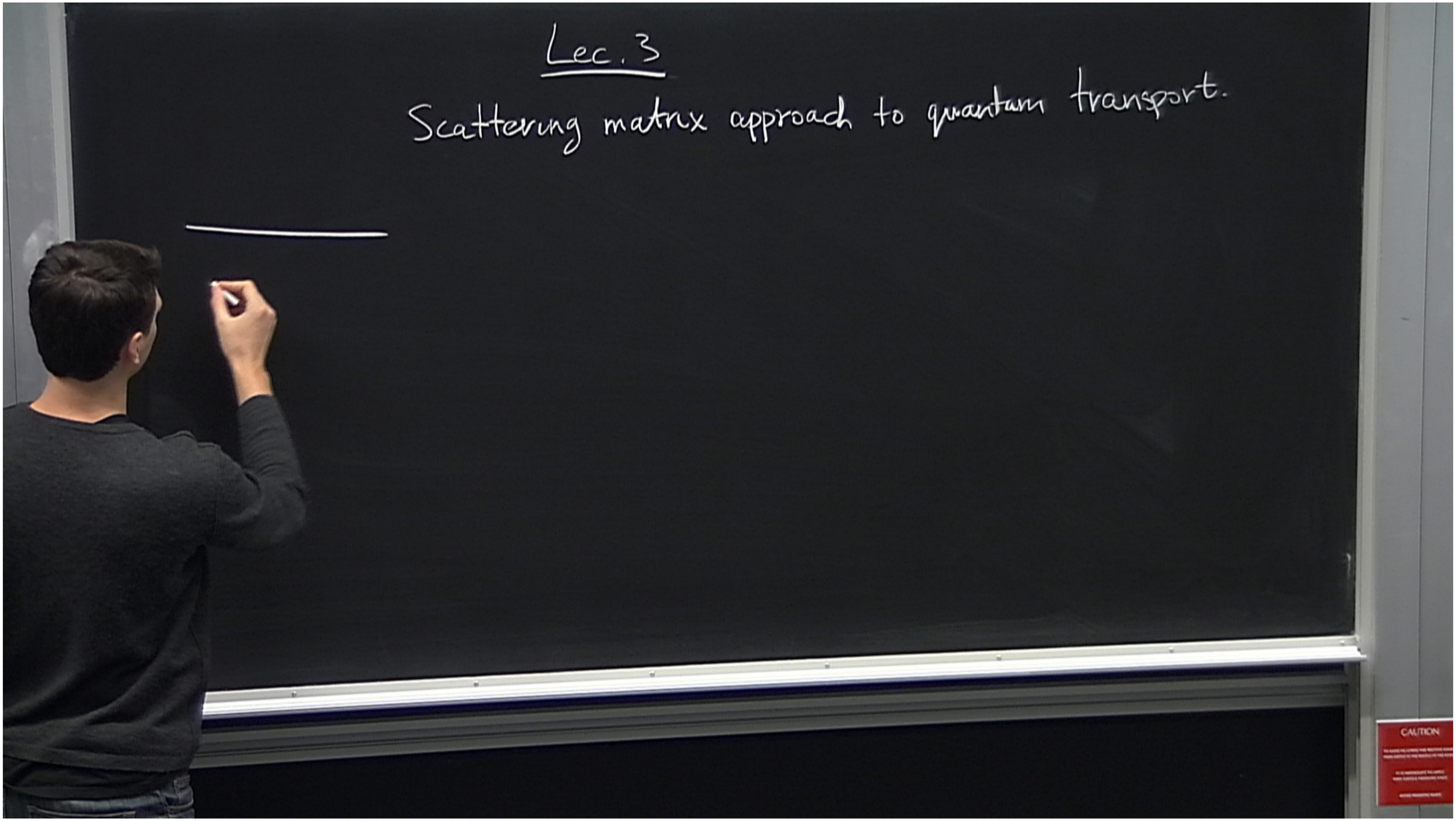
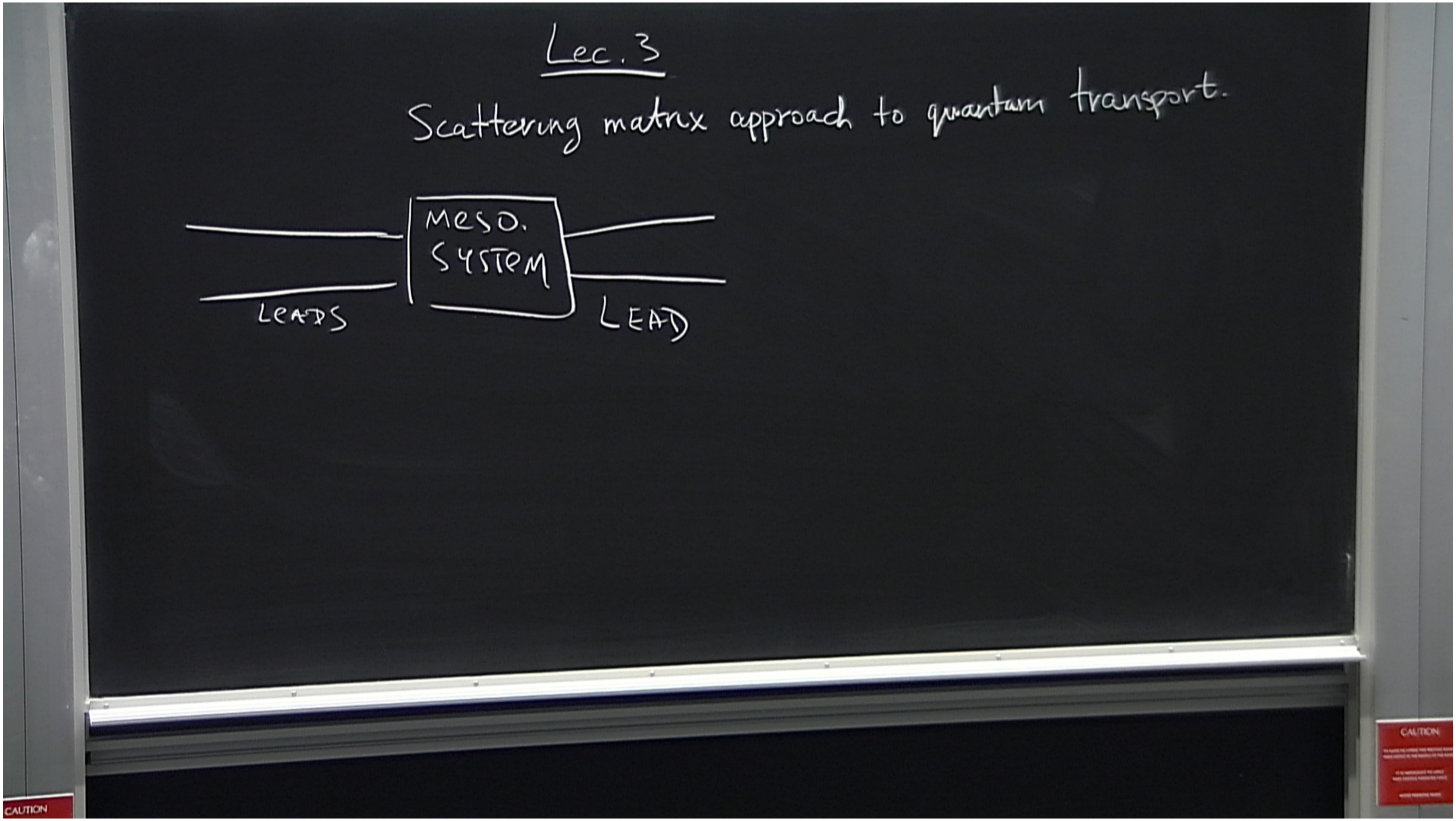
Title: Explorations in Condensed Matter - Lecture 3

