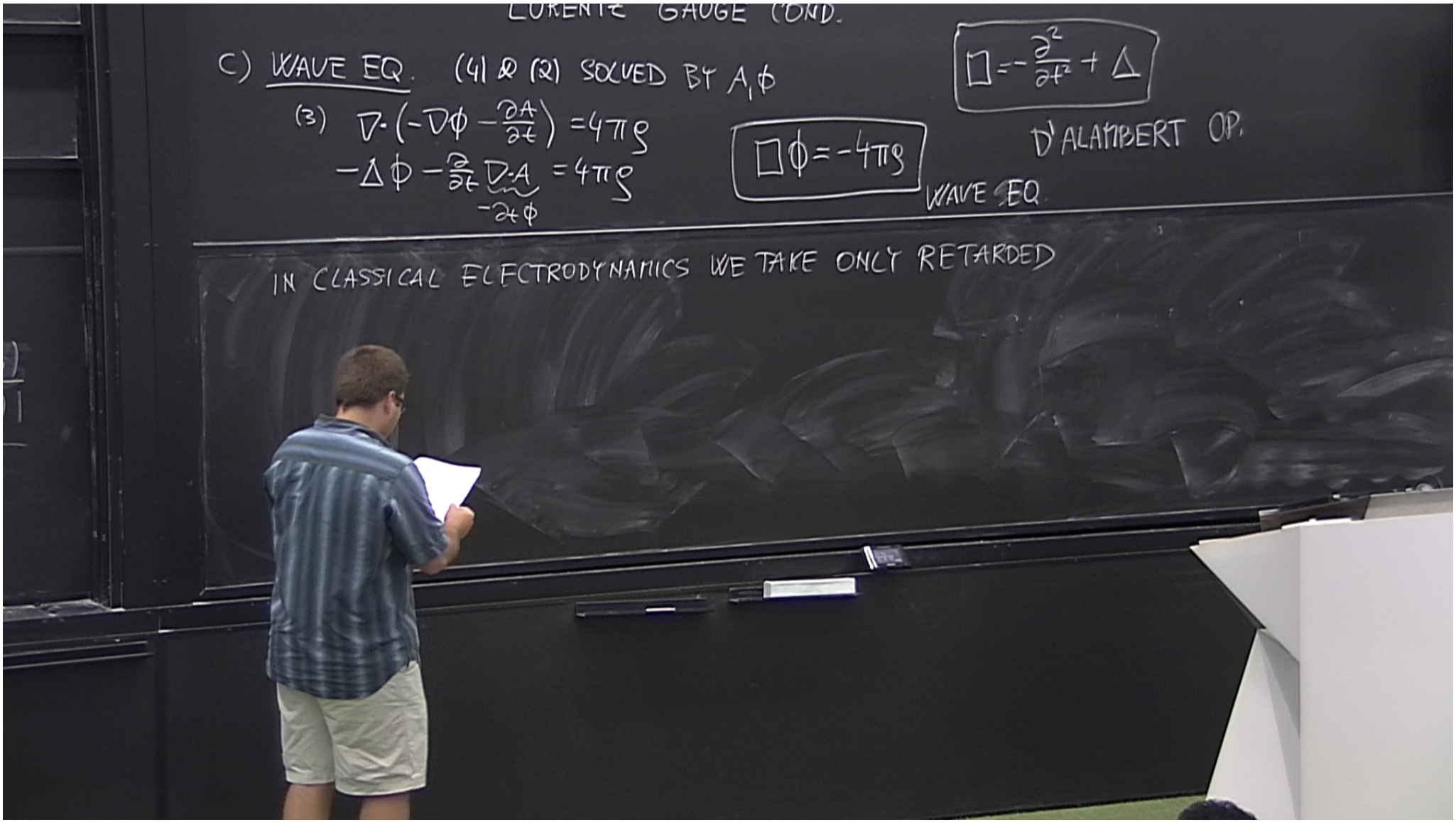
ADVANCED RETARDED

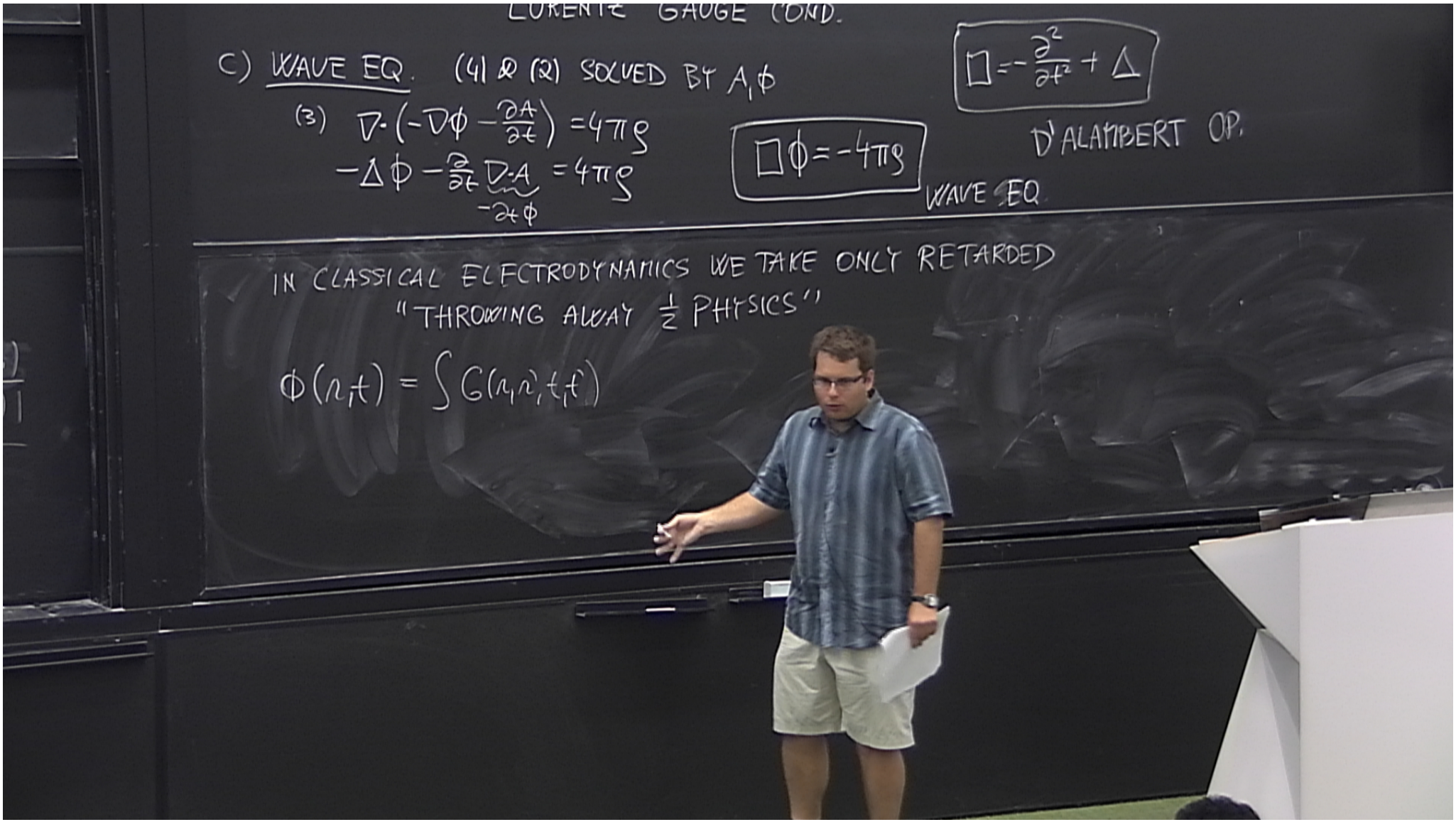
$$\delta(x) = \frac{1}{2\pi}\int dk\, e^{-ixk}$$

$$\delta(f(x)) = \sum_n \frac{\delta(x-a_n)}{|f'(a_n)|}$$

$$f(x) = 0$$


ADVANCED
RETARDED


LORENTZ GAUGE COND.
C) WAVE EQ. (4) & (2) SOLVED BY A, φ
(3) ∇·(−∇φ − ∂A/∂t) = 4πρ
−Δφ − ∂/∂t ∇·A = 4πρ
−∂tφ
□φ = −4πρ
WAVE EQ.
□ = −∂²/∂t² + Δ
D'ALAMBERT OP.
IN CLASSICAL ELECTRODYNAMICS WE TAKE ONLY RETARDED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□ = −∂²/∂t² + Δ
D'ALAMBERT OP.
IN CLASSICAL ELECTRODYNAMICS WE TAKE ONLY RETARDED
"THROWING AWAY ½ PHYSICS"
φ(r,t) = ∫ G(r,r',t,t')

LORENTZ GAUGE COND.

C) WAVE EQ. (4) & (2) SOLVED BY A, ϕ

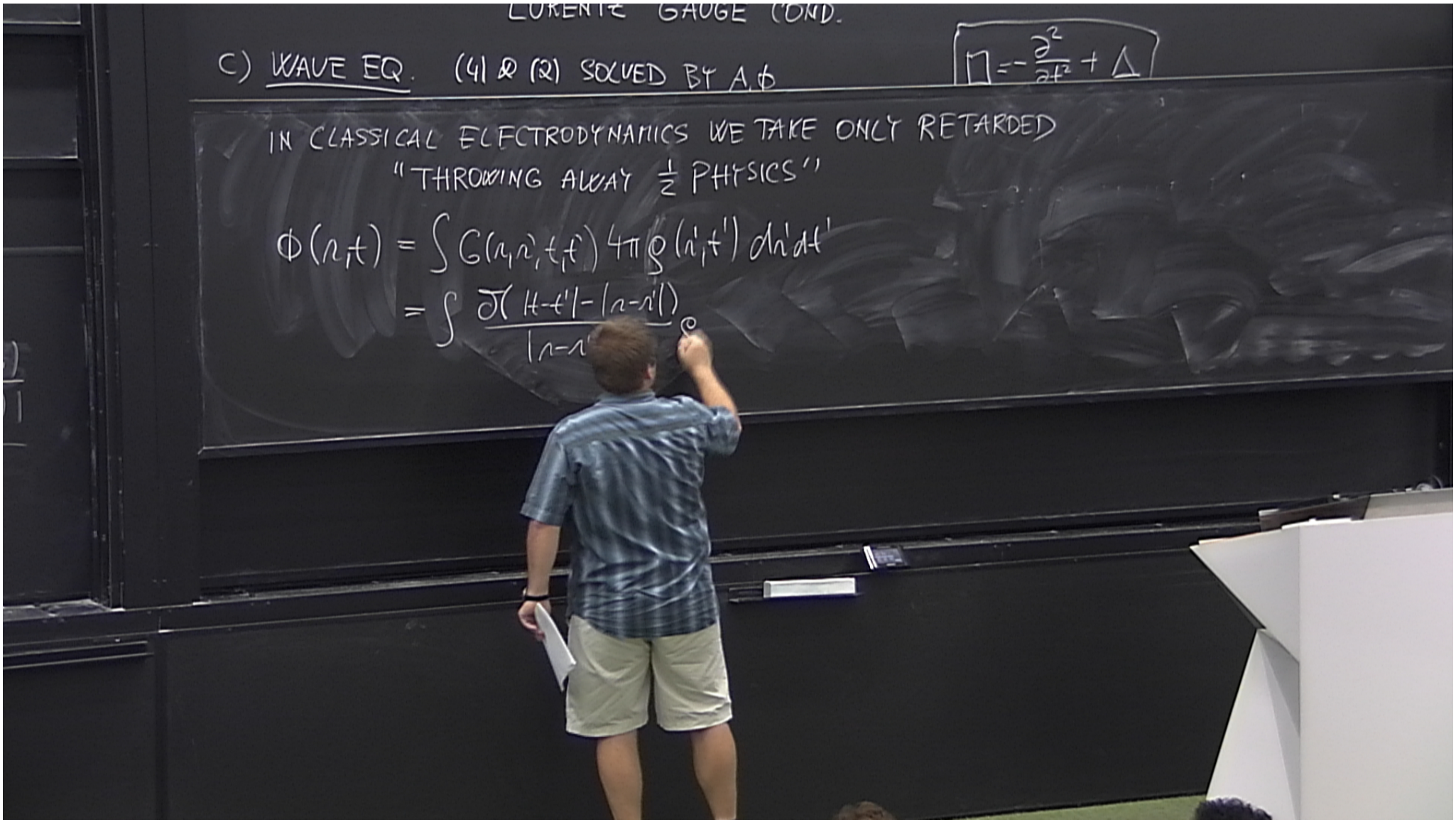
$$\Box = -\frac{\partial^2}{\partial t^2} + \Delta$$