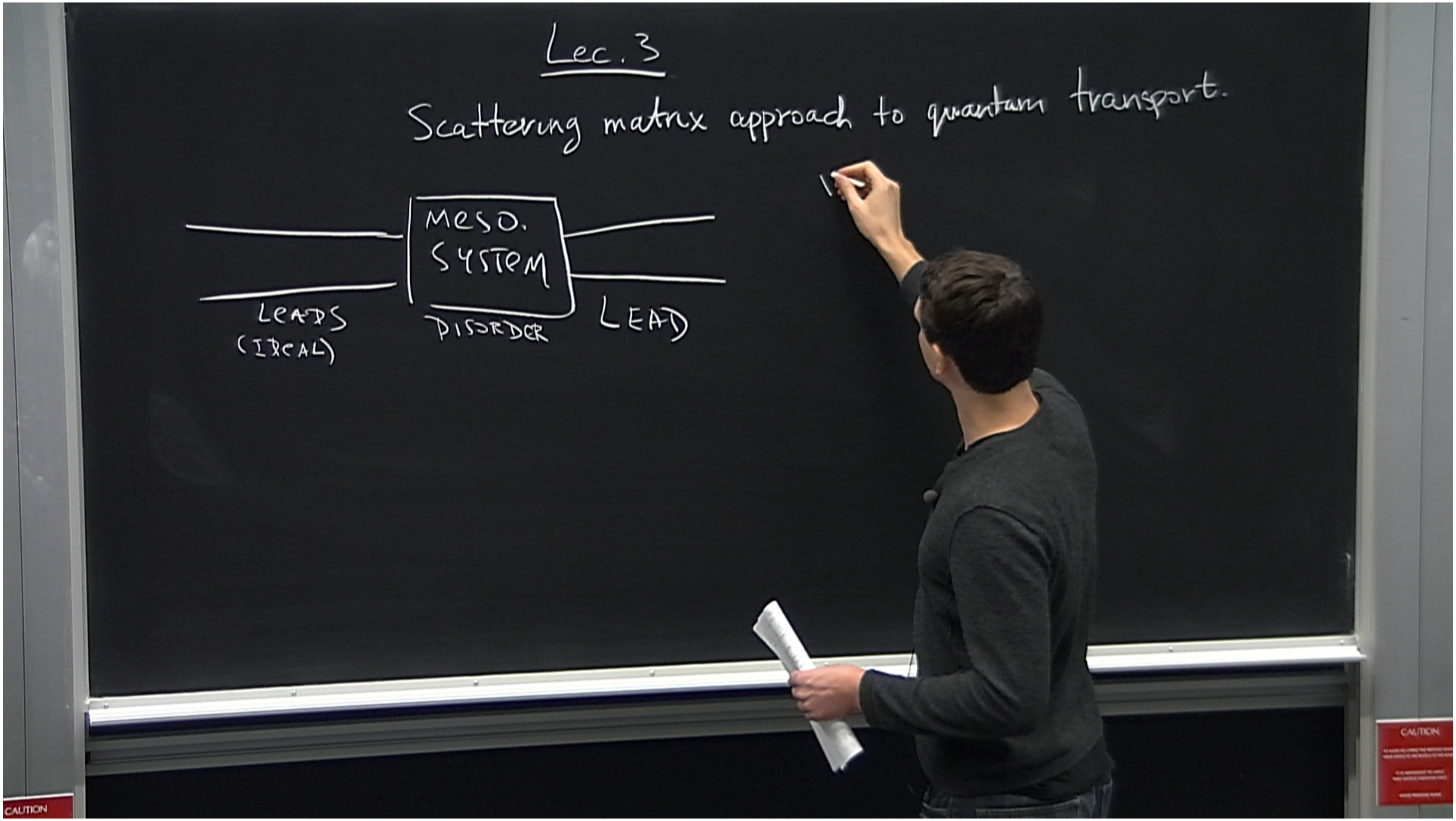
Date: Apr 04, 2012 10:15 AM

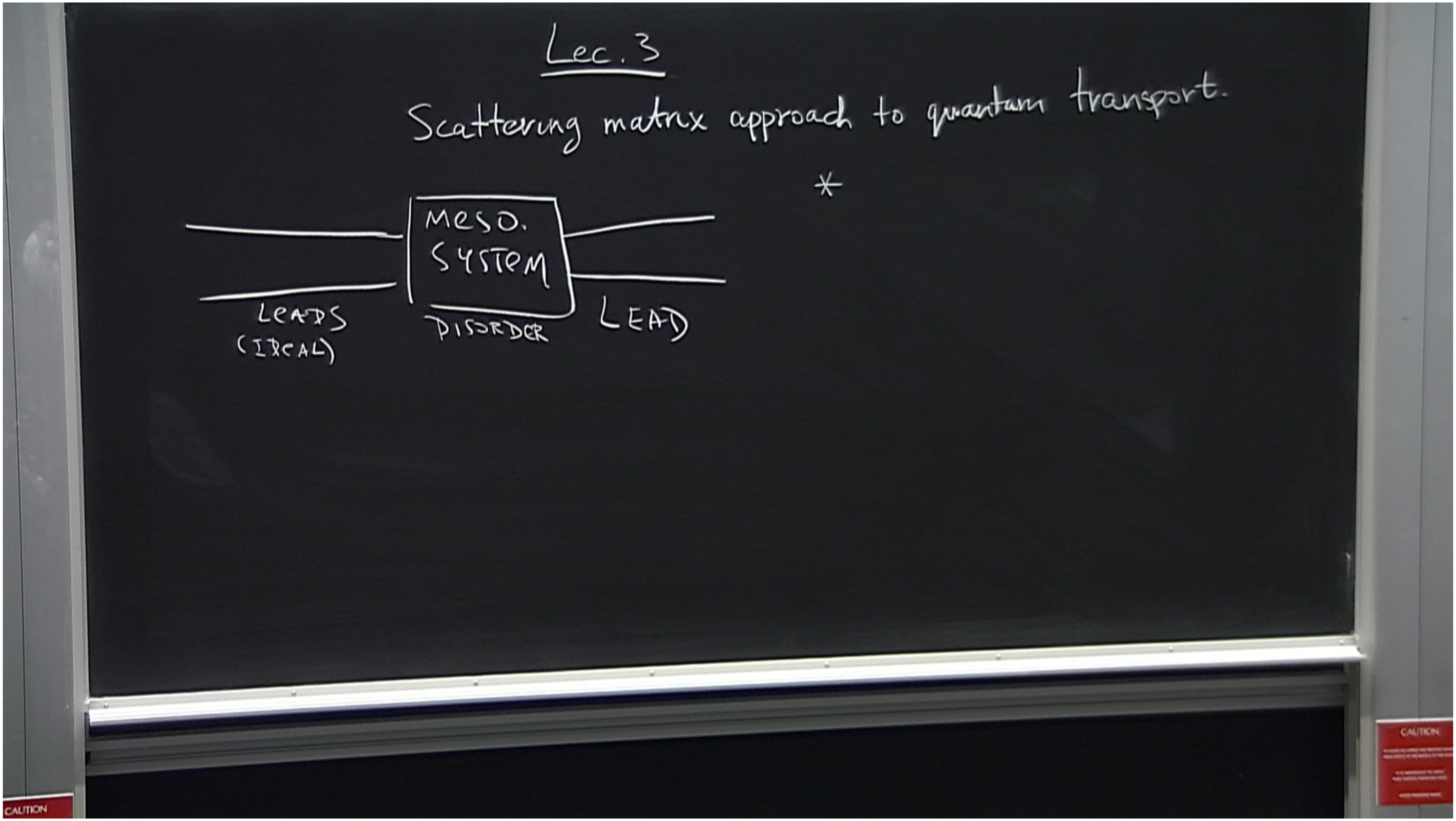
URL: http://www.pirsa.org/12040083

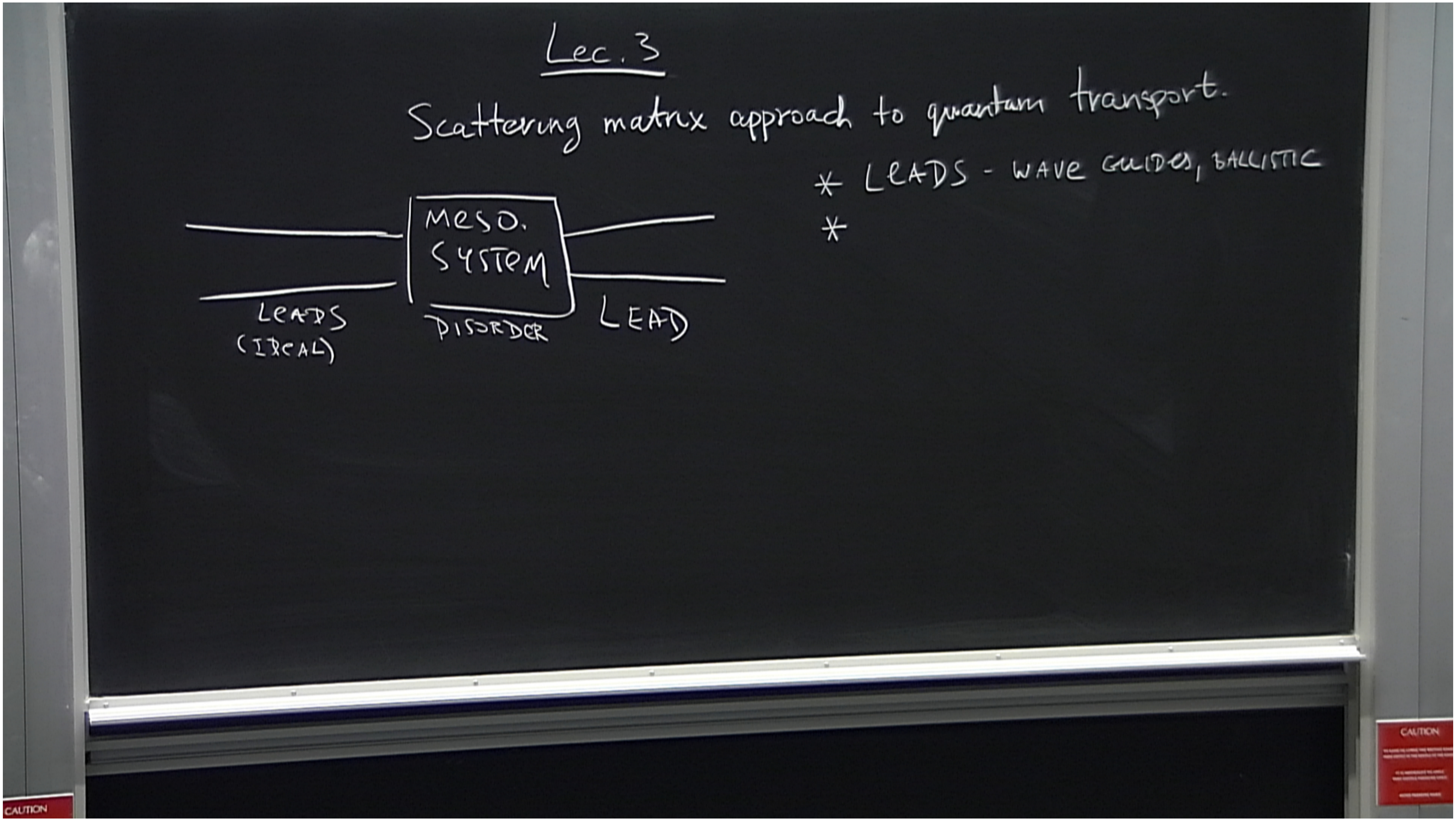
Abstract:


Lec. 3
Scattering matrix approach to quantum transport.


Lec. 3
Scattering matrix approach to quantum transport.
MESO. SYSTEM
LEADS
LEAD
CAUTION
CAUTION

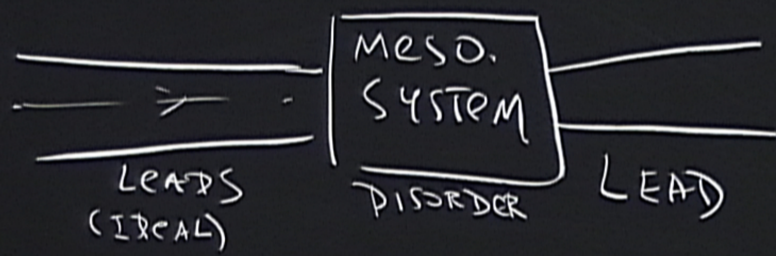

Lec. 3
Scattering matrix approach to quantum transport.
MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD
CAUTION
CAUTION


Lec. 3
Scattering matrix approach to quantum transport.
MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD
CAUTION
CAUTION


Lec. 3
Scattering matrix approach to quantum transport.
* LEADS - WAVE GUIDES, BALLISTIC
*
MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD

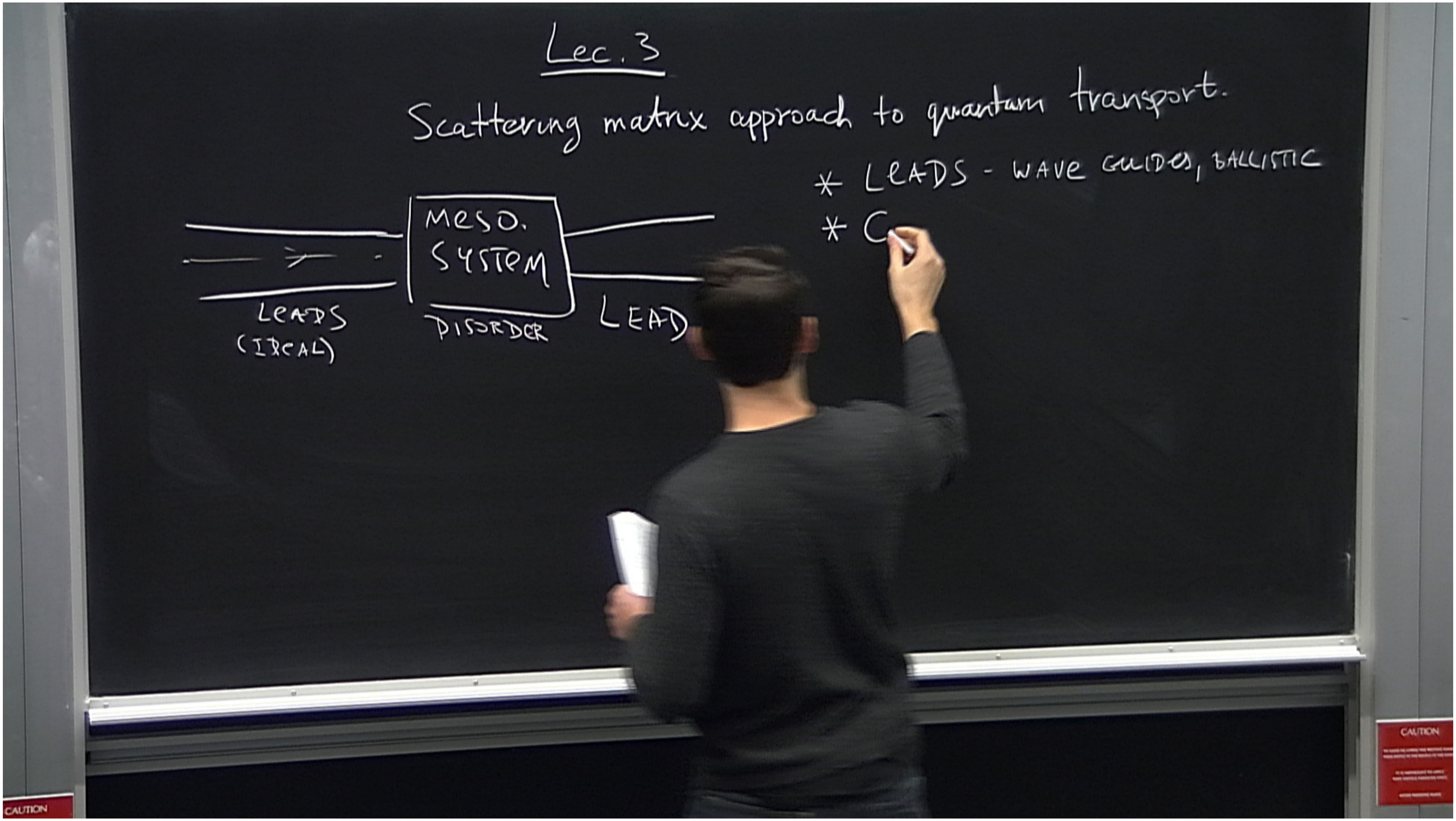
Lec. 3

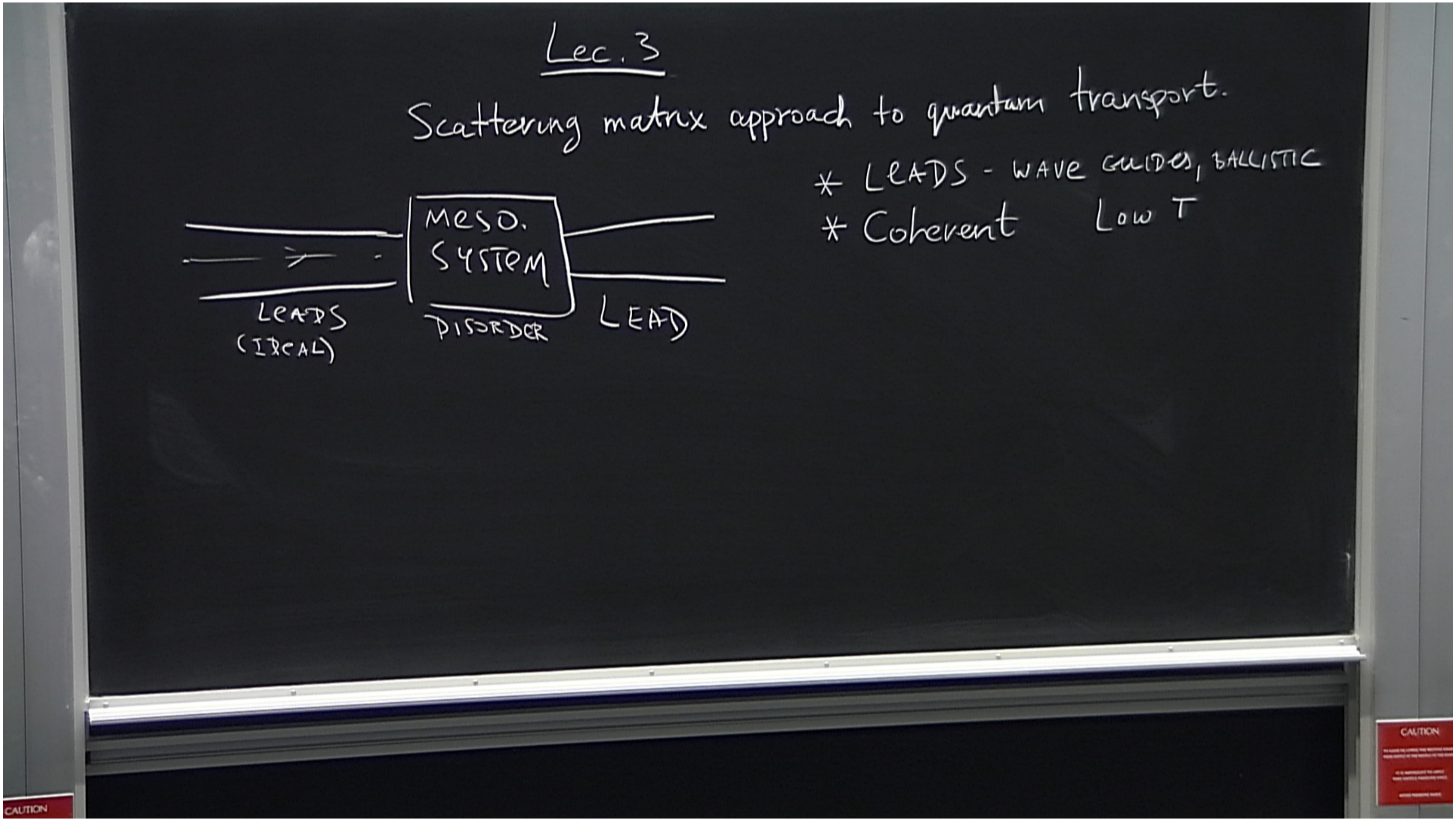
Scattering matrix approach to quantum transport.