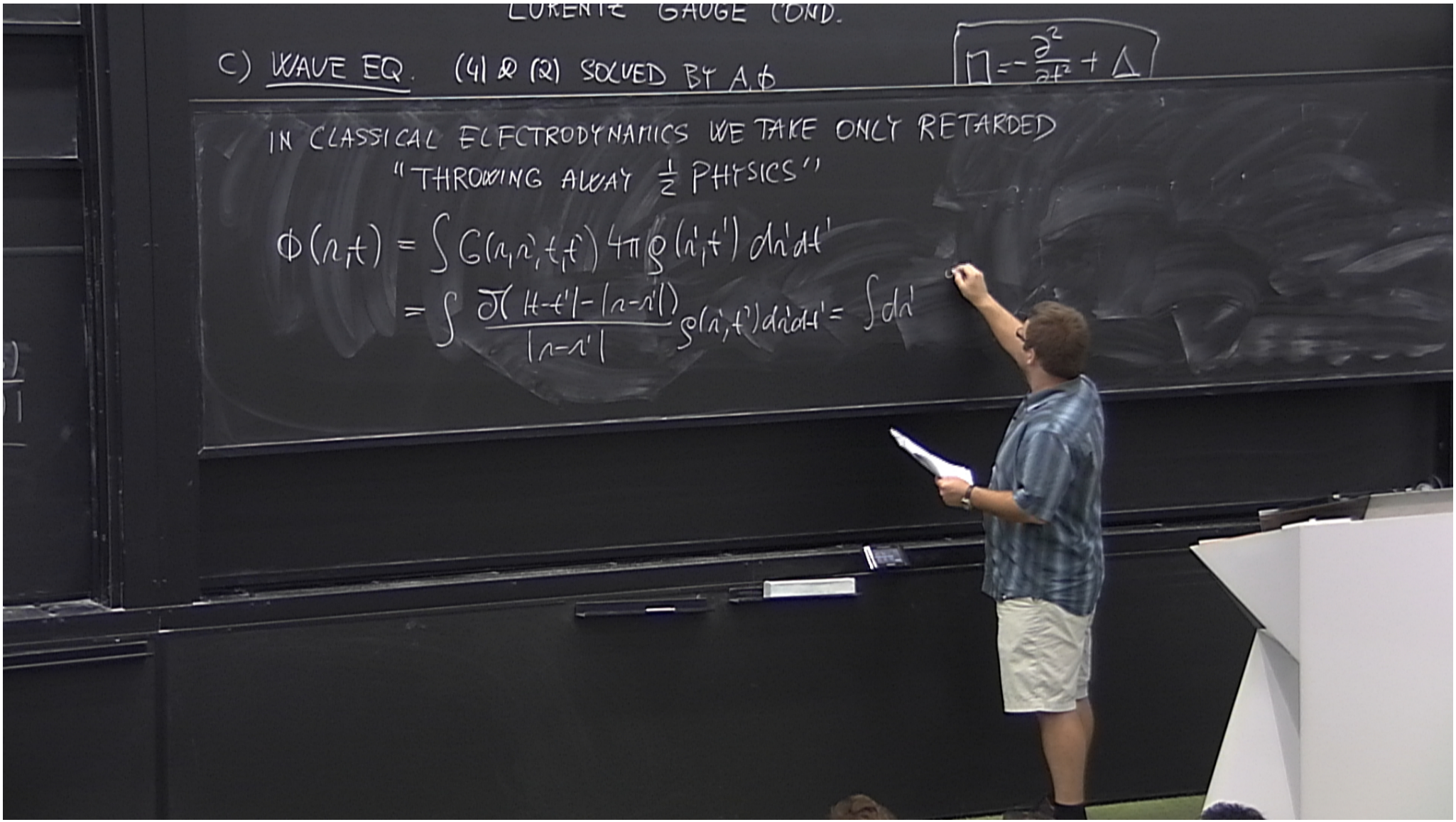
IN CLASSICAL ELECTRODYNAMICS WE TAKE ONLY RETARDED

"THROWING AWAY $\frac{1}{2}$ PHYSICS"