* LEADS - WAVE GUIDES, BALLISTIC
*


Lec 3
Scattering matrix approach to quantum transport.
* LEADS - WAVE GUIDES, BALLISTIC
*
MESO. SYSTEM
LEADS
DISORDER
LEAD

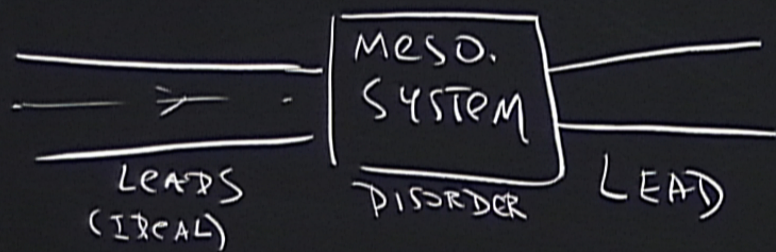

Lec. 3
Scattering matrix approach to quantum transport.
* LEADS - WAVE GUIDES, BALLISTIC
* C
MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD

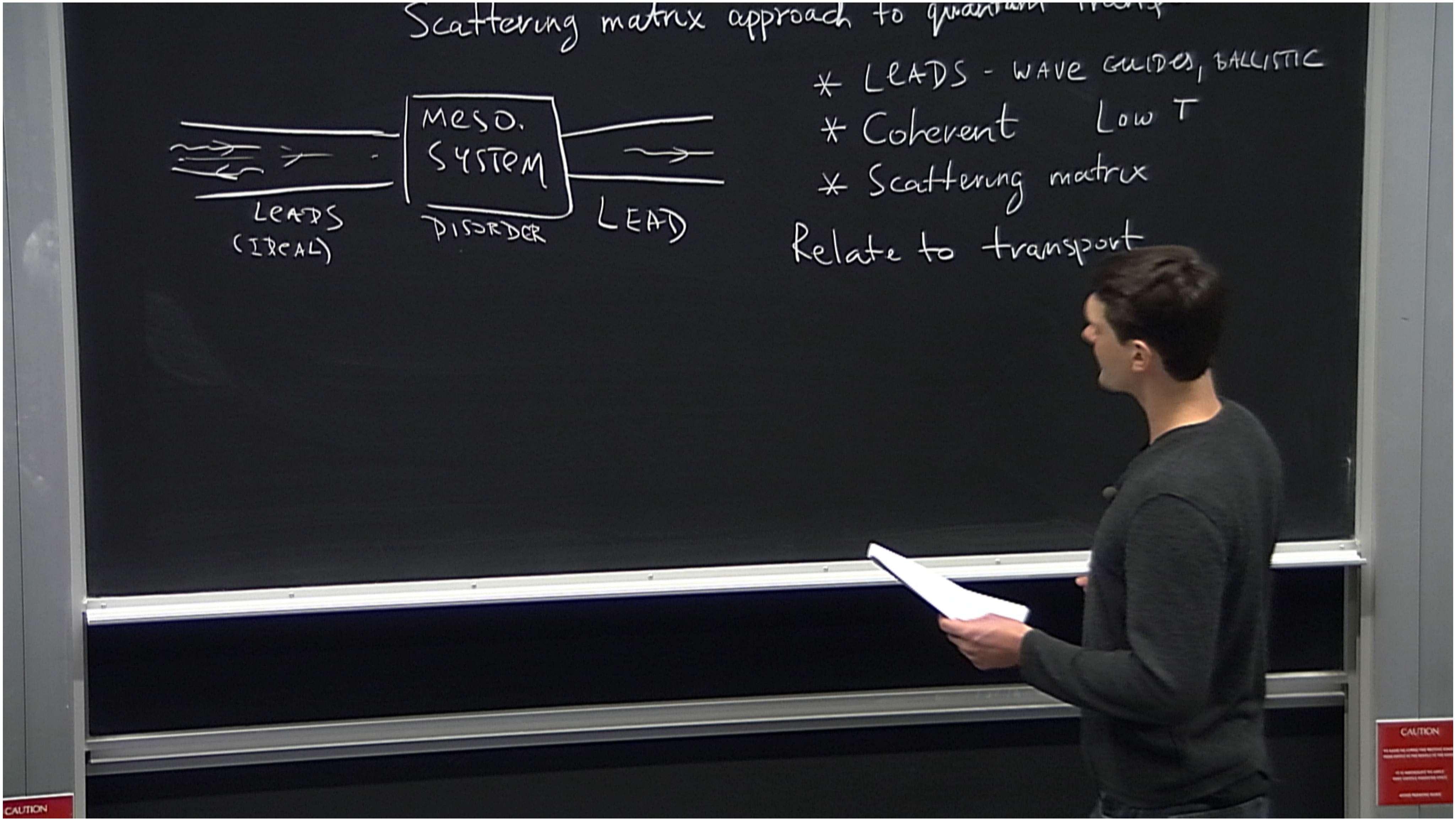

Lec. 3
Scattering matrix approach to quantum transport.
* LEADS - WAVE GUIDES, BALLISTIC
* Coherent
Low T
MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD
CAUTION

Lec. 3

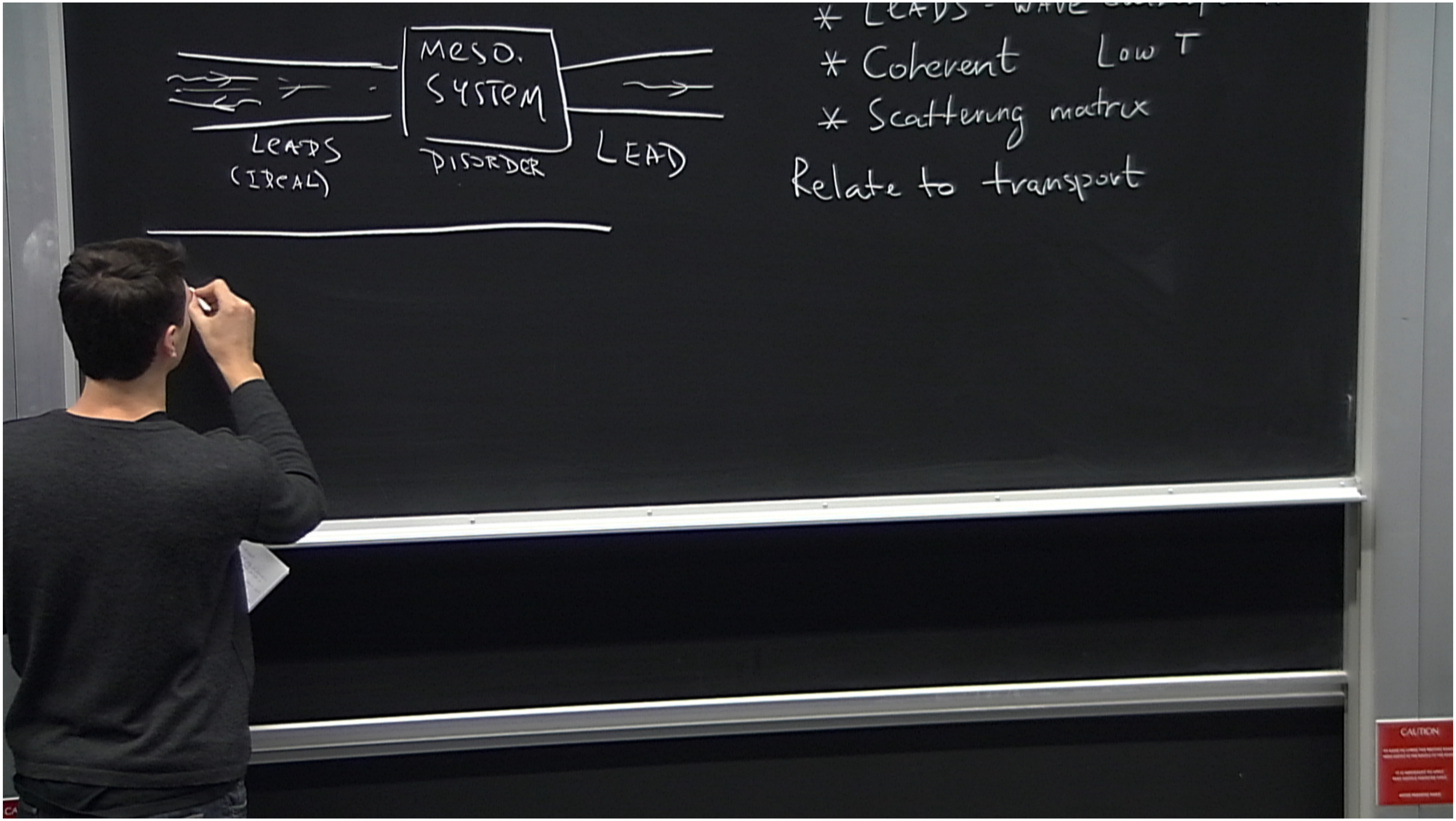
Scattering matrix approach to quantum transport.