$$\Phi(r,t) = \int G(r,r',t,t')\, 4\pi\rho(r',t')\, dr'dt'$$

$$= \int \mathcal{J}$$


LORENTZ GAUGE COND.
C) WAVE EQ. (4) & (2) SOLVED BY A, Φ
$\Box = -\frac{\partial^2}{\partial t^2} + \Delta$
IN CLASSICAL ELECTRODYNAMICS WE TAKE ONLY RETARDED
"THROWING AWAY ½ PHYSICS"
$\Phi(r,t) = \int G(r,r',t,t')\, 4\pi\rho(r',t')\, dr'dt'$
$= \int \frac{\delta(|t-t'| - |r-r'|)}{|r-r'|}$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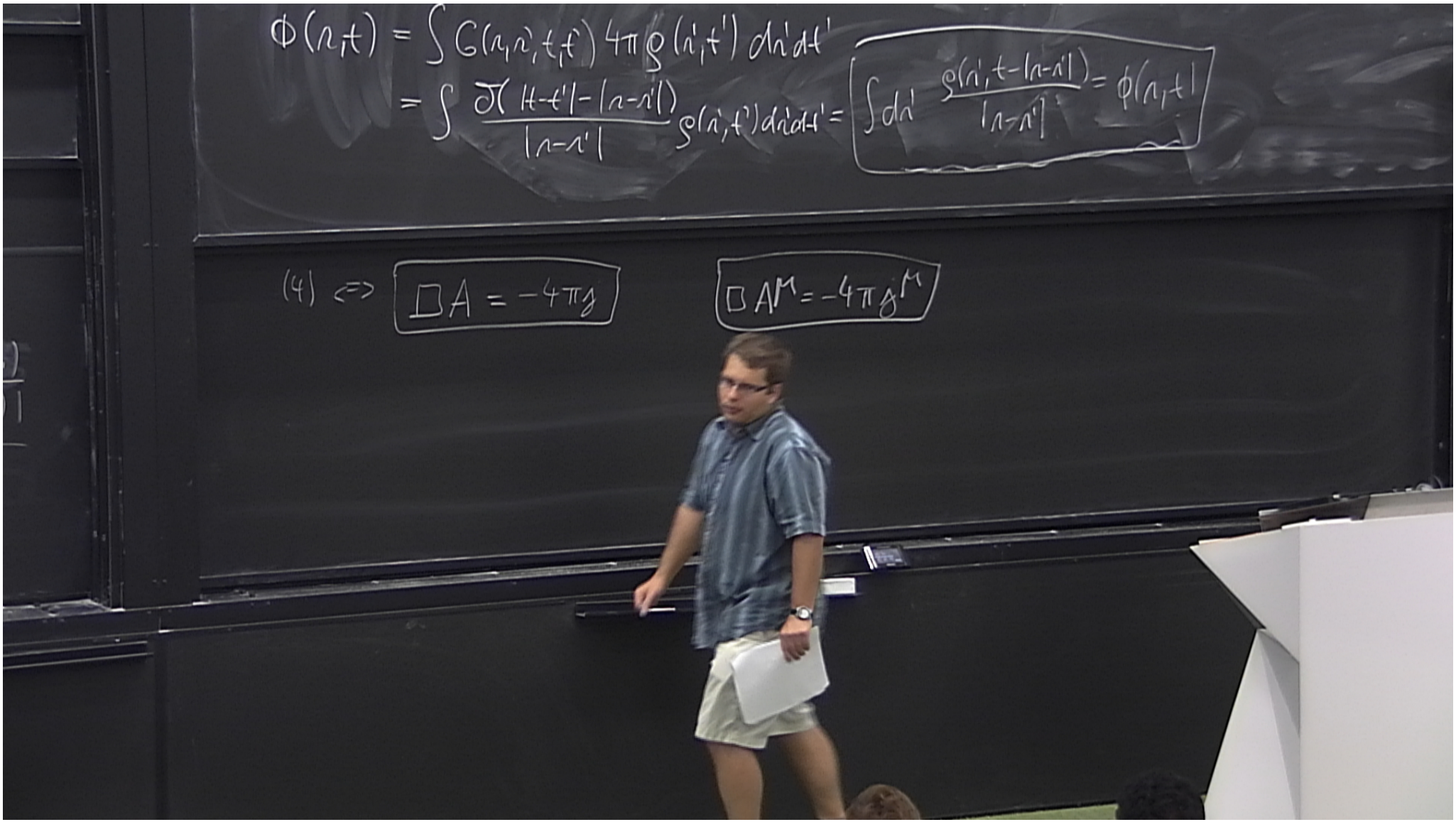
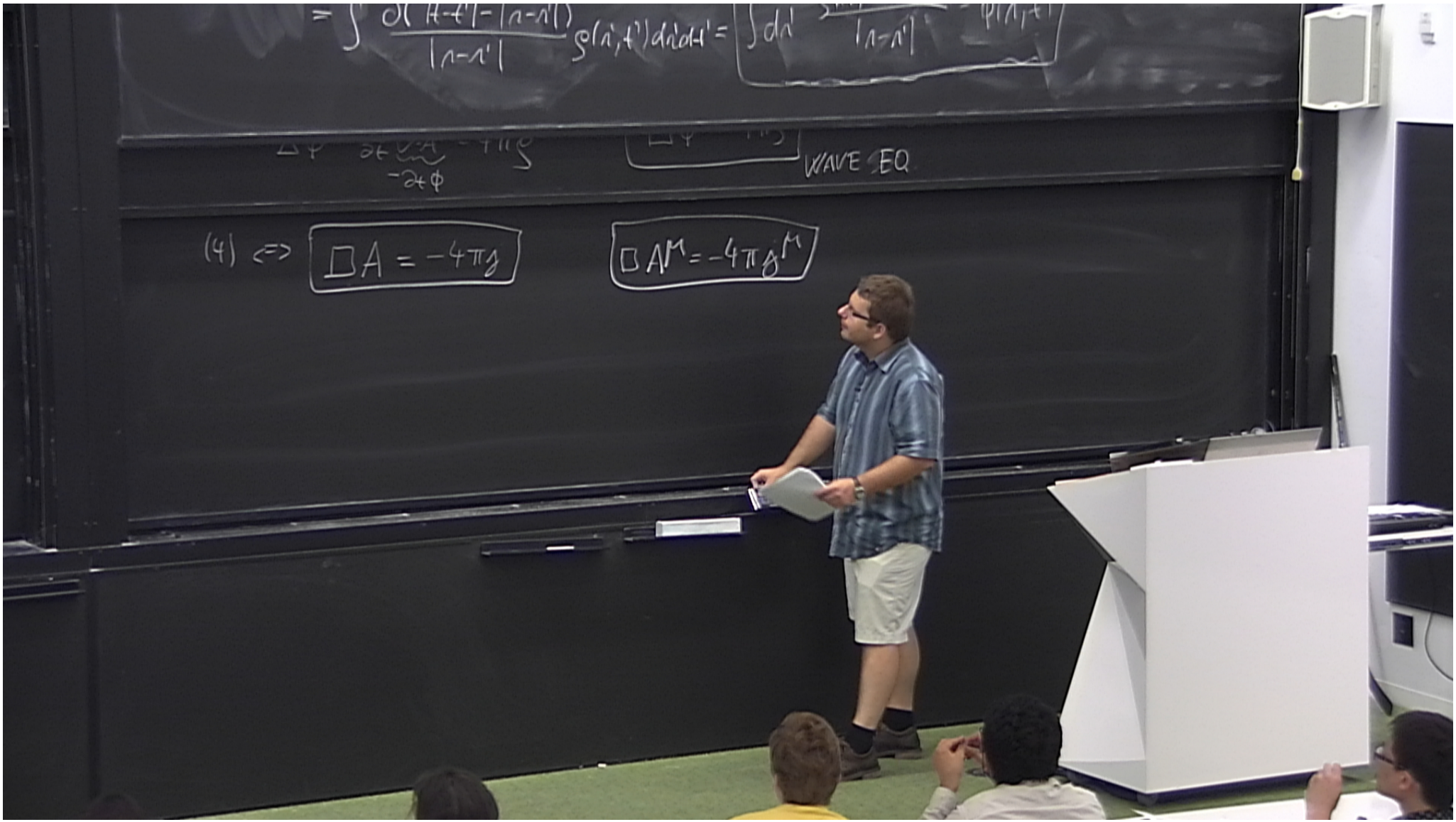
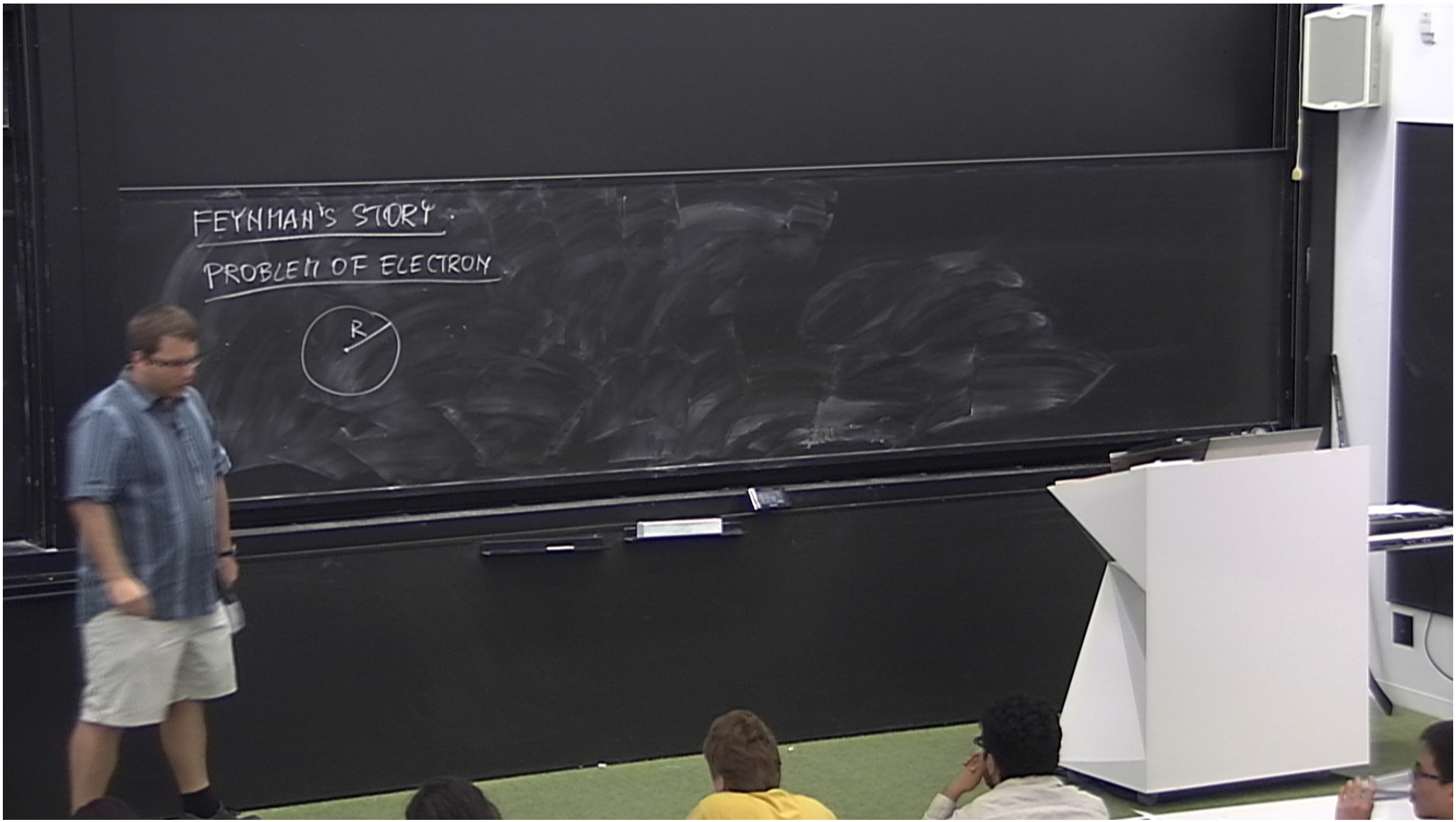
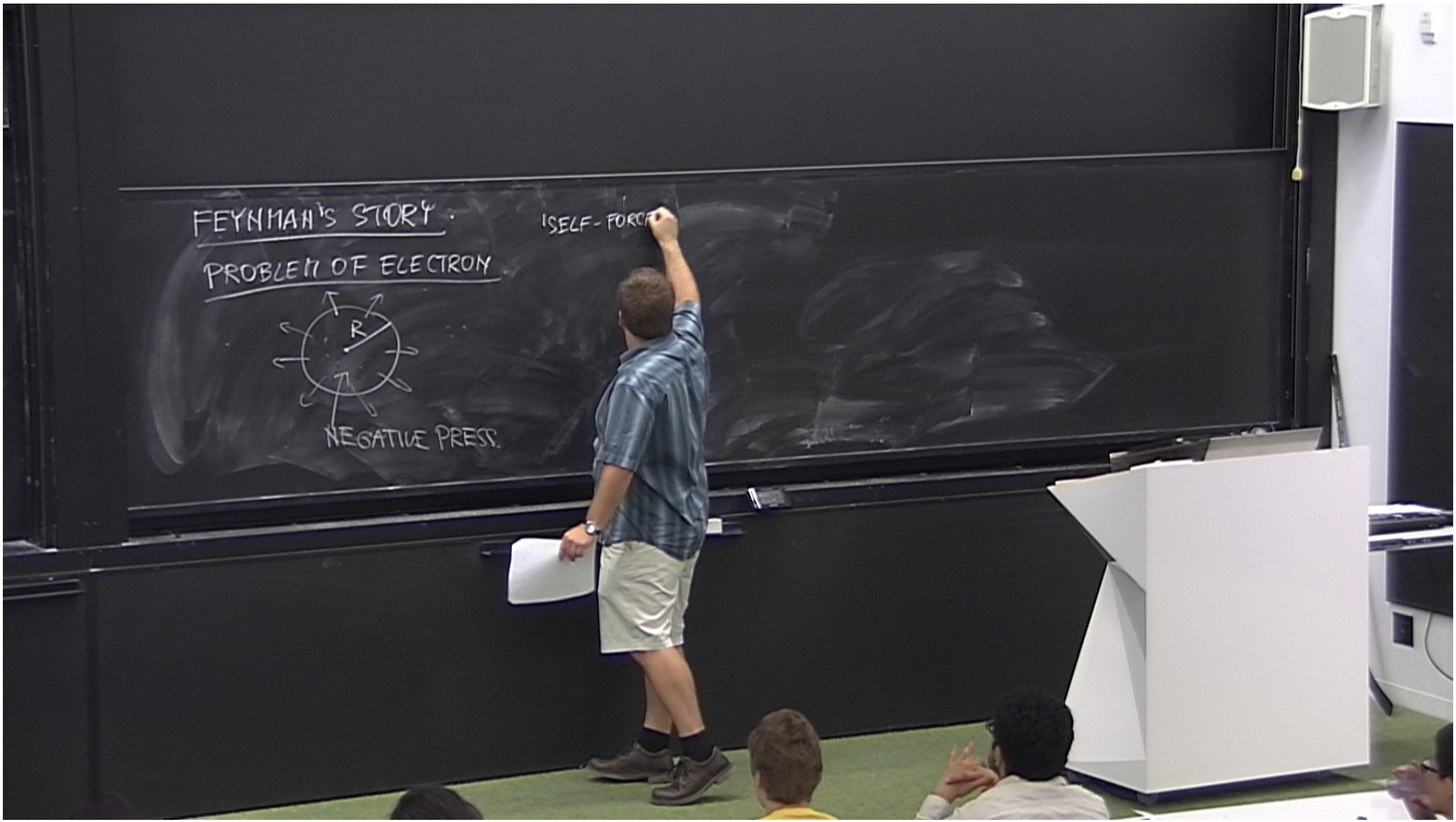
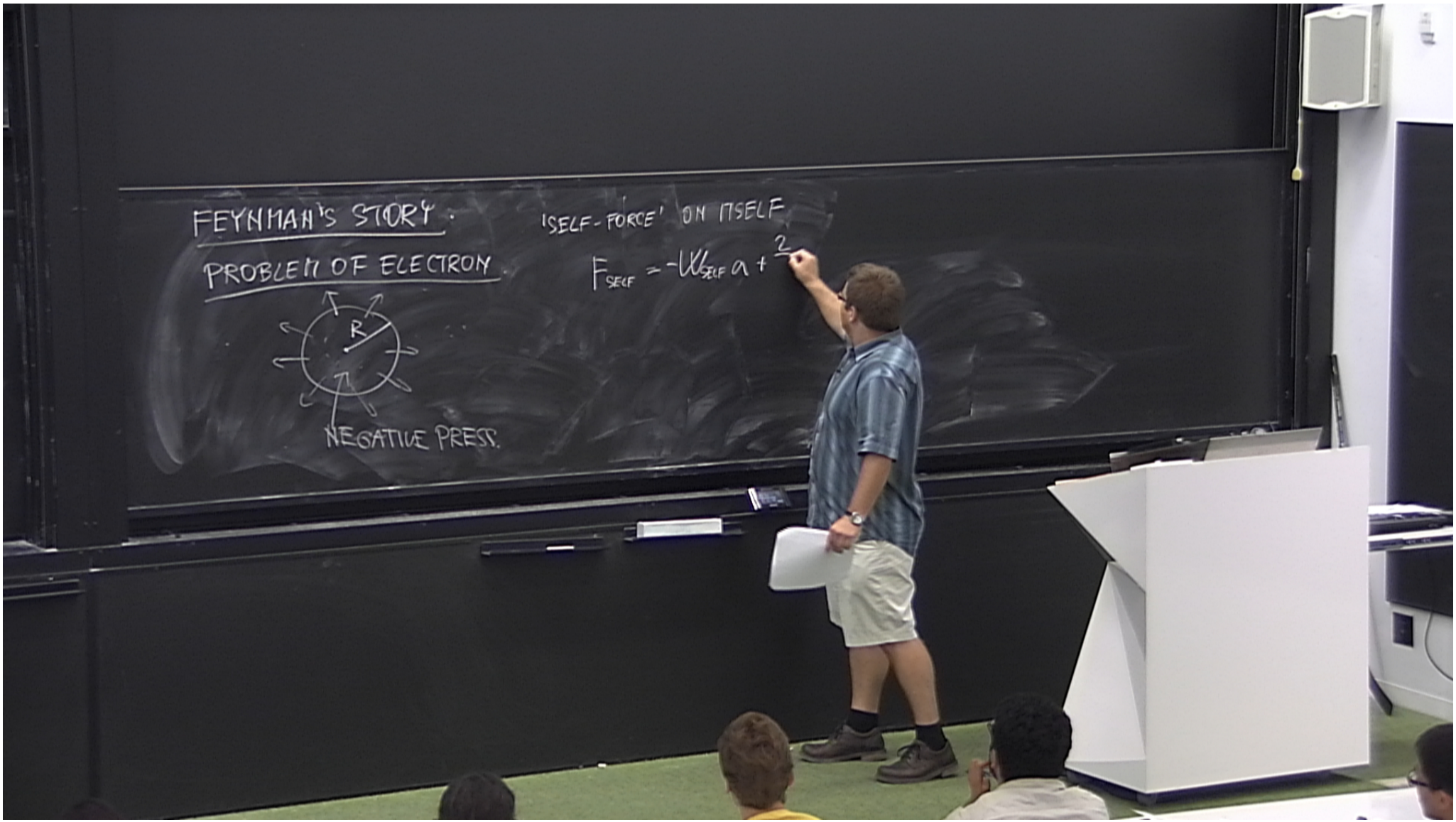
"THROWING AWAY ½ PHYSICS"
$\Phi(r,t) = \int G(r,r',t,t')\, 4\pi \rho(r',t')\, dr'dt'$
$= \int \frac{\delta(|t-t'| - |r-r'|)}{|r-r'|} \rho(r',t')\, dr'dt' = \int dr'$