* LEADS - WAVE GUIDES, BALLISTIC
* Coherent Low T

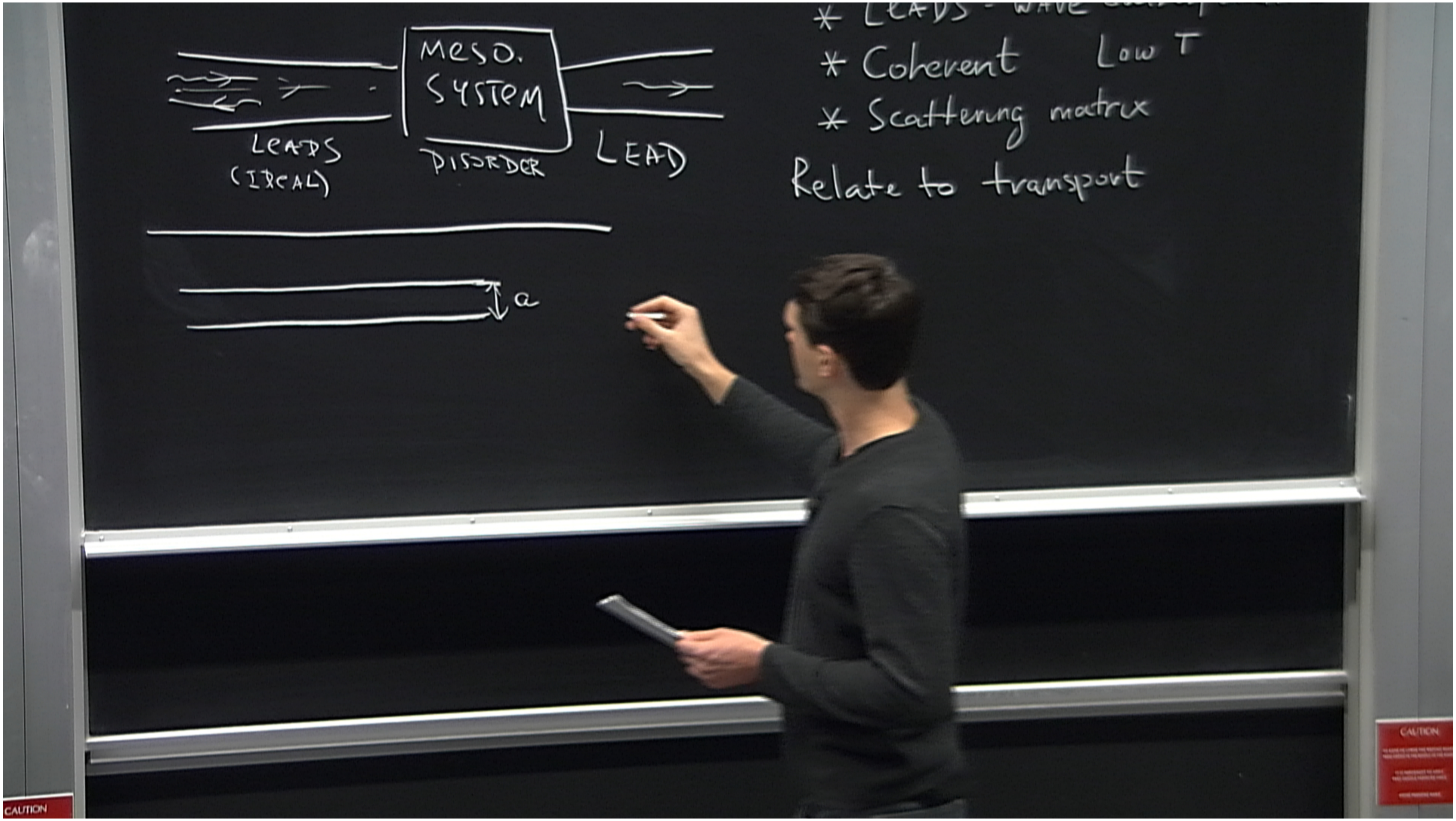


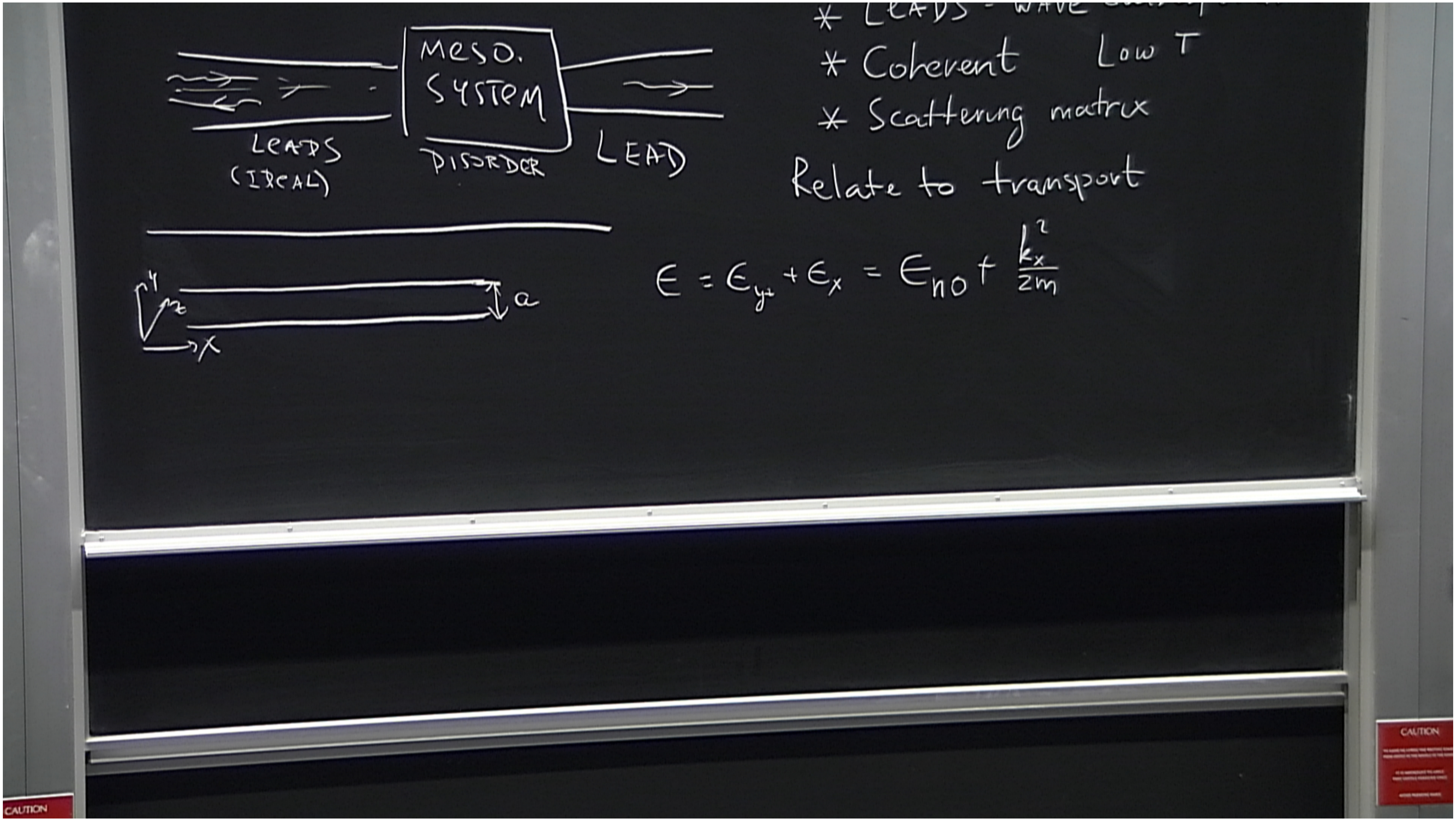


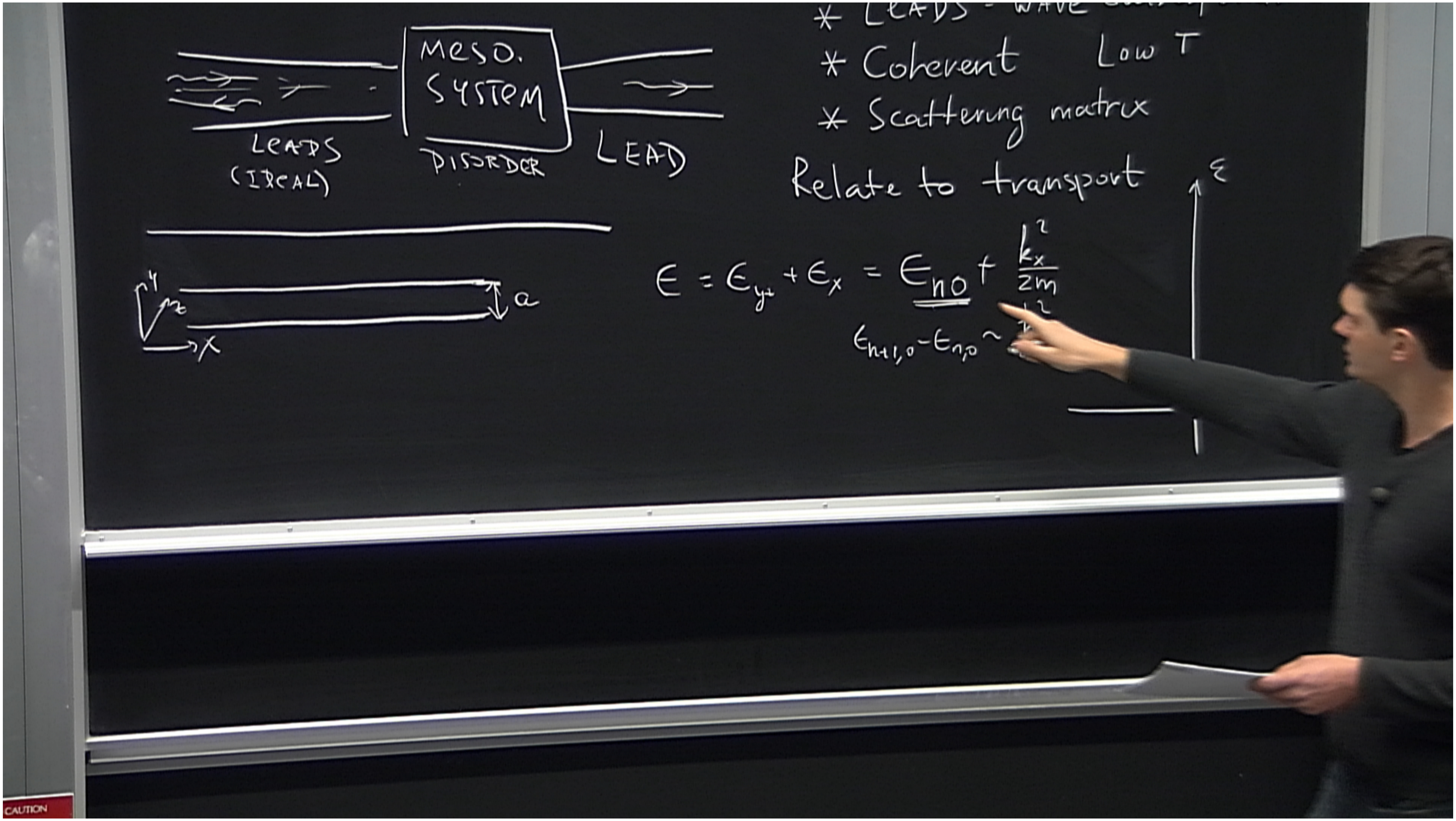
Scattering matrix approach to
* LEADS - WAVE GUIDES, BALLISTIC
* Coherent Low T
* Scattering matrix
Relate to transport
MESO. SYSTEM
LEADS
(IDEAL)
DISORDER
LEAD

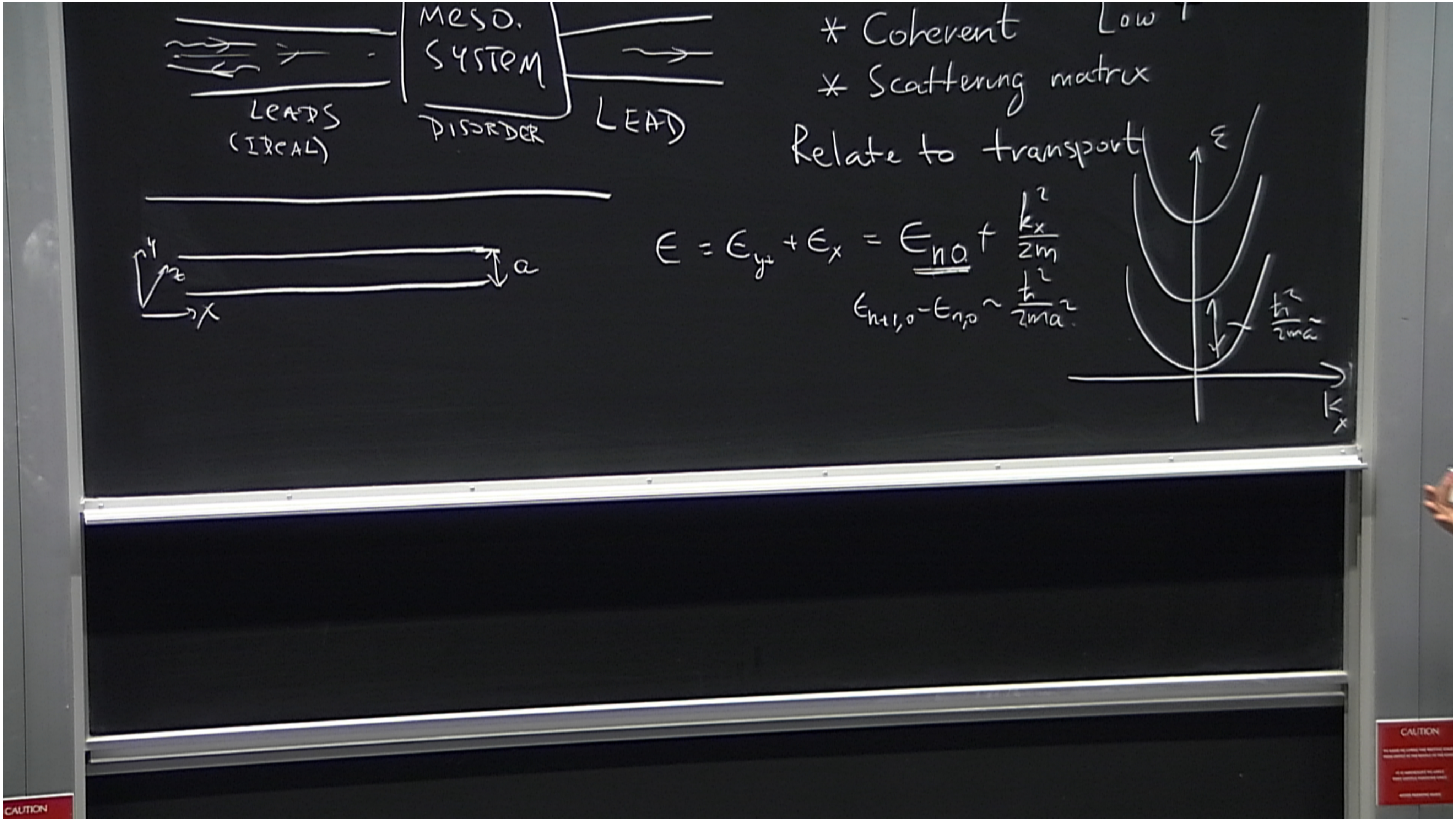


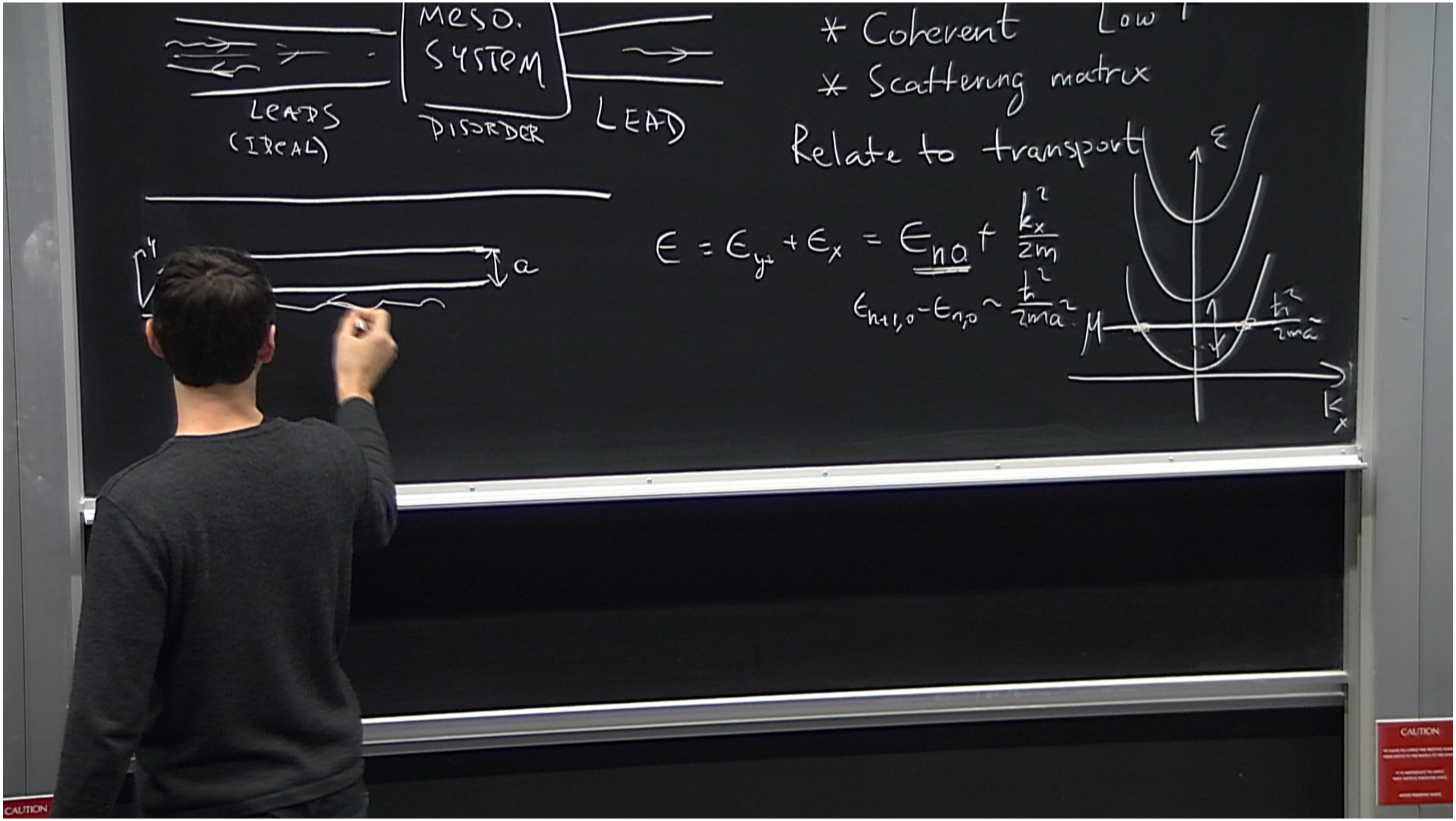
MESO.
SYSTEM
LEADS
(IDEAL)
DISORDER
LEAD
* Coherent Low T
* Scattering matrix
Relate to transport


* LEADS - WAVE
* Coherent Low T
* Scattering matrix
Relate to transport
MESO. SYSTEM
LEADS
(IDEAL)
DISORDER
LEAD
a
CAUTION

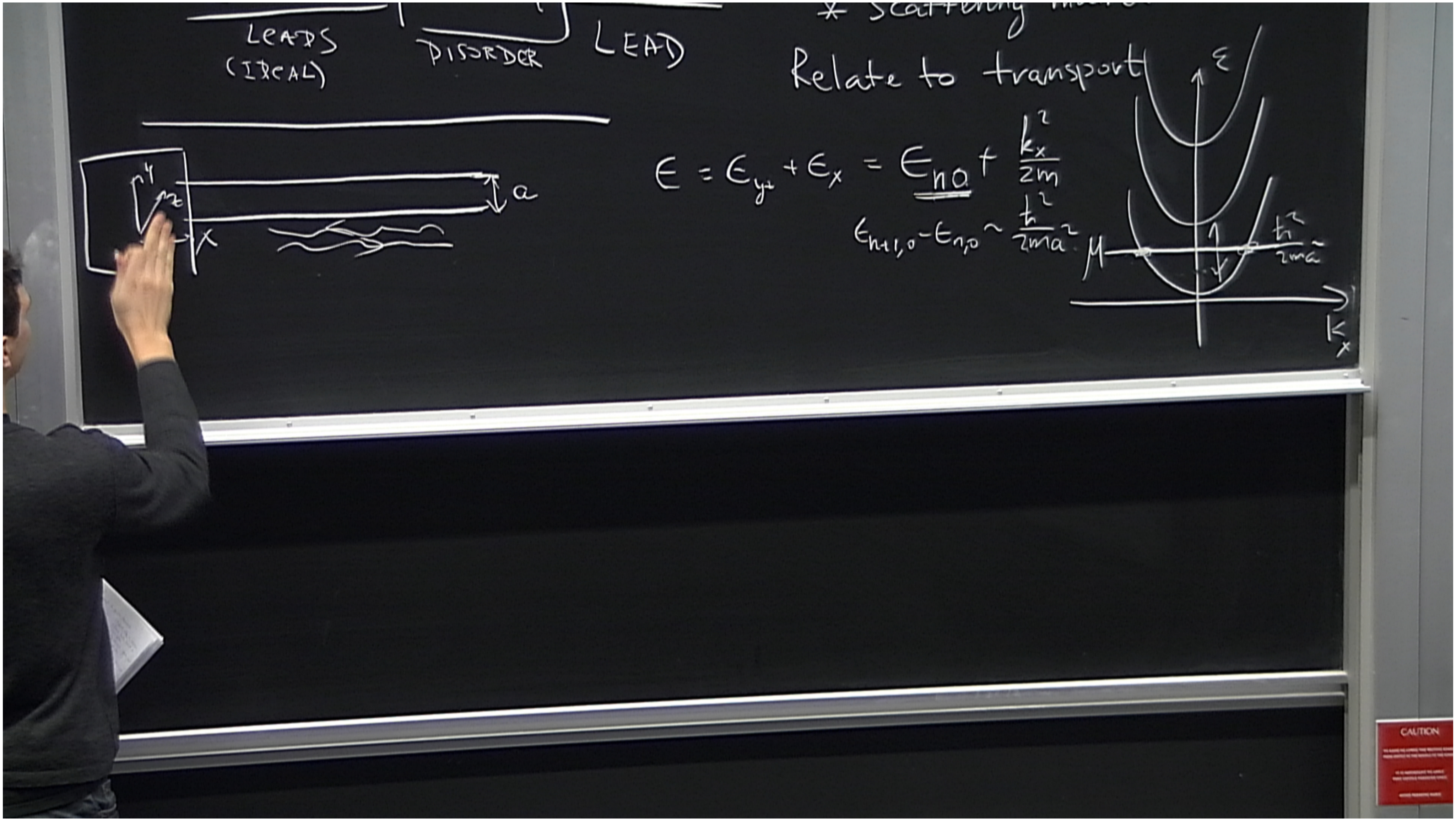

MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD
* Coherent Low T
* Scattering matrix
Relate to transport
$\epsilon = \epsilon_{yz} + \epsilon_x = \epsilon_{n0} + \frac{k_x^2}{2m}$
a
x

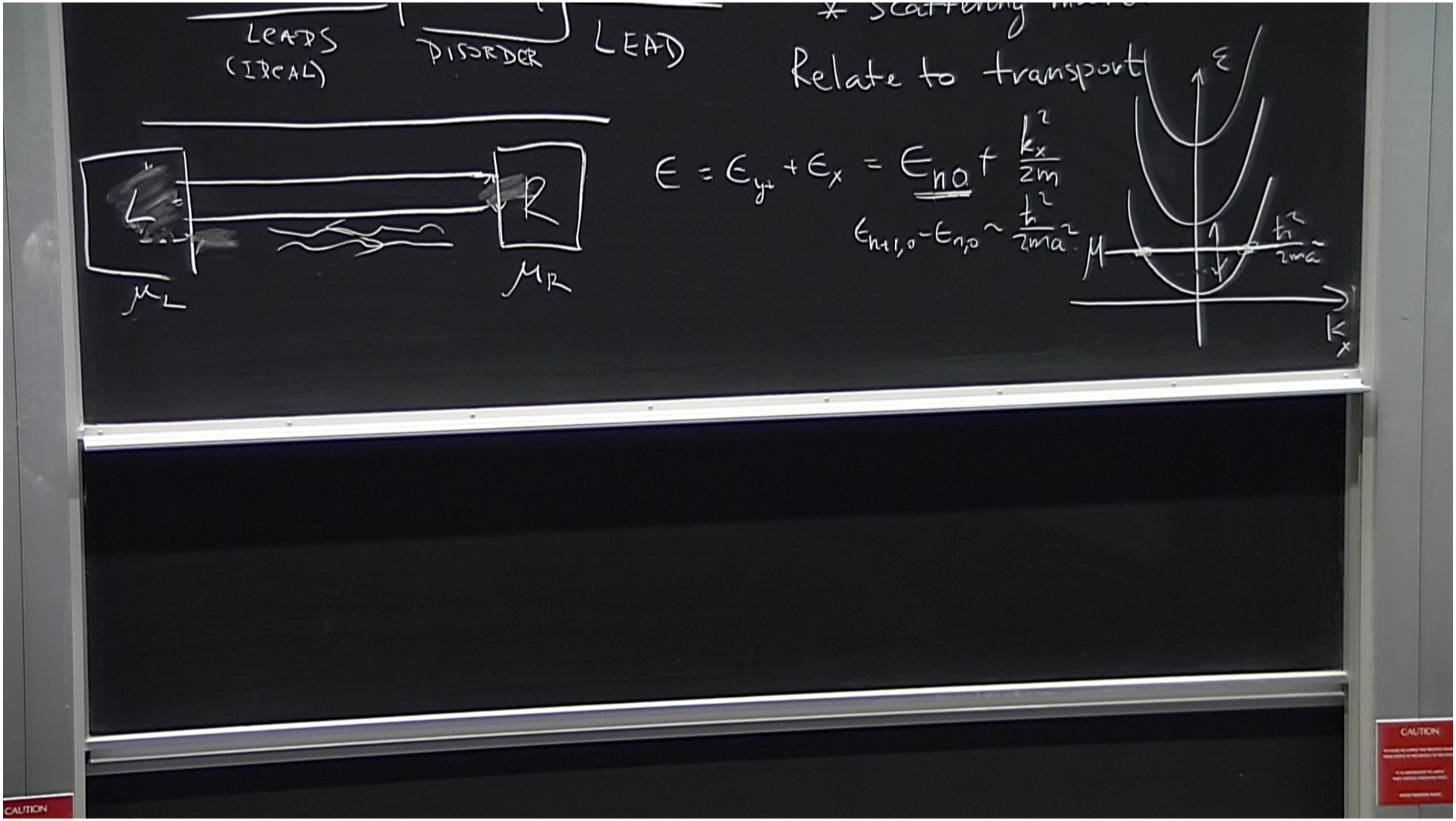

MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD
* Coherent Low T
* Scattering matrix
Relate to transport
a
x
y
z
ε
$\epsilon = \epsilon_{yz} + \epsilon_x = \epsilon_{n0} + \frac{k_x^2}{2m}$
$\epsilon_{n+1,0} - \epsilon_{n,0} \sim$

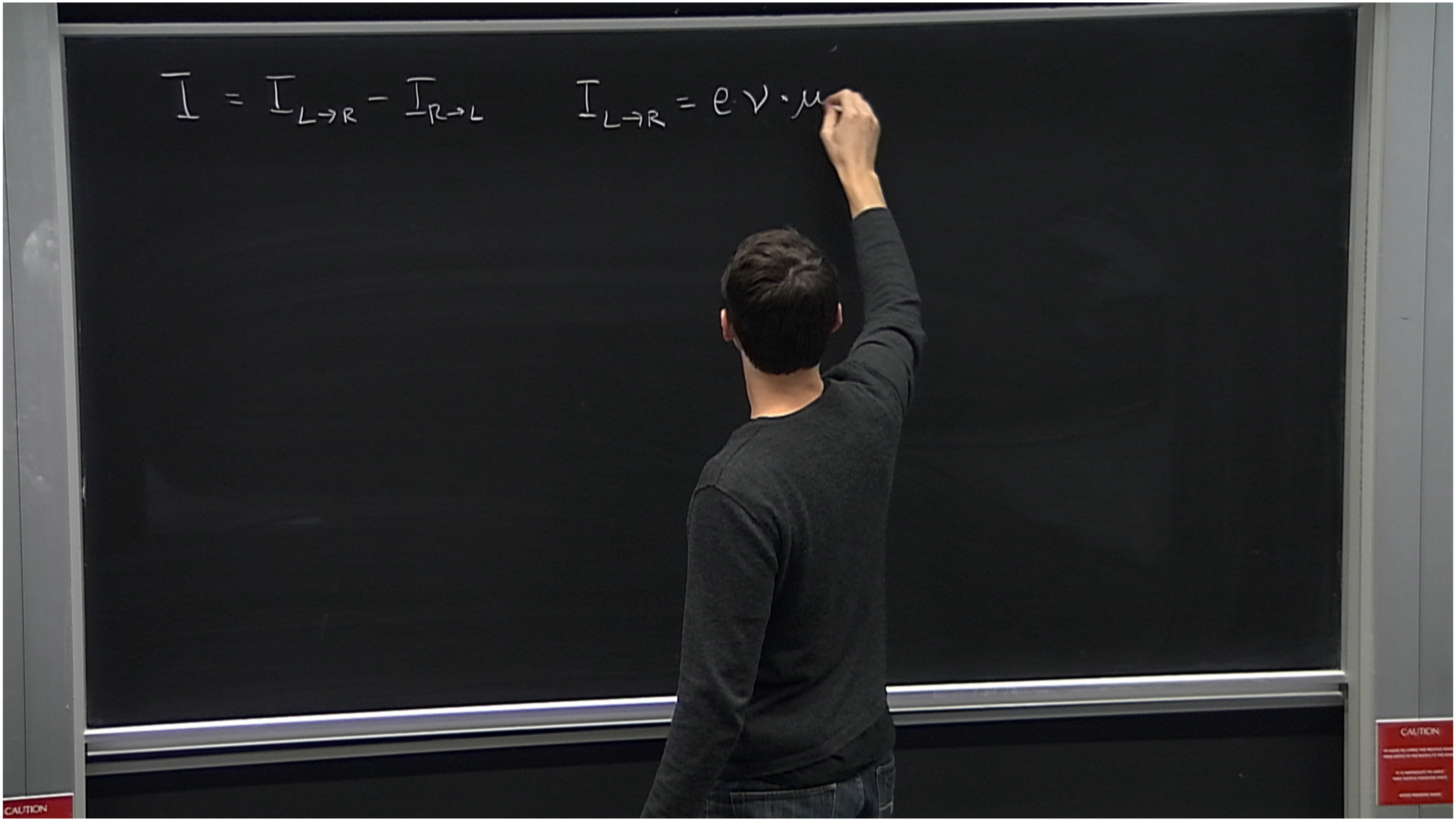

MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD
* Coherent
Low
* Scattering matrix
Relate to transport
$\epsilon = \epsilon_{yz} + \epsilon_x = \epsilon_{n0} + \frac{k_x^2}{2m}$
$\epsilon_{n+1,0} - \epsilon_{n,0} \sim \frac{\hbar^2}{2ma^2}$
a
y
z
x
ϵ
k_x
$\frac{\hbar^2}{2ma^2}$