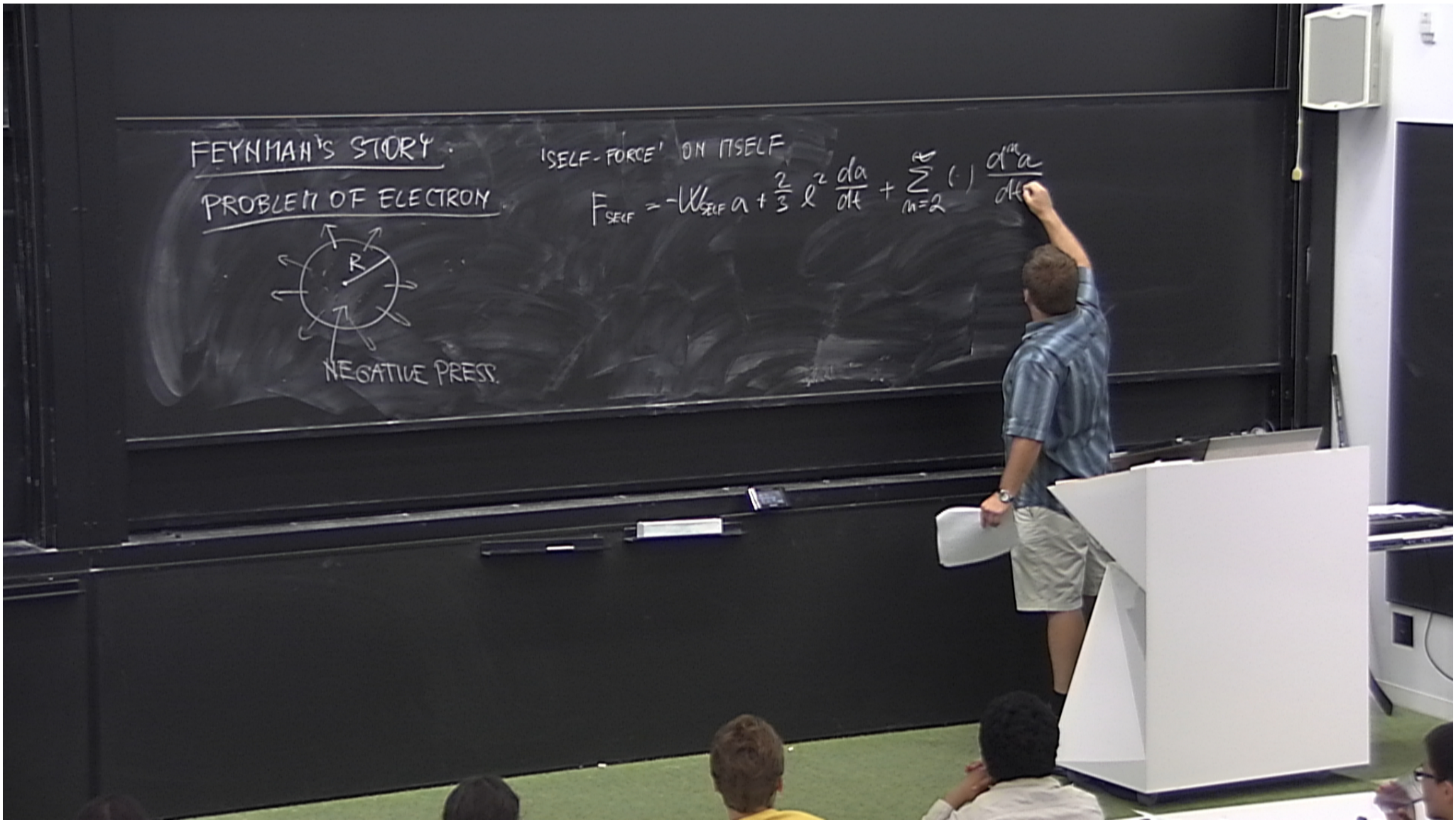

$\Phi(r,t) = \int G(r,r',t,t')\, 4\pi \rho(r',t')\, dr'dt'$
$= \int \frac{\delta(|t-t'| - |r-r'|)}{|r-r'|} \rho(r',t')\, dr'dt' = \boxed{\int dr' \frac{\rho(r', t-|r-r'|)}{|r-r'|} = \phi(r,t)}$
(4) $\Leftrightarrow$ $\boxed{\Box A = -4\pi j}$
$\boxed{\Box A^\mu = -4\pi j^\mu}$