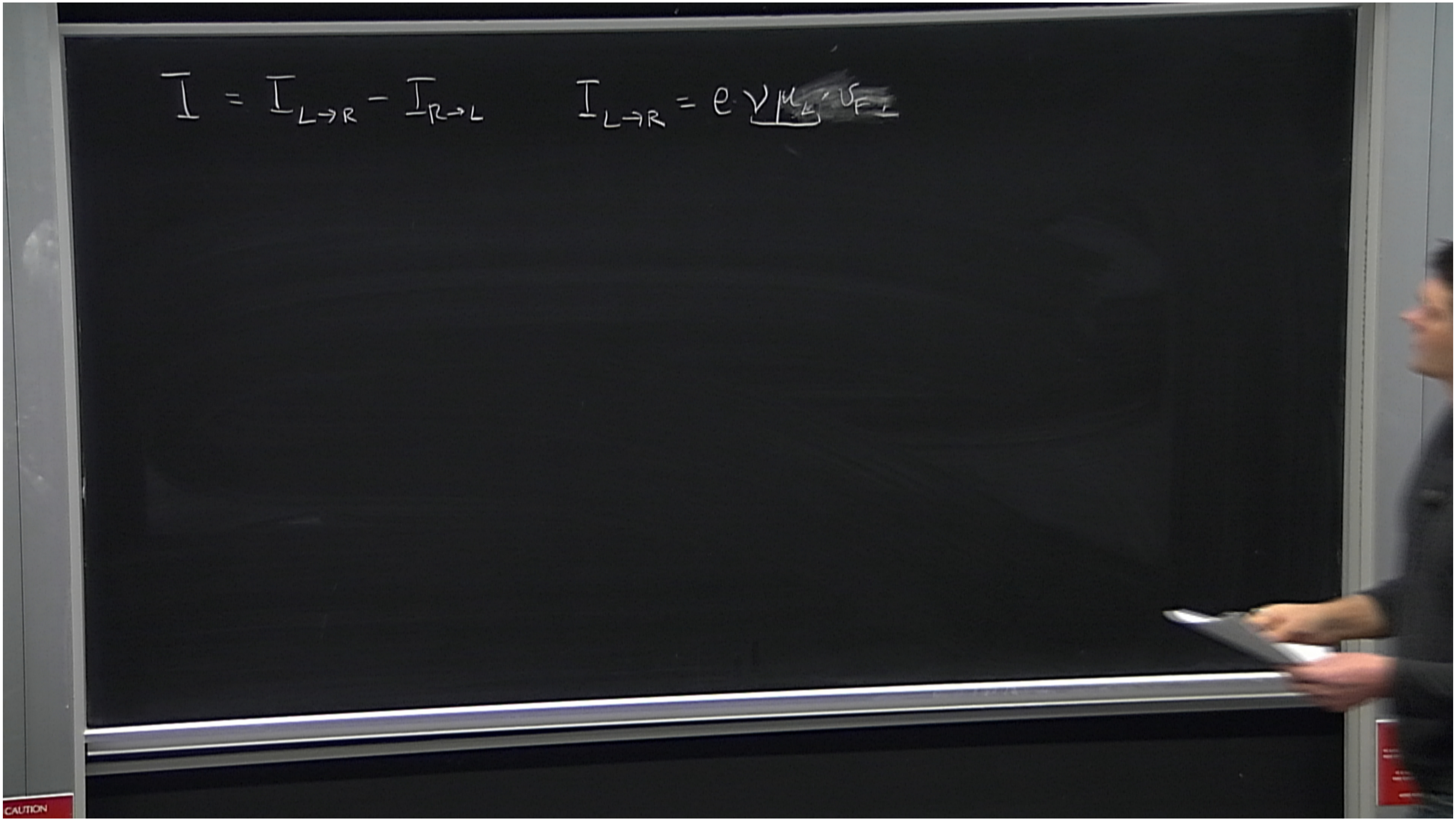


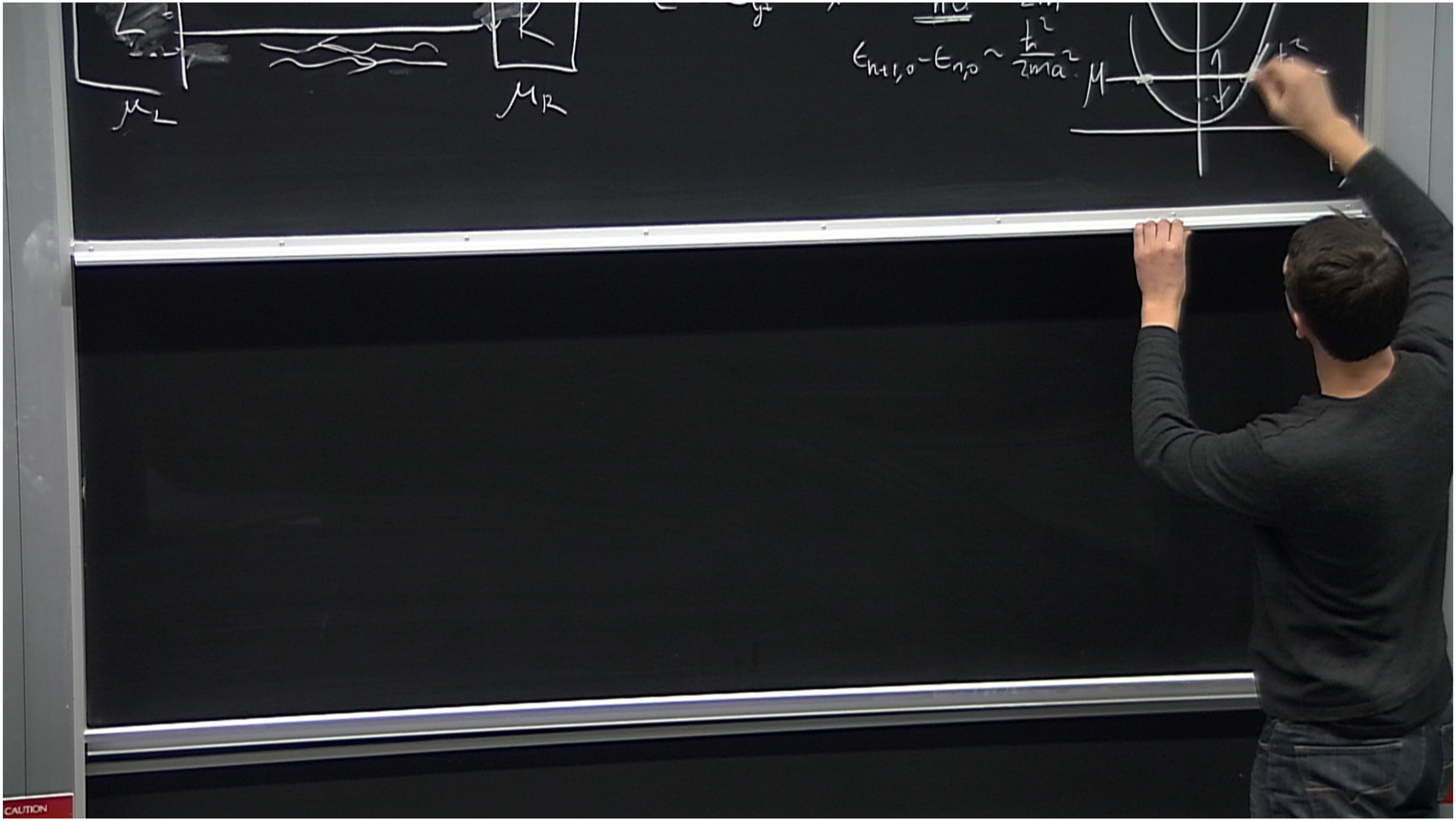
MESO. SYSTEM
LEADS (IDEAL)
DISORDER
LEAD
* Coherent Low
* Scattering matrix
Relate to transport
$\epsilon = \epsilon_{yz} + \epsilon_x = \epsilon_{n0} + \frac{k_x^2}{2m}$
$\epsilon_{n+1,0} - \epsilon_{n,0} \sim \frac{\hbar^2}{2ma^2}$
ϵ
μ
$\frac{\hbar^2}{2ma^2}$
k_x
a

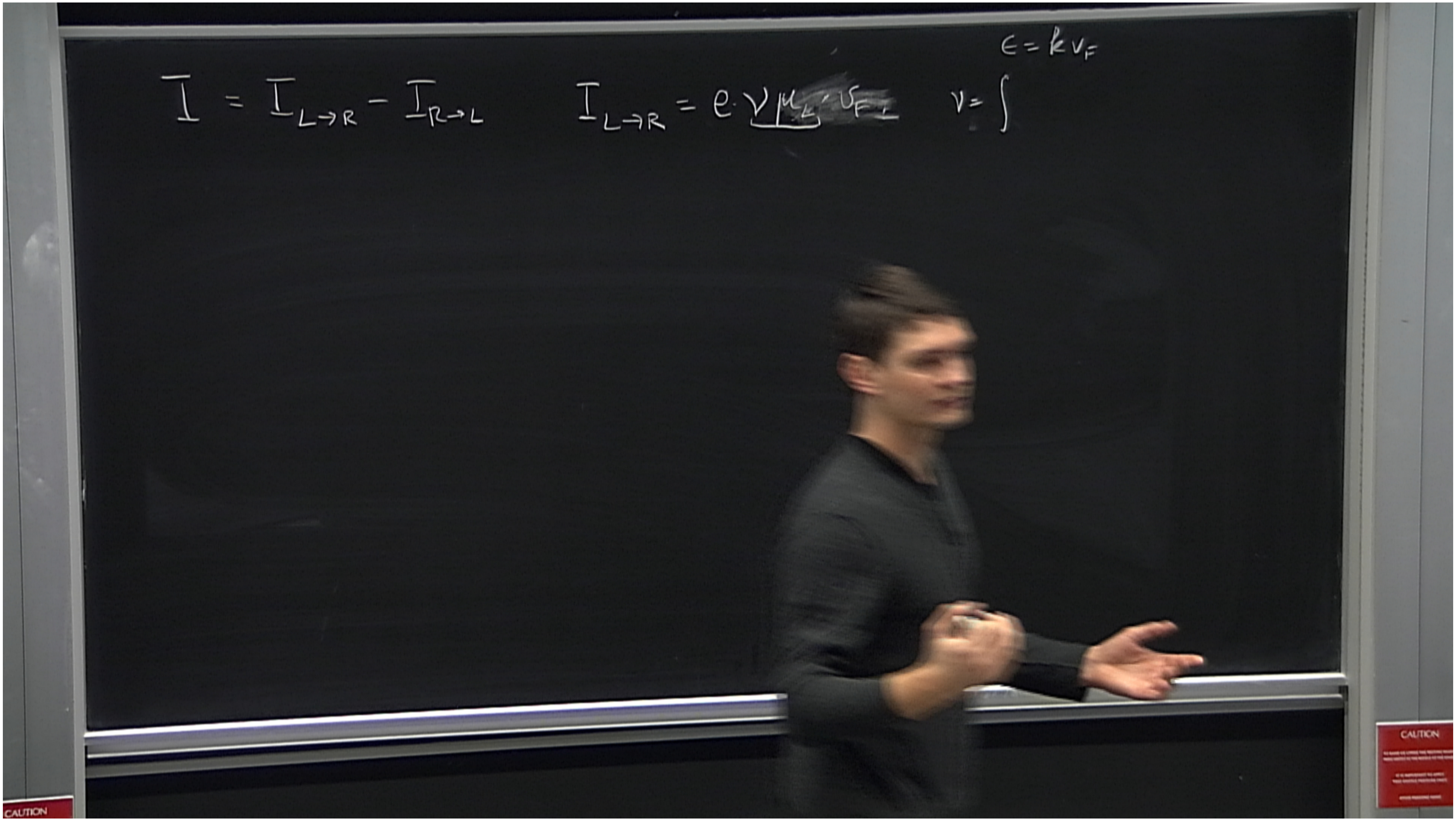

LEADS (IDEAL)
DISORDER
LEAD
Relate to transport
$\epsilon = \epsilon_{yz} + \epsilon_x = \epsilon_{n0} + \frac{k_x^2}{2m}$
$\epsilon_{n+1,0} - \epsilon_{n,0} \sim \frac{\hbar^2}{2ma^2}$
$\frac{\hbar^2}{2ma^2}$
μ
ϵ
k_x
a
x
y
z

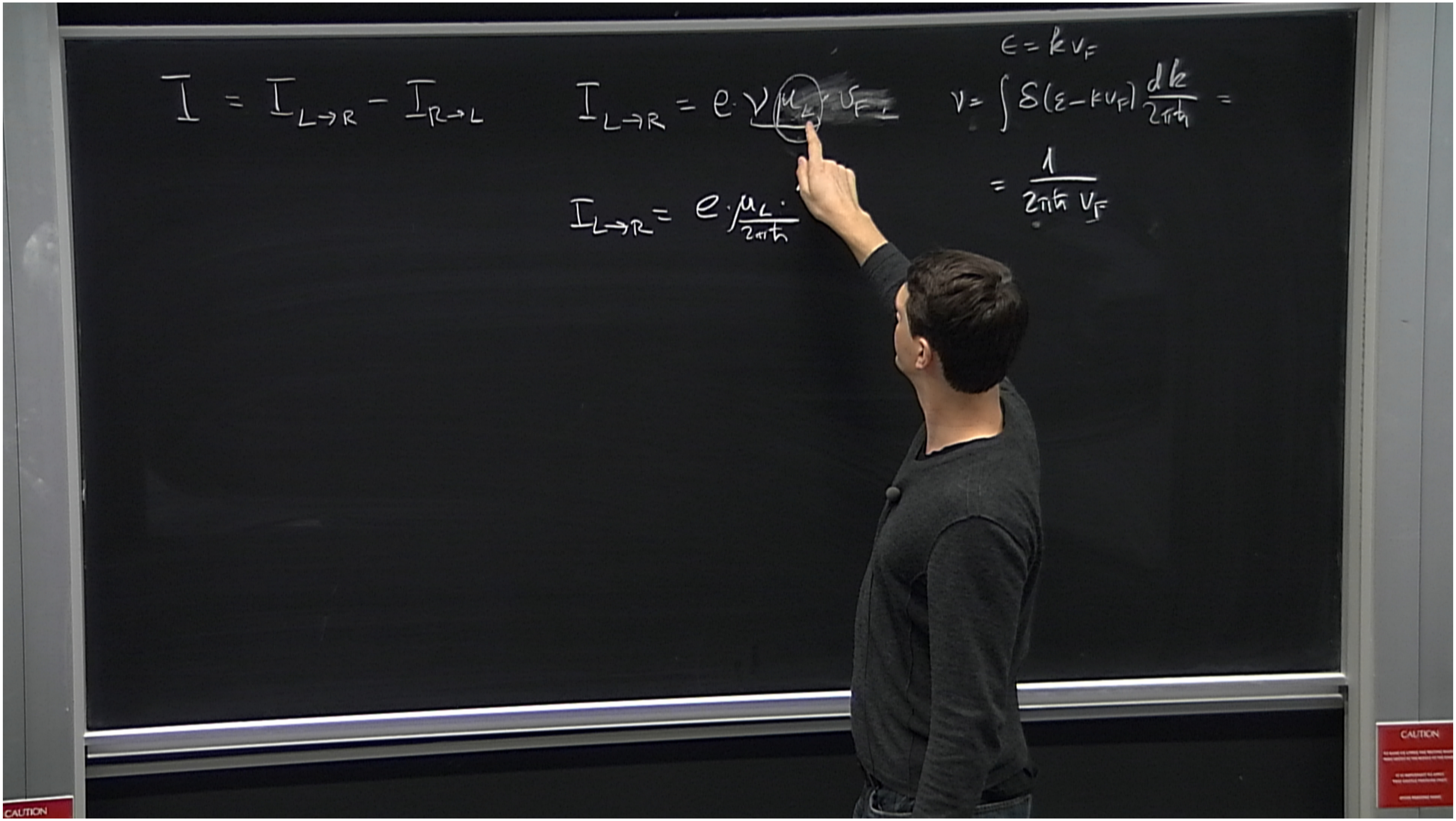

LEADS
(IDEAL)
DISORDER
LEAD
Relate to transport
L
R
μ_L
μ_R
$\epsilon = \epsilon_{yz} + \epsilon_x = \underline{\epsilon_{n0}} + \frac{k_x^2}{2m}$
$\epsilon_{n+1,0} - \epsilon_{n,0} \sim \frac{\hbar^2}{2ma^2}$
ϵ
μ
$\frac{\hbar^2}{2ma^2}$
k_x