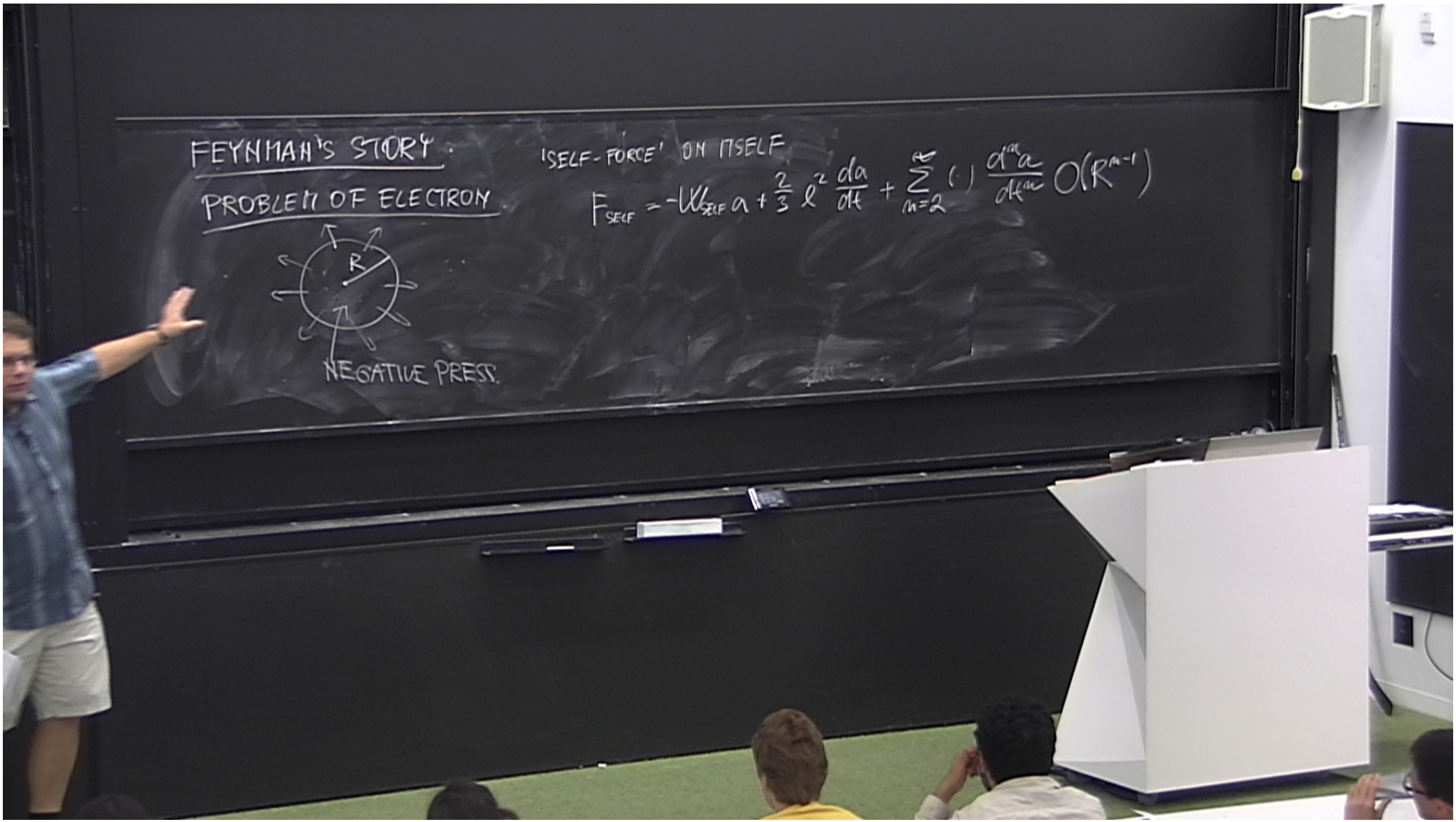

WAVE EQ
(4) <=> □A = -4πj
□A^μ = -4πj^μ

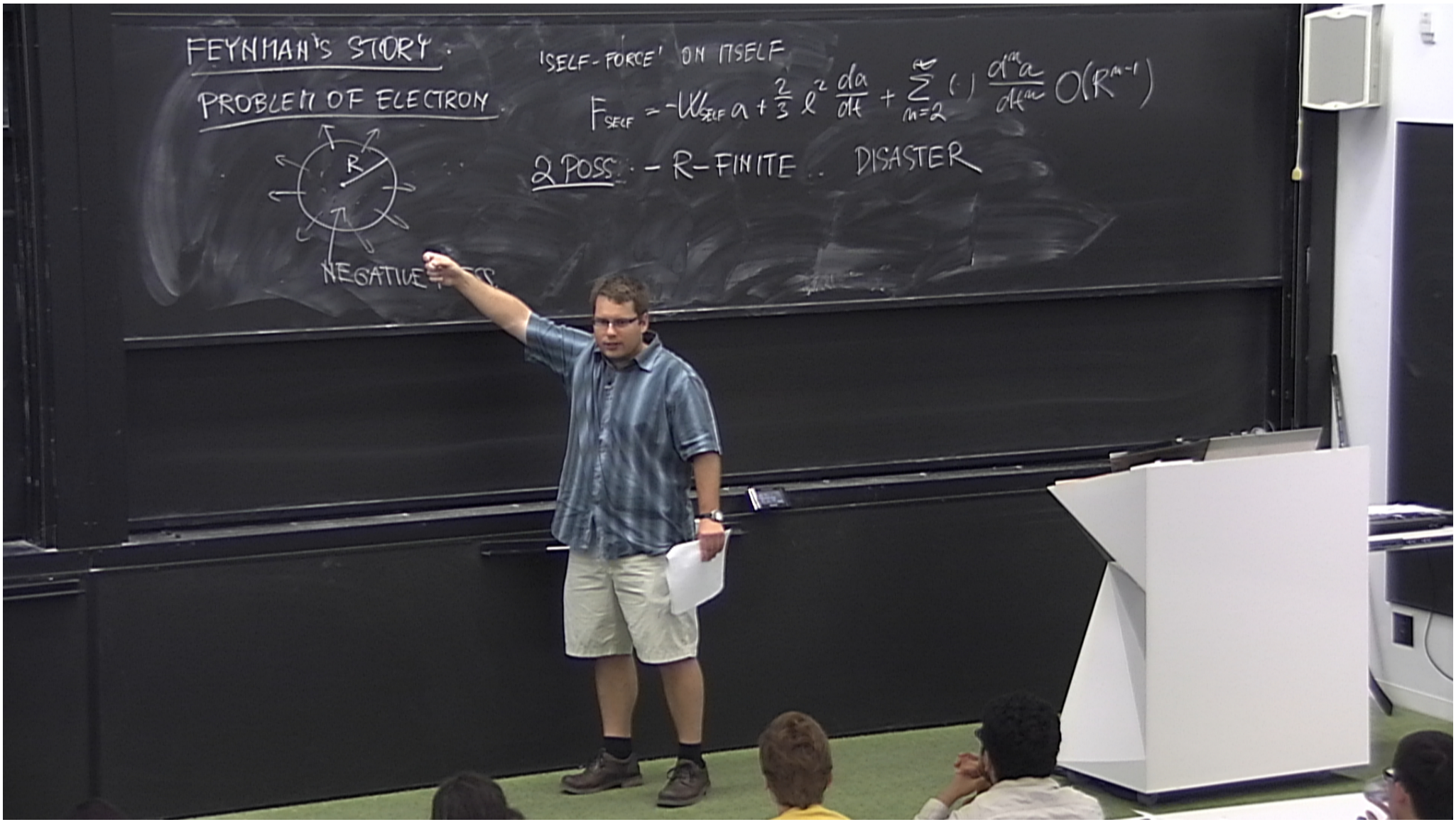

FEYNMAN'S STORY
PROBLEM OF ELECTRON
R

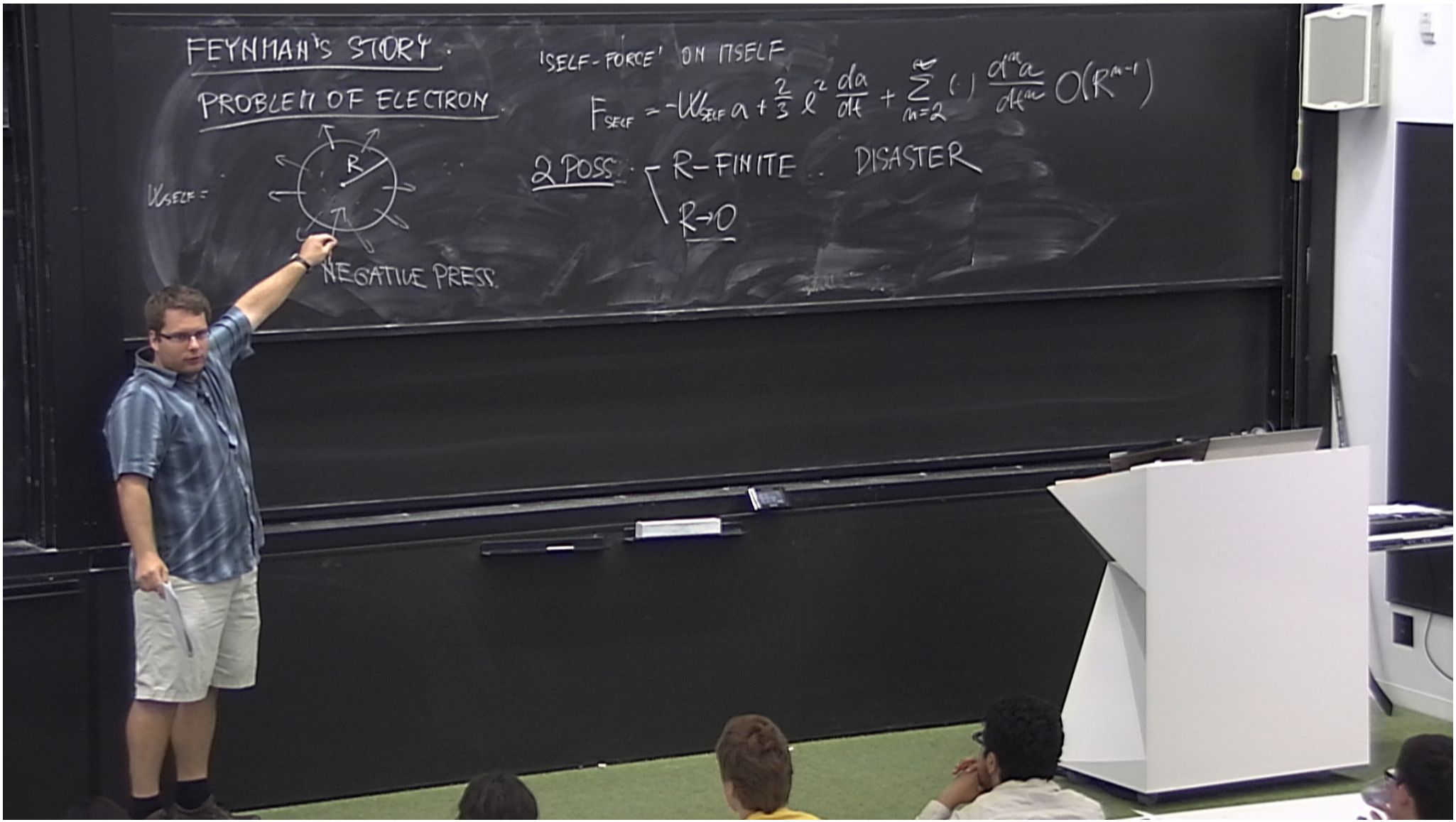

FEYNMAN'S STORY
PROBLEM OF ELECTRON
R
NEGATIVE PRESS.
SELF-FORCE

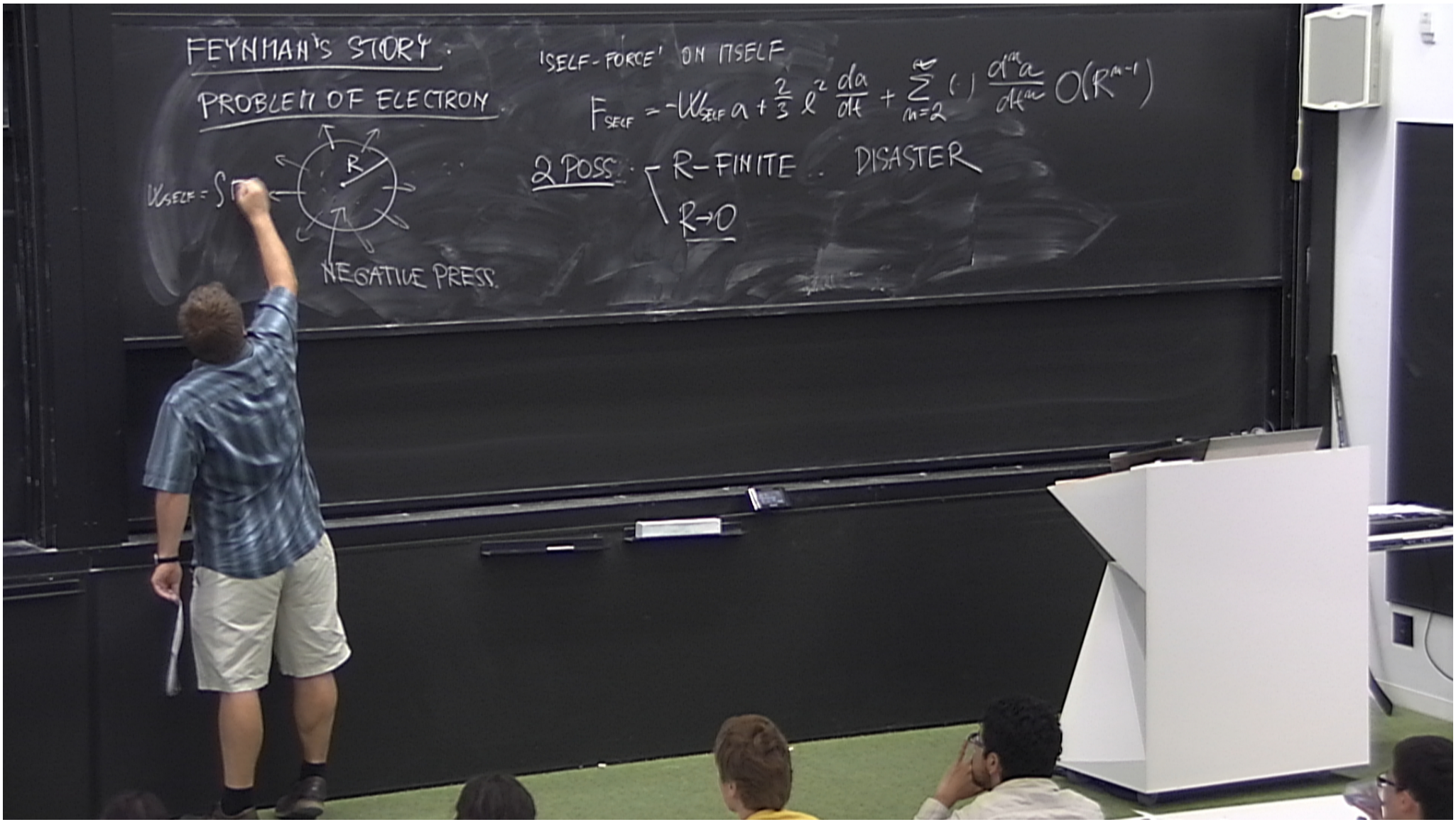

FEYNMAN'S STORY.
PROBLEM OF ELECTRON.
R
NEGATIVE PRESS.
'SELF-FORCE' ON ITSELF
$F_{SELF} = -W_{SELF}\, a + \frac{2}{}$

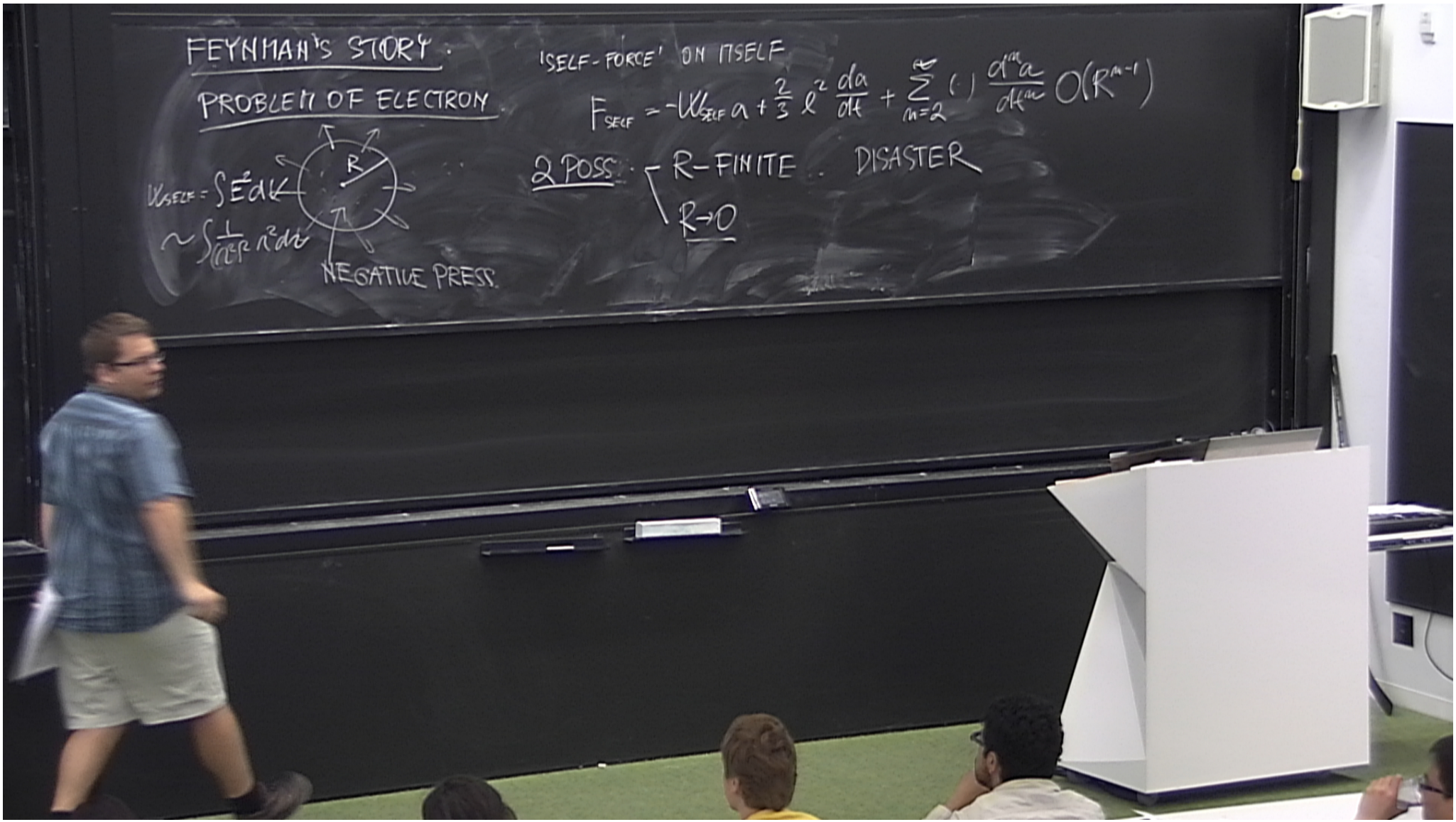

FEYNMAN'S STORY
PROBLEM OF ELECTRON
R
NEGATIVE PRESS.
'SELF-FORCE' ON ITSELF
$F_{SELF} = -W_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{n=2}^{\infty} (\cdot) \frac{d^n a}{dt^n}$


FEYNMAN'S STORY
PROBLEM OF ELECTRON
R
NEGATIVE PRESS.
'SELF-FORCE' ON ITSELF
$F_{SELF} = -M_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{n=2}^{\infty} (\cdot) \frac{d^n a}{dt^n} O(R^{n-1})$


FEYNMAN'S STORY
PROBLEM OF ELECTRON
R
NEGATIVE
'SELF-FORCE' ON ITSELF
$F_{SELF} = -W_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{m=2}^{\infty} ( ) \frac{d^m a}{dt^m} O(R^{m-1})$
2 POSS: - R-FINITE .. DISASTER


FEYNMAN'S STORY
PROBLEM OF ELECTRON
'SELF-FORCE' ON ITSELF
$F_{SELF} = -W_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{n=2}^{\infty} ( ) \frac{d^n a}{dt^n} O(R^{n-1})$
$W_{SELF} =$
R
NEGATIVE PRESS.
2 POSS.
R-FINITE
DISASTER
$R \to 0$


FEYNMAN'S STORY
PROBLEM OF ELECTRON
'SELF-FORCE' ON ITSELF
$F_{SELF} = -W_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{m=2}^{\infty} ( ) \frac{d^m a}{dt^m} O(R^{m-1})$
R
NEGATIVE PRESS.
2 POSS.
R-FINITE
DISASTER
R→0


FEYNMAN'S STORY
PROBLEM OF ELECTRON
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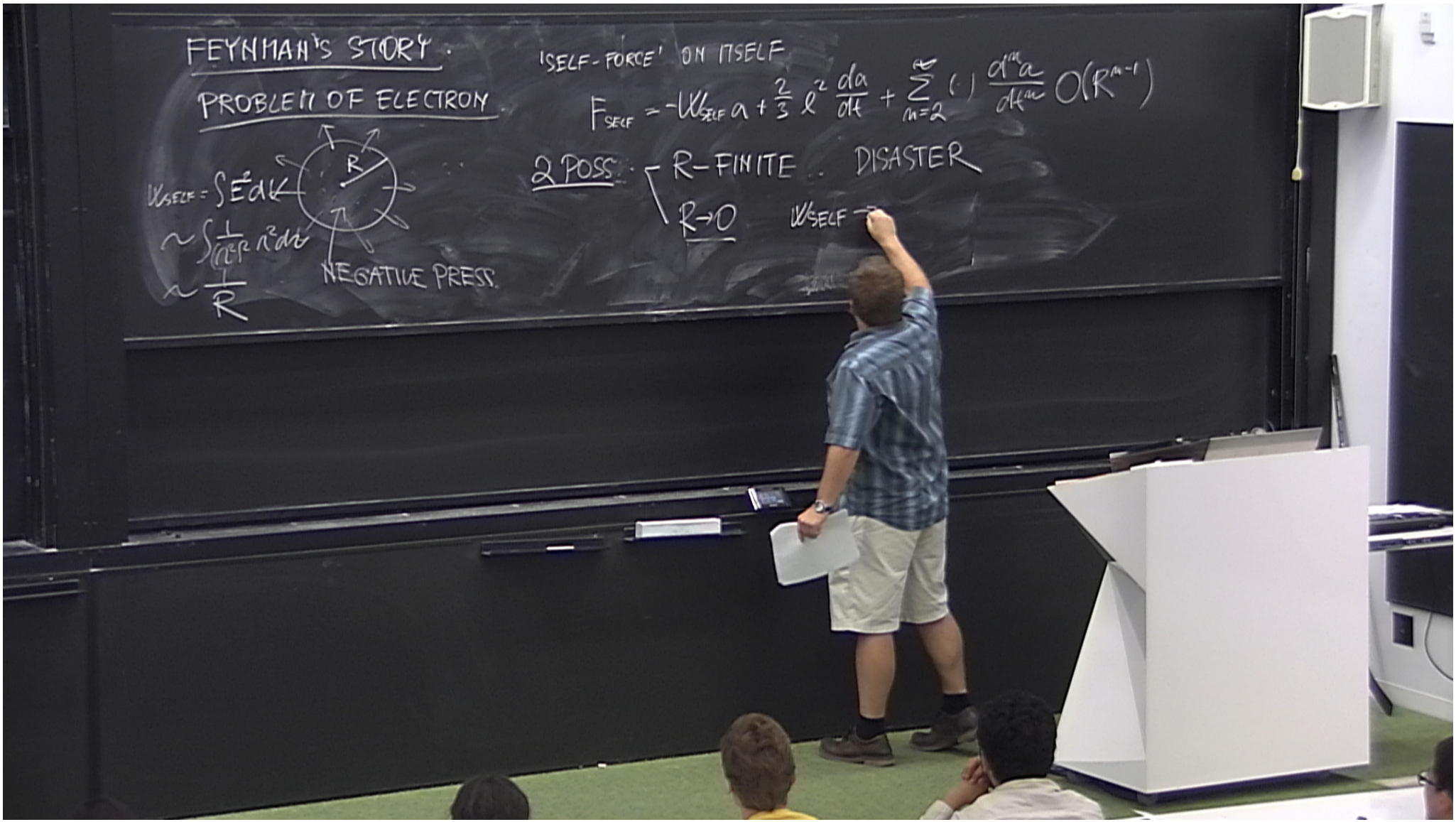
$F_{SELF} = -W_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{n=2}^{\infty} ( ) \frac{d^n a}{dt^n} O(R^{n-1})$
$W_{SELF} = \int E^2 dV$
$\sim \int \frac{1}{(R)^2} r^2 dr$
R
NEGATIVE PRESS.
2 POSS.
R-FINITE
DISASTER
$R \to 0$


FEYNMAN'S STORY
PROBLEM OF ELECTRON
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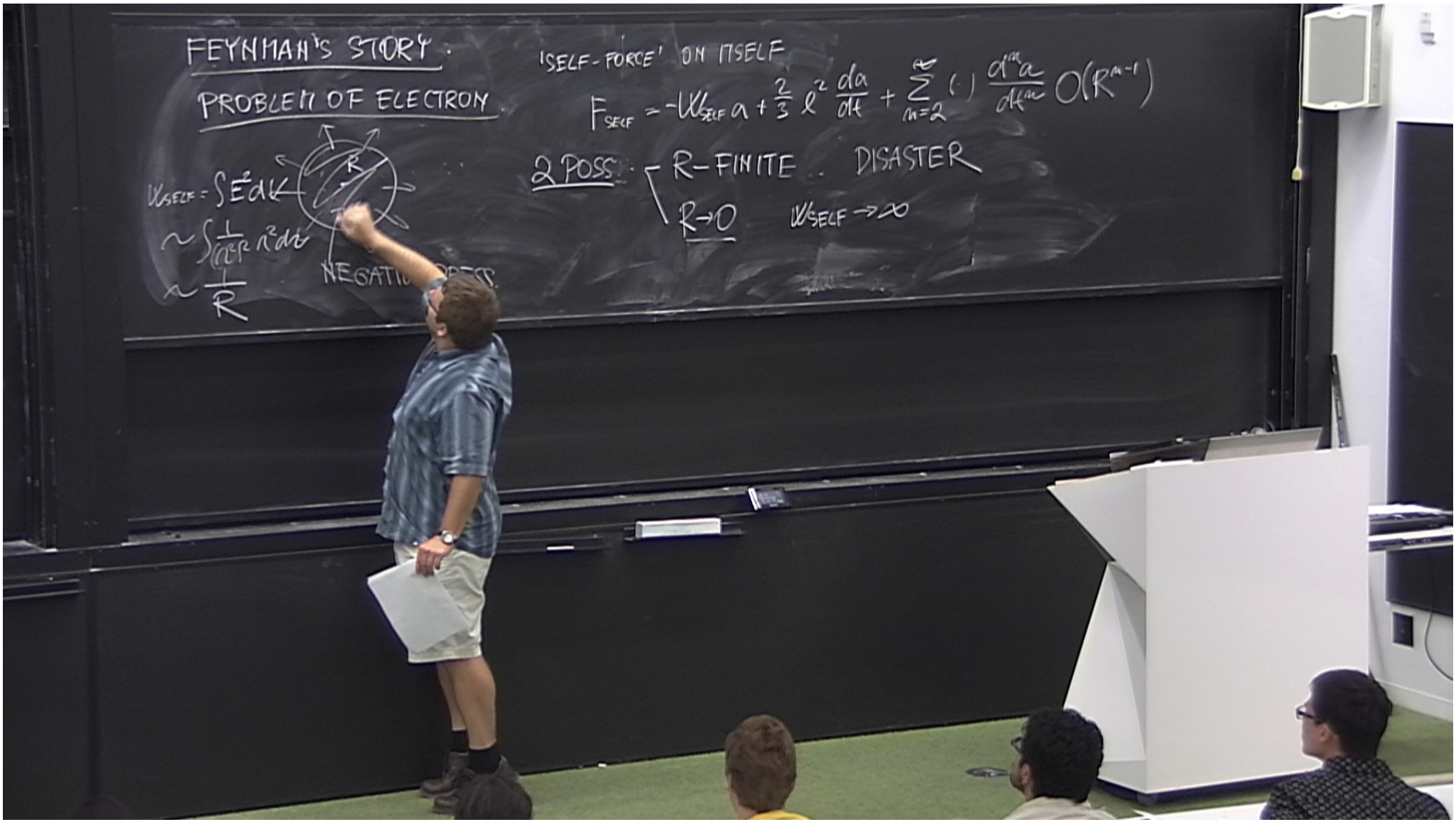
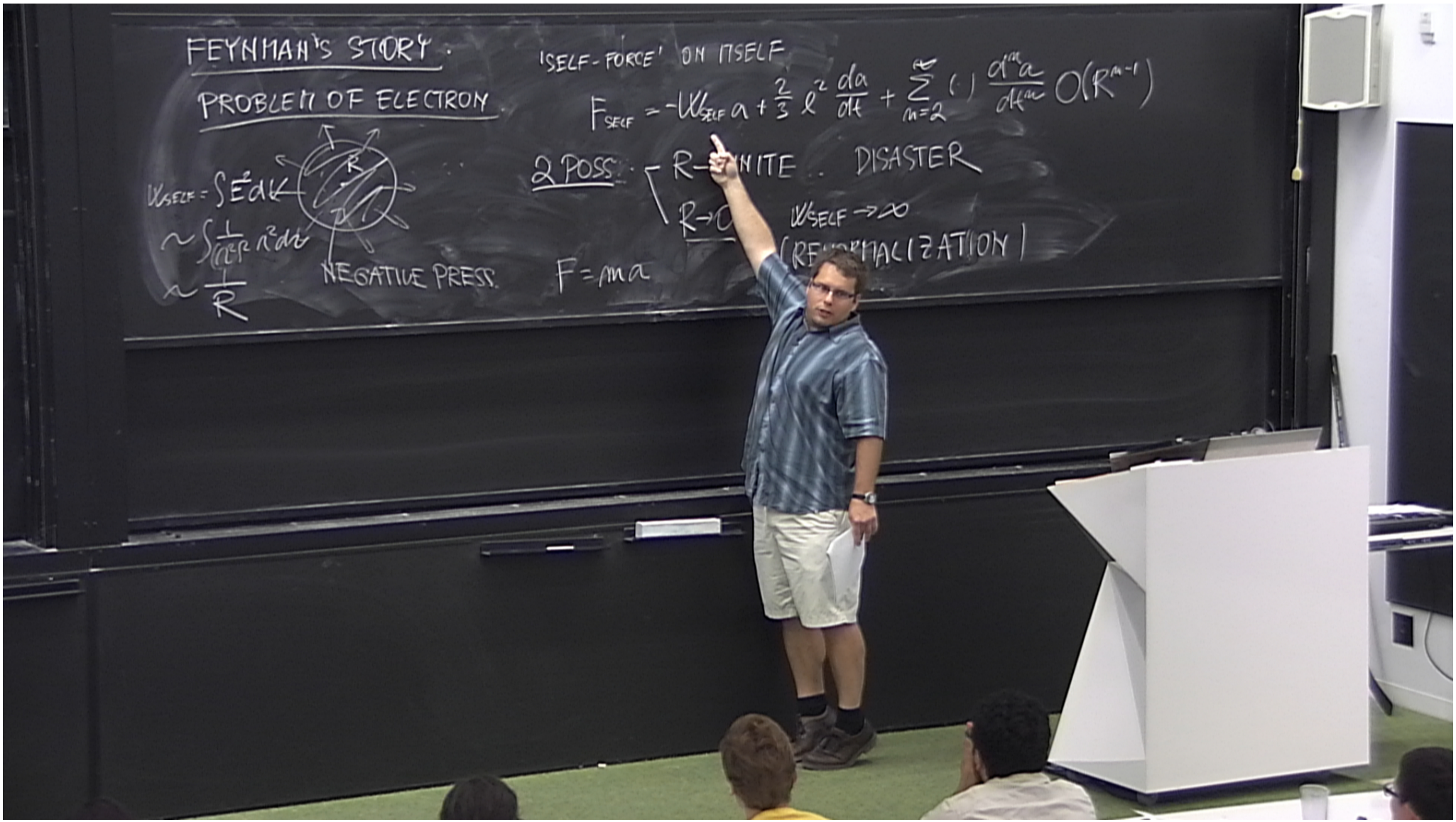
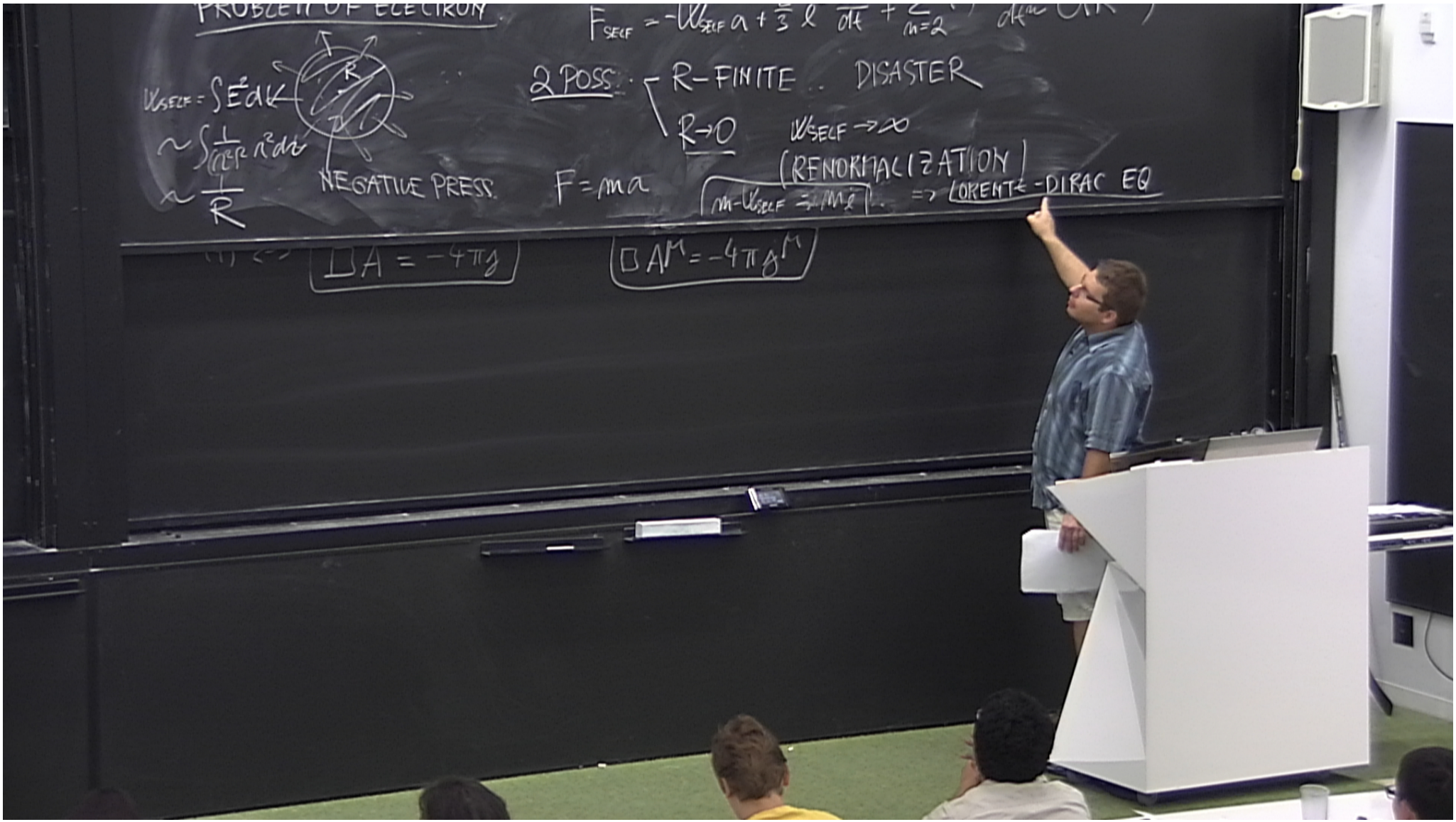
$F_{SELF} = -W_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{n=2}^{\infty} ( ) \frac{d^n a}{dt^n} O(R^{n-1})$
$W_{SELF} = \int E^2 dV$
$\sim \int \frac{1}{(r^2)^2} r^2 dr$
$\sim \frac{1}{R}$
R
NEGATIVE PRESS.
2 POSS.
R-FINITE .. DISASTER
R→0
W_{SELF}