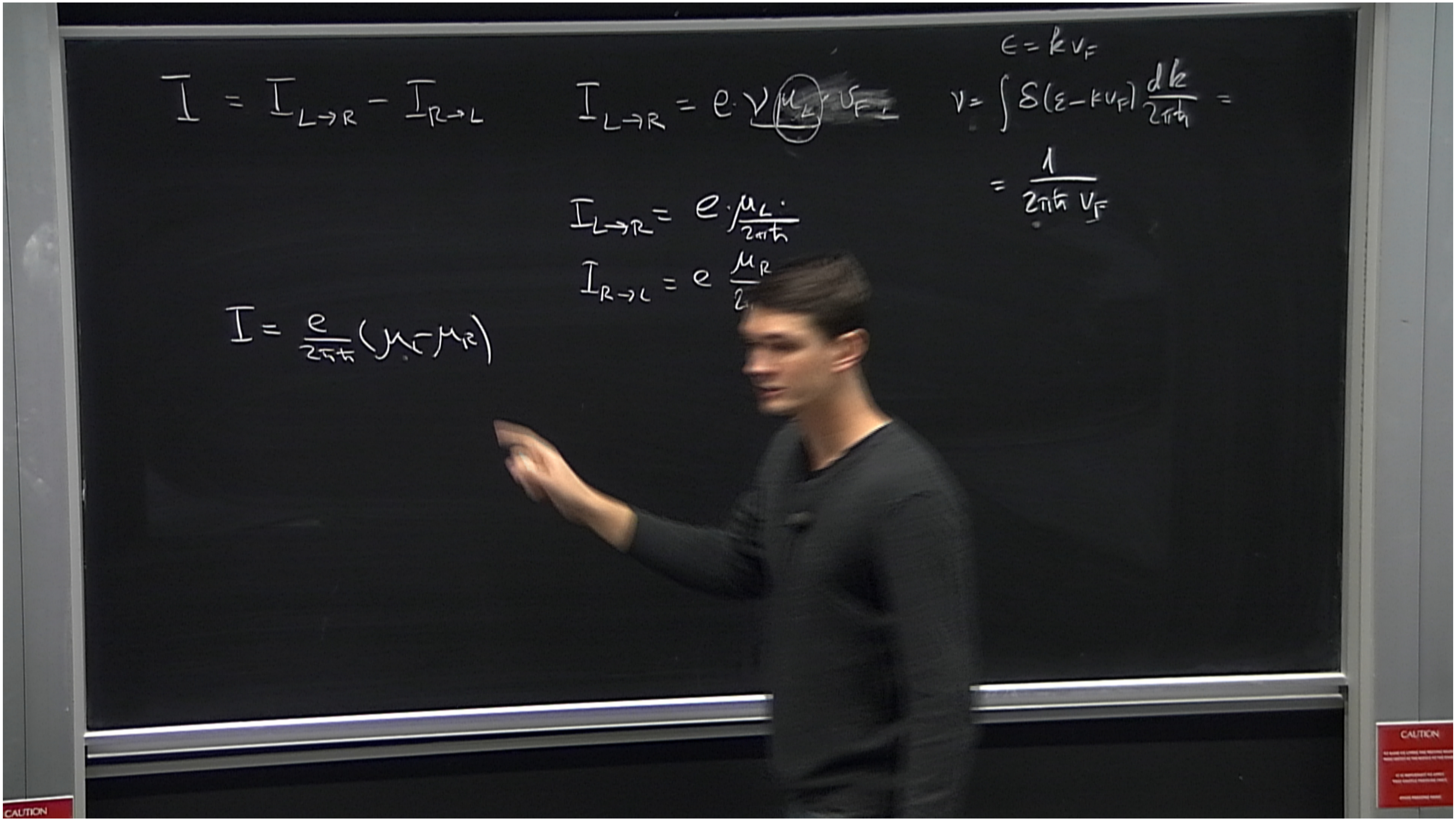

$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e\cdot\nu\cdot\mu$

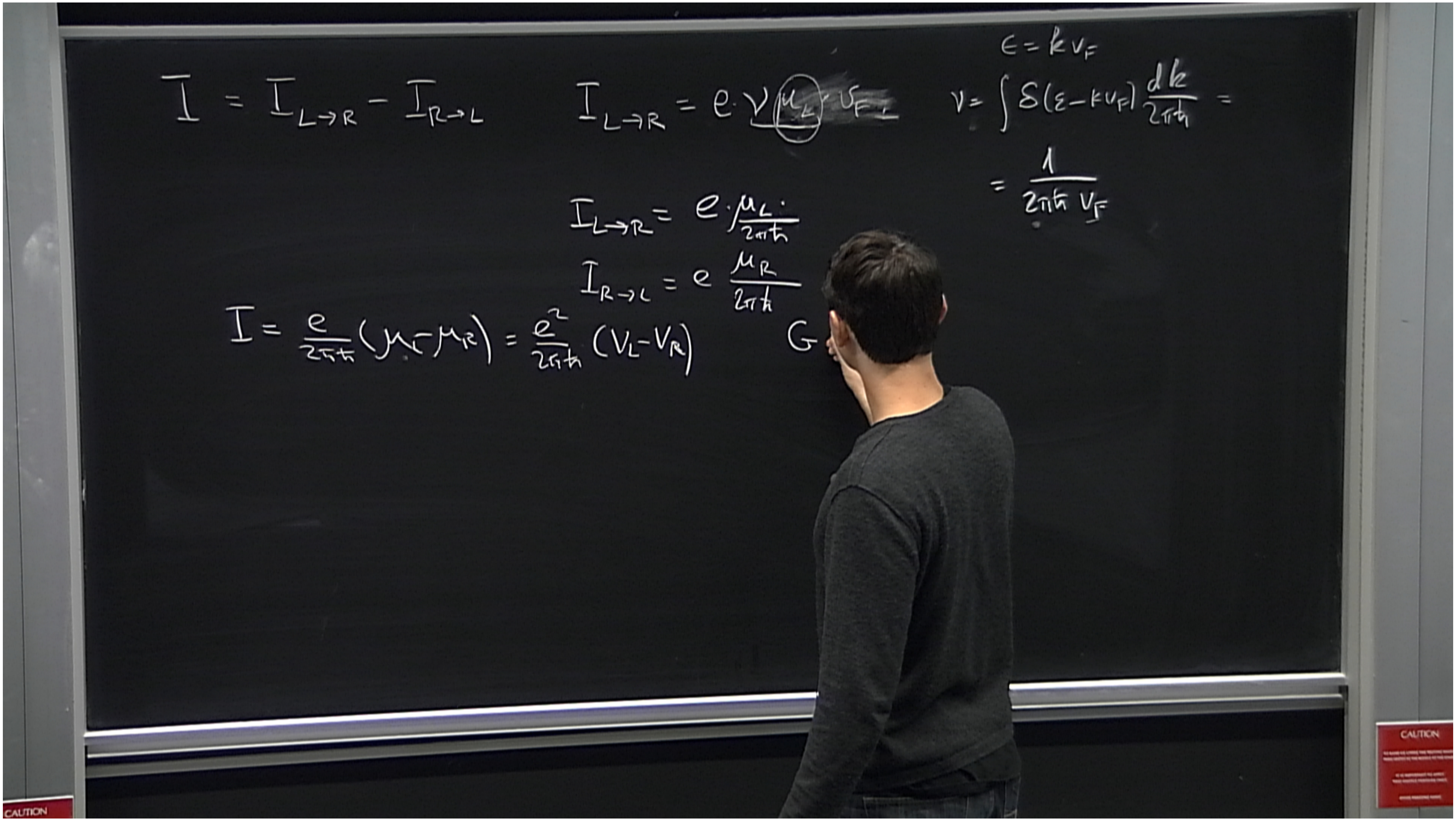

$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e\cdot\nu\,\mu_L\cdot v_F$


μ_L
μ_R
$\epsilon_{n+1,0} - \epsilon_{n,0} \sim \frac{\hbar^2}{2ma^2}$
μ
CAUTION


$\epsilon = k v_F$
$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e \cdot \nu \mu_L \cdot v_F$
$\nu = \int$
CAUTION


$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e \cdot \nu \, \mu_L \cdot v_F$
$\epsilon = k v_F$
$\nu = \int \delta(\epsilon - k v_F) \frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$
$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar} \cdot$
CAUTION


$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e \cdot \nu\, \mu_L\, v_F$
$\epsilon = k v_F$
$\nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} =$
$= \frac{1}{2\pi\hbar\, v_F}$
$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e\, \frac{\mu_R}{2}$
$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R)$


$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e \cdot \nu\, \mu_L\, v_F$
$\epsilon = k v_F$
$\nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar\, v_F}$
$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$
$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R)$
G
CAUTION

$$\epsilon = k v_F$$

$$I = I_{L\to R} - I_{R\to L} \qquad I_{L\to R} = e \cdot \nu(\mu_L)\, v_F \qquad \nu = \int \delta(\varepsilon - k v_F)\frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar\, v_F}$$

$$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$$

$$I_{R\to L} = e\,\frac{\mu_R}{2\pi\hbar}$$

$$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R) \qquad G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$$

$$\epsilon = k v_F$$

$$I = I_{L\to R} - I_{R\to L} \qquad I_{L\to R} = e \cdot \nu\, \mu_L \cdot v_F \qquad \nu = \int \delta(\varepsilon - k v_F)\,\frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar\, v_F}$$

$$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$$

$$I_{R\to L} = e\,\frac{\mu_R}{2\pi\hbar}$$

$$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R) \qquad G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$$

* Finite

* Fundamental constant

$$\epsilon = k v_F$$

$$I = I_{L\to R} - I_{R\to L} \qquad I_{L\to R} = e\cdot \nu\, \mu_L \cdot v_F \qquad \nu = \int \delta(\varepsilon - k v_F)\frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$$

$$I_{L\to R} = e\cdot\frac{\mu_L}{2\pi\hbar}$$

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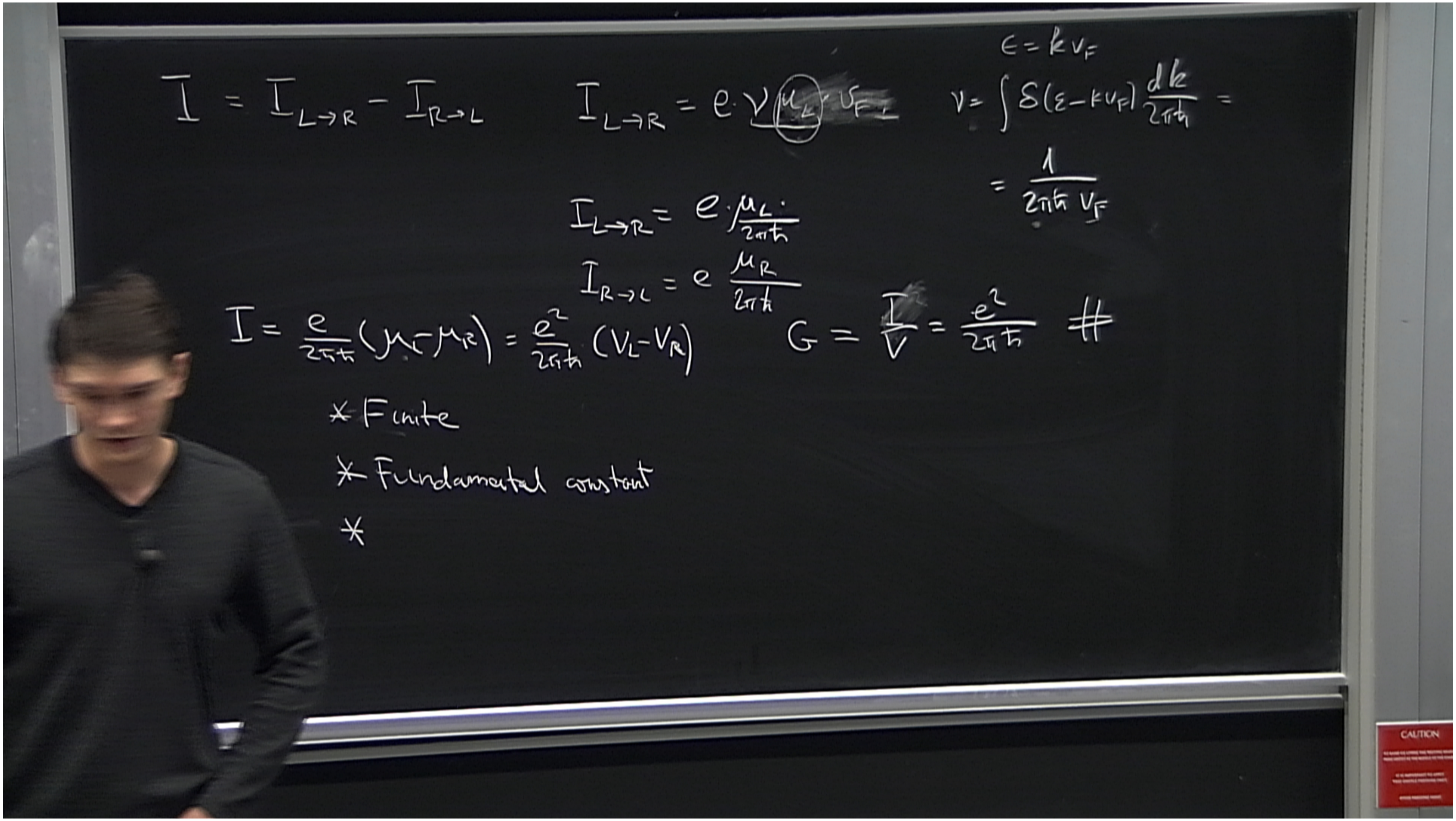
* Finite