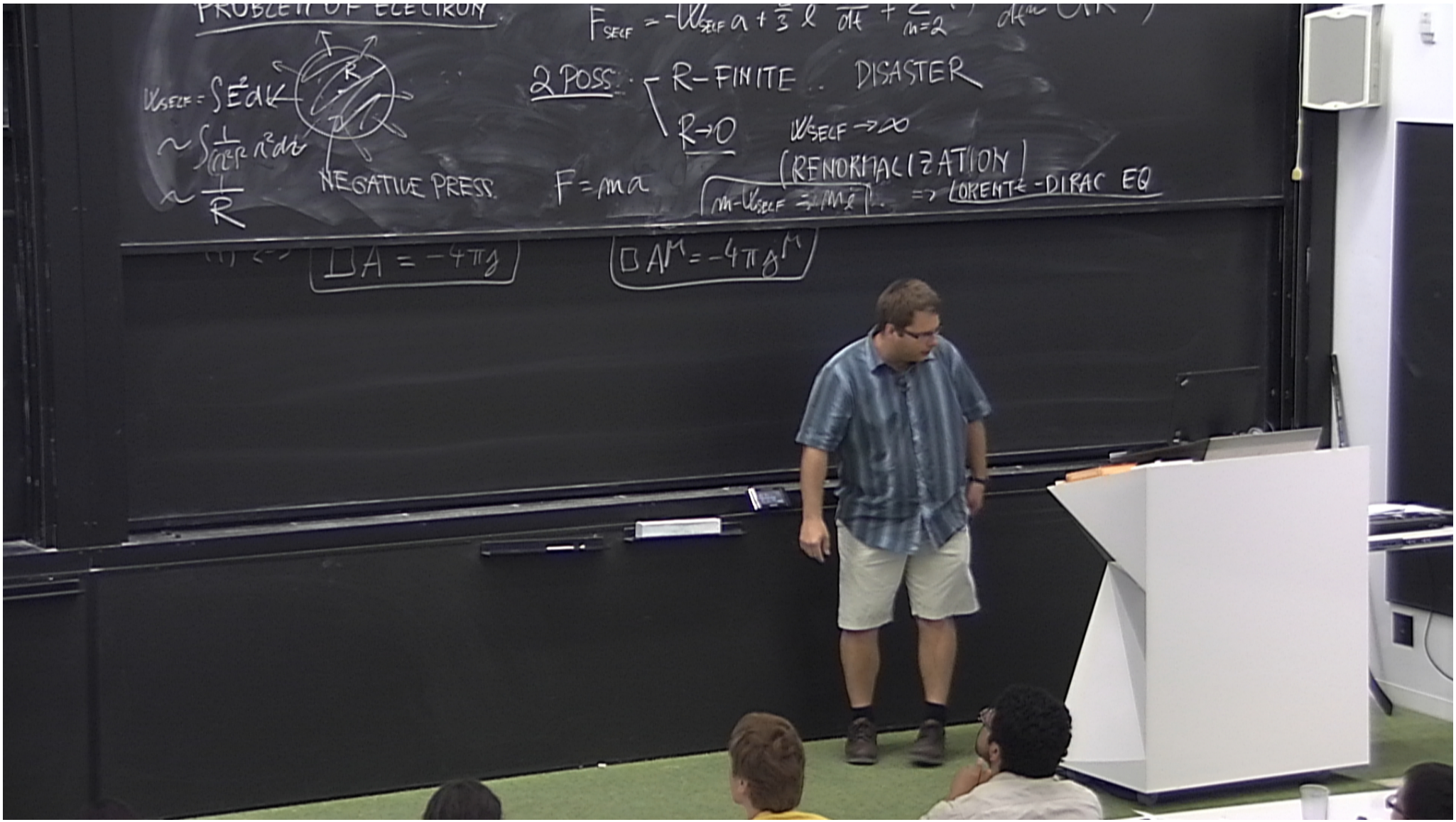

FEYNMAN'S STORY
PROBLEM OF ELECTRON
'SELF-FORCE' ON ITSELF
$F_{SELF} = -W_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{n=2}^{\infty} ( ) \frac{d^n a}{dt^n} O(R^{n-1})$
2 POSS
R-FINITE
DISASTER
$R \to 0$
$W_{SELF} \to \infty$
$W_{SELF} = \int E^2 dV$
$\sim \int \frac{1}{(R^2)^2} r^2 dr$
$\sim \frac{1}{R}$
R


FEYNMAN'S STORY
PROBLEM OF ELECTRON
'SELF-FORCE' ON ITSELF
$F_{SELF} = -W_{SELF}\, a + \frac{2}{3} \ell^2 \frac{da}{dt} + \sum_{m=2}^{\infty} ( ) \frac{d^m a}{dt^m} O(R^{m-1})$
$W_{SELF} = \int E^2 dV$
$\sim \int \frac{1}{(R^2)^2} r^2 dr$
$\sim \frac{1}{R}$
R
NEGATIVE PRESS.
2 POSS.
R-FINITE
DISASTER
$W_{SELF} \to \infty$
(RENORMALIZATION)
$F = ma$


PROBLEM OF ELECTRON
R
NEGATIVE PRESS.
2 POSS.
R-FINITE .. DISASTER
R→0
(RENORMALIZATION)
F=ma
LORENTZ-DIRAC EQ


PROBLEM OF ELECTRON
R
NEGATIVE PRESS.
2 POSS.
R-FINITE .. DISASTER
R→0
(RENORMALIZATION)
F=ma
LORENTZ-DIRAC EQ
□A = -4πj
□A^μ = -4πj^μ


PROBLEM OF ELECTRON
2 POSS:
R-FINITE .. DISASTER
R→0
NEGATIVE PRESS.
F=ma
(RENORMALIZATION)
=> LORENTZ-DIRAC EQ


PROBLEM OF ELECTRON
2 POSS:
R-FINITE .. DISASTER
R→0
NEGATIVE PRESS.
F=ma
(RENORMALIZATION)
=> LORENTZ-DIRAC EQ

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„MAKING THE THEORY"

E: • ACTION AT A DISTANCE DOESN'T NEED FIELD ⇒

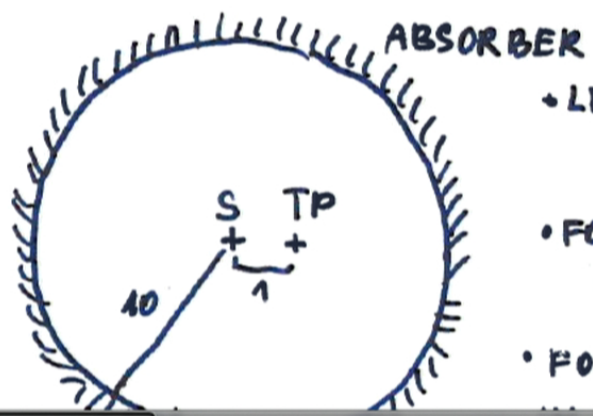
⇒ NO SELF ENERGY PROBLEM

• HOW EXPLAIN RADIATION DAMPING FORCE ?

W: • F_D WOULD DEPEND ON $q_2, m_2, \frac{1}{R^2}$, THICKNESS OF LAYER AND OCCURS AT THE WRONG TIME

„YOU HAVE DESCRIBED ORDINARY REFLECTED LIGHT"

•



• LET ALL CHARGES PRODUCE

$$F_{\mu\nu} = k\, F_{\mu\nu}^{RET} + (1-k)\, F_{\mu\nu}^{ADV}$$

• FOR $k = 1/2$ TP SUFFERS JUST FROM RETARDED POTENTIALS

• FOR LIMITED NUMBER OF CHARGES

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W: • F_D WOULD DEPEND ON $q_2, m_2, \frac{1}{R^2}$, THICKNESS OF LAYER AND OCCURS AT THE WRONG TIME

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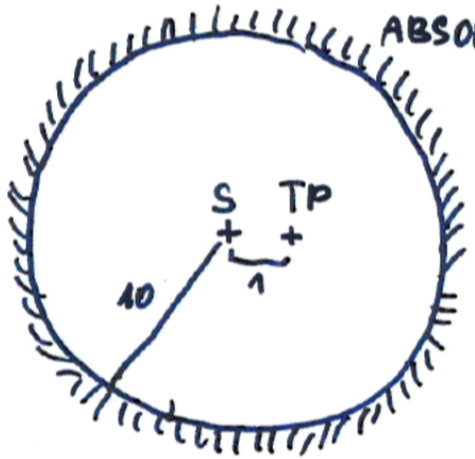
•



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• FOR LIMITED NUMBER OF CHARGES IN UNIVERSE ADVANCED EFFECTS OCCUR EXPLICITLY $\Rightarrow$ NO SEPARATION BETWEEN PAST AND FUTURE

• BUT FOR PERFECT ABSORBER THE REACTION BACK IS INDEPENDENT OF IT'S STRUCTURE

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W: • F_D WOULD DEPEND ON $q_2, m_2, \frac{1}{R^2}$, THICKNESS OF LAYER AND OCCURS AT THE WRONG TIME

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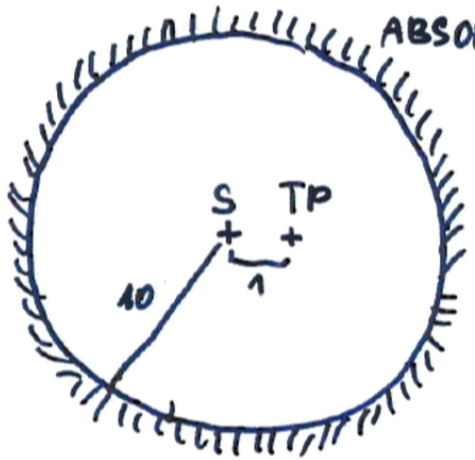
•



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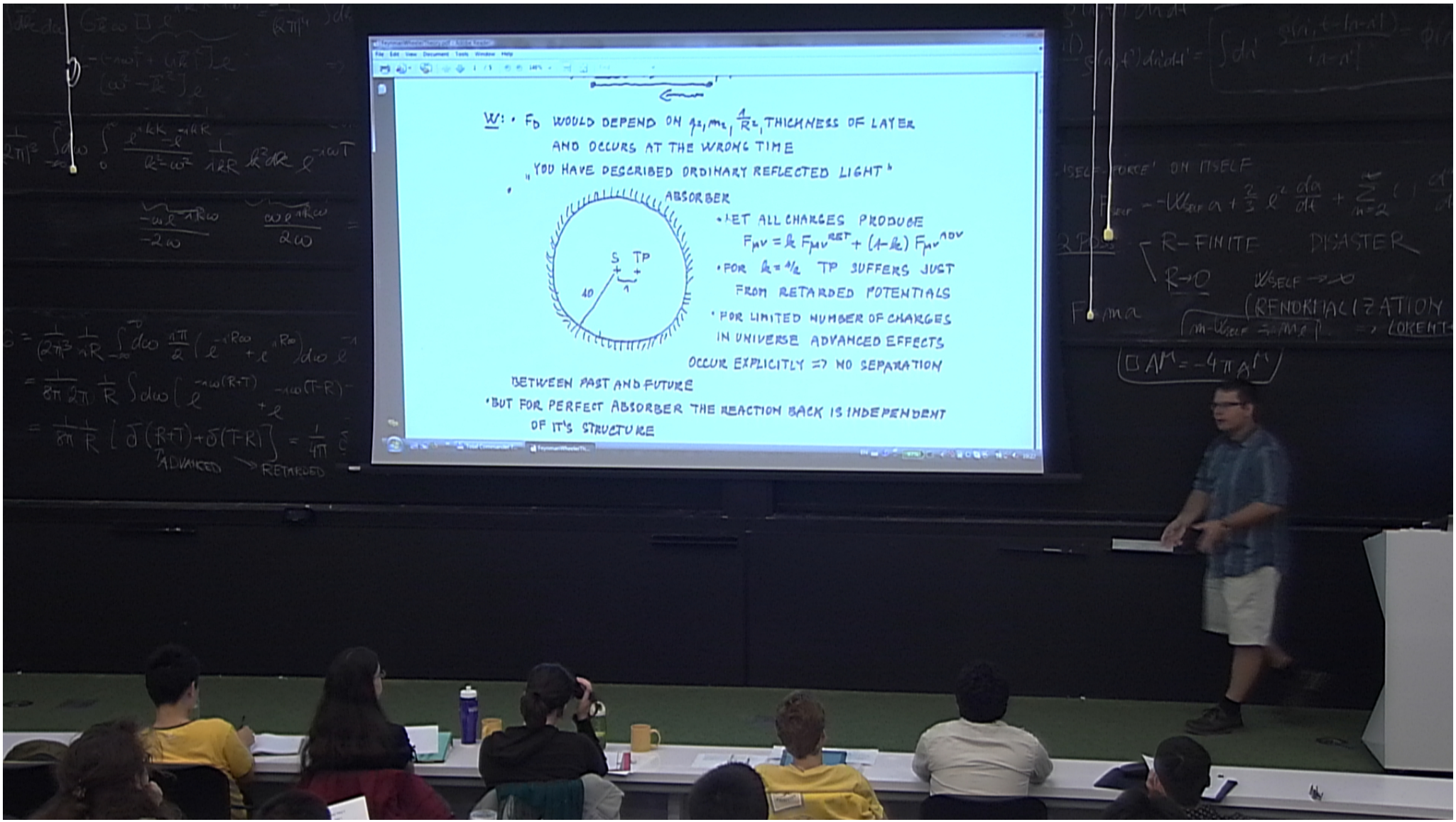
Total Commander 7... FeynmanWheelerTh... EN 97% 10:21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AND OCCURS AT THE WRONG TIME
„YOU HAVE DESCRIBED ORDINARY REFLECTED LIGHT"
ABSORBER
S TP
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• LET ALL CHARGES PRODUCE
$F_{\mu\nu} = k F_{\mu\nu}^{RET} + (1-k) F_{\mu\nu}^{ADV}$
• FOR $k = 1/2$ TP SUFFERS JUST
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R-FINITE
DISASTER
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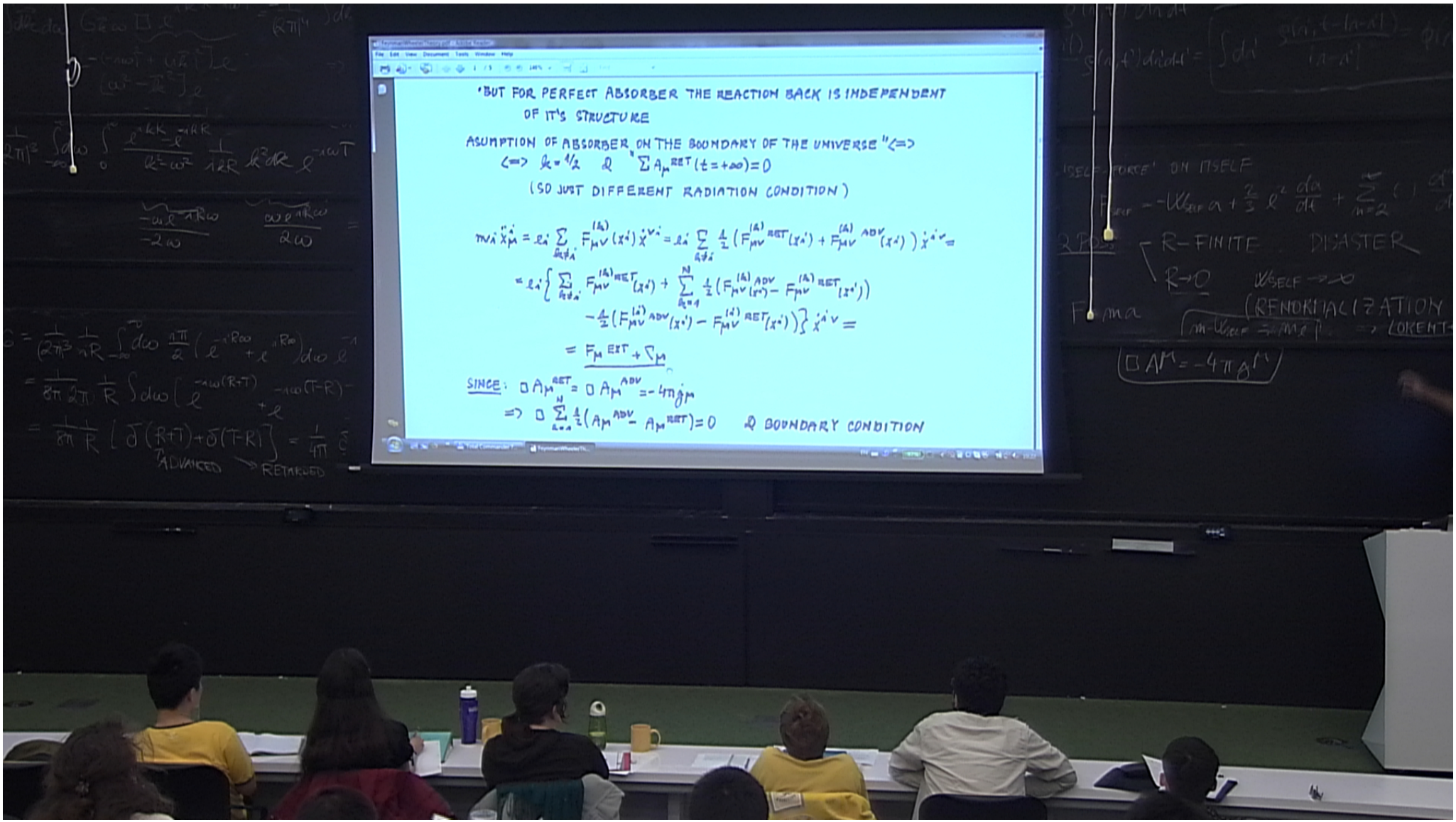
(RENORMALIZATION
$\Box A^\mu = -4\pi A^\mu$


"BUT FOR PERFECT ABSORBER THE REACTION BACK IS INDEPENDENT
OF IT'S STRUCTURE
ASUMPTION OF ABSORBER ON THE BOUNDARY OF THE UNIVERSE" <=>
<=> k = 1/2 & "$\sum A_\mu^{RET}(t=+\infty)=0$
(SO JUST DIFFERENT RADIATION CONDITION)
$m_i \ddot{x}_\mu^i = e_i \sum_{k\neq i} F_{\mu\nu}^{(k)}(x^i)\dot{x}^{\nu i} = e_i \sum_{k\neq i} \frac{1}{2}\left(F_{\mu\nu}^{(k)\,RET}(x^i) + F_{\mu\nu}^{(k)\,ADV}(x^i)\right)\dot{x}^{i\nu} =$
$= e_i \Big\{ \sum_{k\neq i} F_{\mu\nu}^{(k)\,RET}(x^i) + \sum_{k=1}^{N} \frac{1}{2}\left(F_{\mu\nu}^{(k)\,ADV}(x^i) - F_{\mu\nu}^{(k)\,RET}(x^i)\right)$
$-\frac{1}{2}\left(F_{\mu\nu}^{(i)\,ADV}(x^i) - F_{\mu\nu}^{(i)\,RET}(x^i)\right)\Big\}\dot{x}^{i\nu} =$
$= F_\mu^{EXT} + \Sigma_\mu$
SINCE: $\Box A_\mu^{RET} = \Box A_\mu^{ADV} = -4\pi j_\mu$
$\Rightarrow \Box \sum_{k=1}^{N} \frac{1}{2}(A_\mu^{ADV} - A_\mu^{RET}) = 0$ & BOUNDARY CONDITION
R-FINITE
DISASTER
R→0
(RENORMALIZATION
$\Box A^\mu = -4\pi j^\mu$

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NOTIONS: 1) THEORY IS MICROSCOPICALLY REVERSIBLE (TIME SYMMETRIC)

2) DESPITE THIS IT IS ABLE TO DESCRIBE DAMPING FORCE (ABSORBER ENTROPY IS INCREASING)

3) CAN BE DESCRIBED BY FOKKER'S ACTION

$$A_F = -\sum_{i=1}^{N} m_i \int (\dot{x}^{\mu}_{(i)} \dot{x}_{(i)\mu})^{1/2} d\tau_i + \frac{1}{2} \sum_{i \neq j} \sum e_i e_j \iint \delta((x_{(i)} - x_{(j)})^2)\, \dot{x}^{\mu}_{(i)} \dot{x}_{\mu(j)}\, d\tau_i\, d\tau_j$$

$\Rightarrow$ PURE PARTICLE-PARTICLE INTERACTION

- THANKS TO $\delta((x_{(i)} - x_{(j)})^2)$ PARTICLES INTERACT ONLY AT ZERO FOUR-DIMENSIONAL DISTANCE

4) IT IS **ADJUNCT FIELD THEORY**:

FIELD THEORY $\approx$ HAMILTONIAN METHOD (TIME DIF. METH.)

- I HAVE CONCEPT OF FIELD ($\approx$ MATHEMATICAL DESCR.)

– THIS FIELD HAS TO BE GIVEN EVERYWHERE AT t

DIF. EQUATIONS GIVE ME THE FIELD AT THE NEXT TIME

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2) BESIDE THIS IT IS HOLE TO DESCRIBE DAMPING FORCE

(ABSORBER ENTROPY IS INCREASING)

3) CAN BE DESCRIBED BY FOKKER'S ACTION

$$A_F = -\sum_{i=1}^{N} m_i \int (\dot{x}^{\mu}_{(i)} \dot{x}_{\mu(i)})^{1/2} d\tau_i + \frac{1}{2} \sum_{i \neq j} \sum e_i e_j \iint \delta((x_{(i)} - x_{(j)})^2) \dot{x}^{\mu}_{(i)} \dot{x}_{\mu(j)} d\tau_i d\tau_j$$

$\Rightarrow$ PURE PARTICLE-PARTICLE INTERACTION

- THANKS TO $\delta((x_{(i)} - x_{(j)})^2)$ PARTICLES INTERACT ONLY AT ZERO FOUR-DIMENSIONAL DISTANCE

4) IT IS <u>ADJUNCT FIELD THEORY</u>:

<u>FIELD THEORY</u> $\approx$ HAMILTONIAN METHOD (TIME DIF. METH.)

- I HAVE CONCEPT OF FIELD ($\approx$ MATHEMATICAL DESCR.)
  - THIS FIELD HAS TO BE GIVEN EVERYWHERE AT t
  - DIF. EQUATIONS GIVE ME THE FIELD AT THE NEXT TIME

NOTE: 'PHYSICAL FIELD' IS A SOLENOID:

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Einstein says, "Nooooooooooooo," a nice, German-sounding "No,"—very polite. "I find only that it would be very difficult to make a corresponding theory for gravitational interaction." He meant for the general theory of relativity, which was his baby. He continued: "Since we have at this time not a great deal of experimental evidence, I am not absolutely sure of the correct gravitational theory." Einstein appreciated that things might be different from what his theory stated; he was very tolerant of other ideas.

I wish I had remembered what Pauli said, because I discovered years later that the theory was not satisfactory when it came to making the quantum theory. It's possible that that great man noticed the difficulty immediately and explained it to me in the question, but I was so relieved at not having to answer the questions that I didn't really listen to them carefully. I do remember walking up the steps of Palmer Library with Pauli, who said to me, "What is Wheeler going to say about the quantum theory when he gives his talk?"

I said, "I don't know. He hasn't told me. He's working it out himself."

"Oh?" he said. "The man works and doesn't tell his assistant what he's doing on the quantum theory?" He came closer to me and said in a low, secretive voice, "Wheeler will never give that seminar."

And it's true. Wheeler didn't give the seminar. He thought it would be easy to work out the quantum part; he thought he had it, almost. But he didn't. And by the time the seminar came around, he realized he didn't know how to do it, and therefore didn't have anything to say.

I never solved it, either—a quantum theory of half-advanced, half-retarded potentials—and I worked on it for years.

Mixing Paints

got *written*—that never struck me! So I developed a negative attitude toward the guy who studies French literature, or studies too much music or poetry—all those "fancy" things. I admired better the steelworker, the welder, or the machine shop man. I always thought the guy who worked in the machine shop and could make things, now *he* was a *real guy!* That was my attitude. To be a practical man was, to me, always somehow a positive virtue, and to be "cultured" or "intellectual" was not. The first was right, of course, but the second was crazy.

I still had this feeling when I was doing my graduate study at Princeton, as you'll see. I used to eat often in a nice little restaurant called Papa's Place. One day, while I was eating there, a painter in his painting clothes came down from an upstairs room he'd been painting, and sat near me. Somehow we struck up a conversation and he started talking about how you've got to learn a lot to be in the painting business. "For example," he said, "in this restaurant, what colors would you use to paint the walls, if *you* had the job to do?"

I said I didn't know, and he said, "You have a dark band up to such-and-such a height, because, you see, people who sit at the tables rub their elbows against the walls, so you don't want a nice, white wall