* Fundamental constant



$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e \cdot \nu \, \mu_L \cdot v_F$
$\epsilon = k v_F$
$\nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$
$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$
$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R)$
$G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$ #
* Finite
* Fundamental constant
*

$$I = I_{L\to R} - I_{R\to L}$$

$$I_{L\to R} = e \cdot \nu \, \mu_L \, v_F$$

$$\epsilon = k v_F$$

$$\nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$$

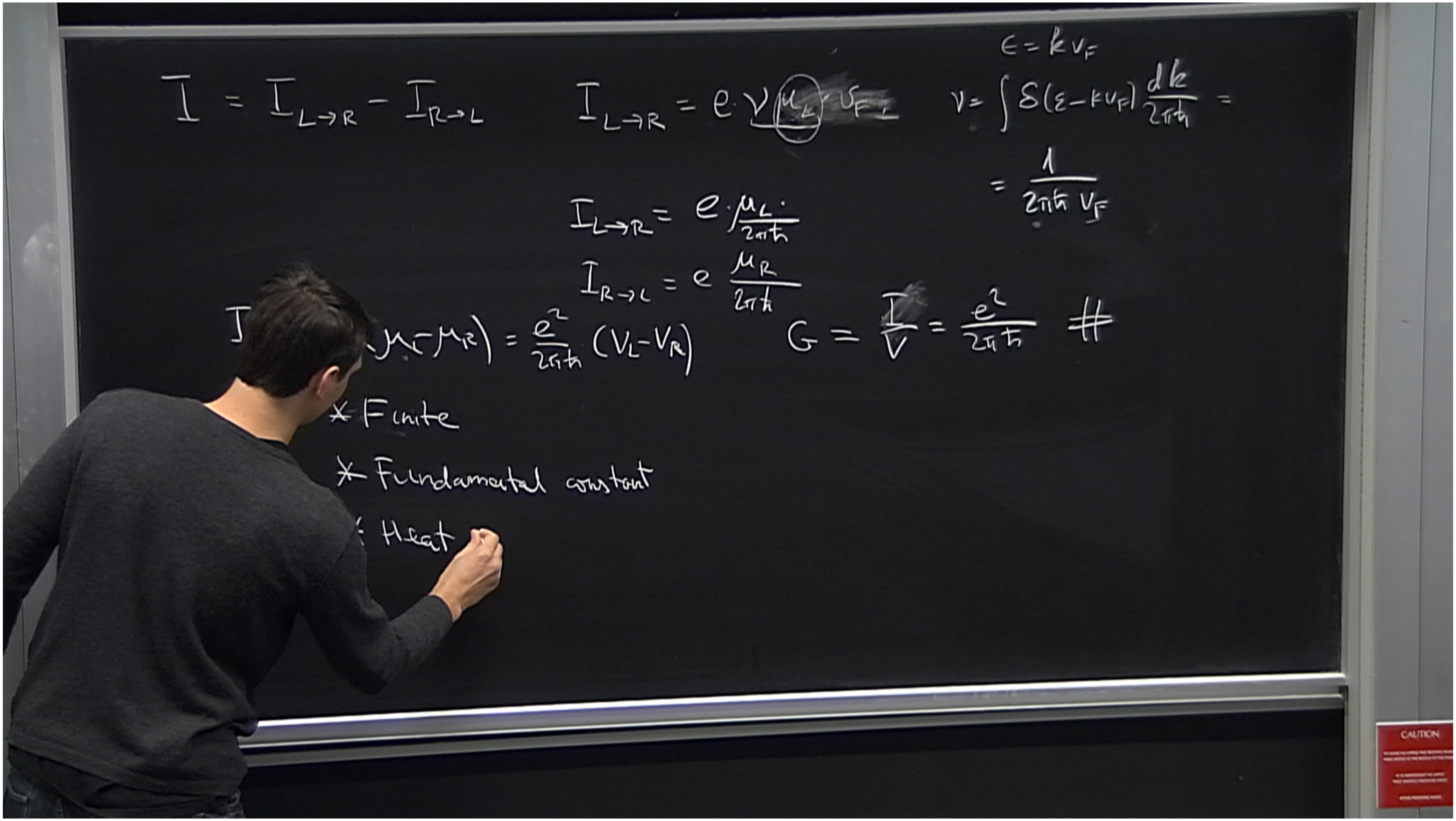
$$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$$

$$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$$

$$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R)$$

$$G = \frac{I}{V} = \frac{e^2}{2\pi\hbar} \quad \#$$

* Finite
* Fundamental constant
*


$\epsilon = k v_F$
$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e \cdot \nu \, \mu_L \, v_F$
$\nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} =$
$= \frac{1}{2\pi\hbar v_F}$
$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$
$(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R)$
$G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$ #
* Finite
* Fundamental constant
Heat
CAUTION

$$\epsilon = k v_F$$

$$I = I_{L\to R} - I_{R\to L} \qquad I_{L\to R} = e \cdot \nu \, \mu_L \, v_F \qquad \nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$$

$$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$$

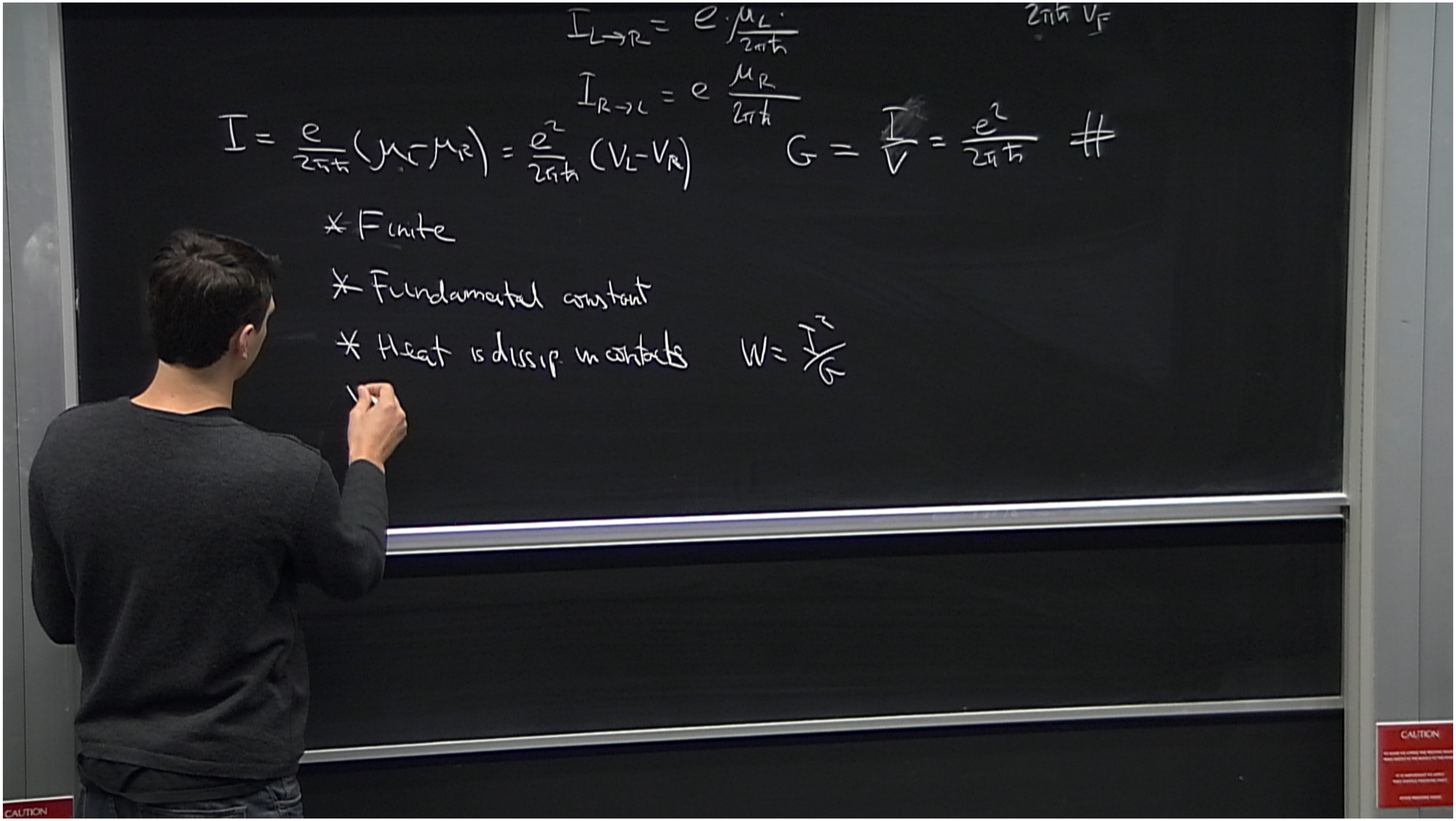
$$I_{R\to L} = e \, \frac{\mu_R}{2\pi\hbar}$$

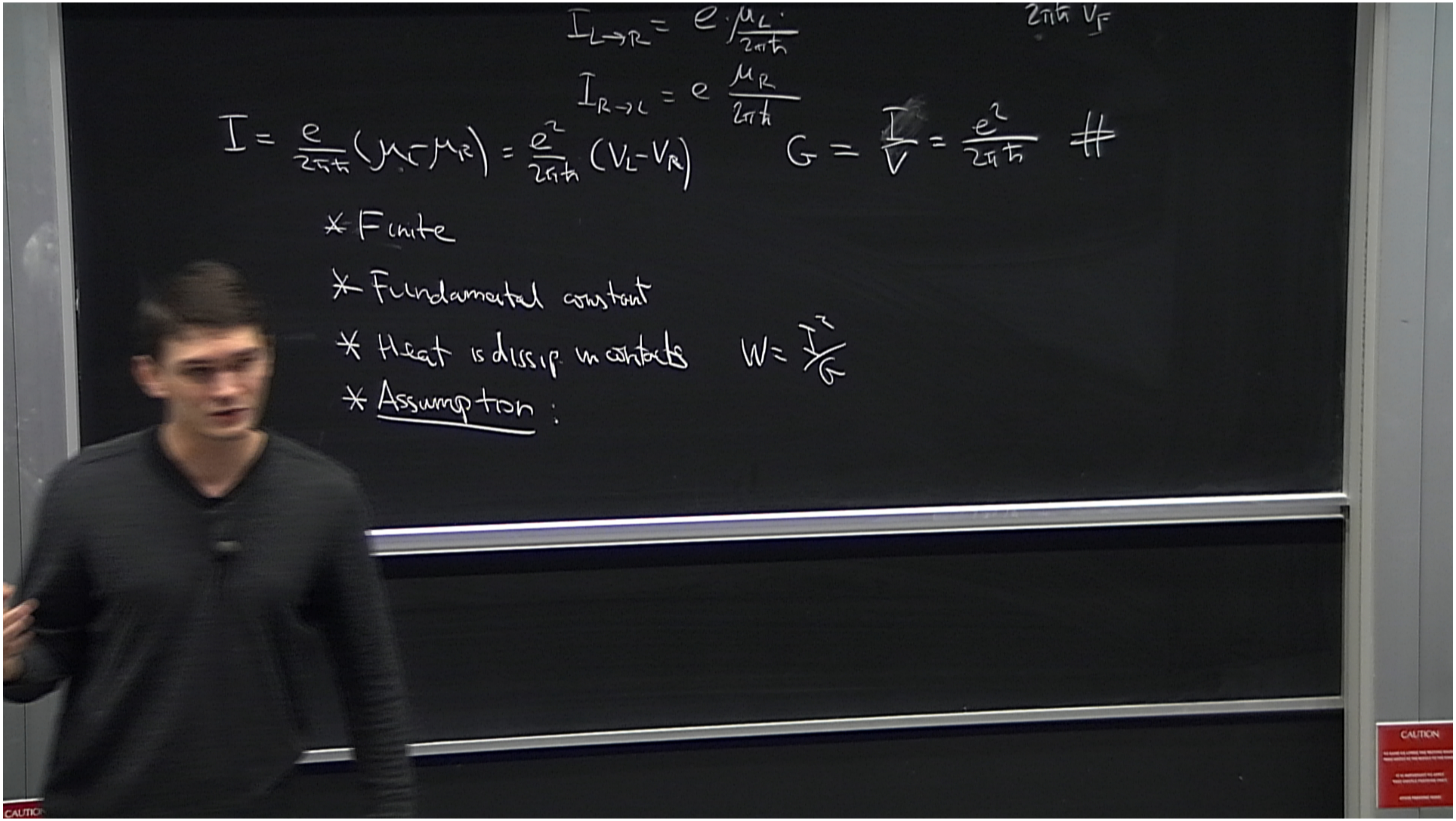
$$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R) \qquad G = \frac{I}{V} = \frac{e^2}{2\pi\hbar} \quad \#$$

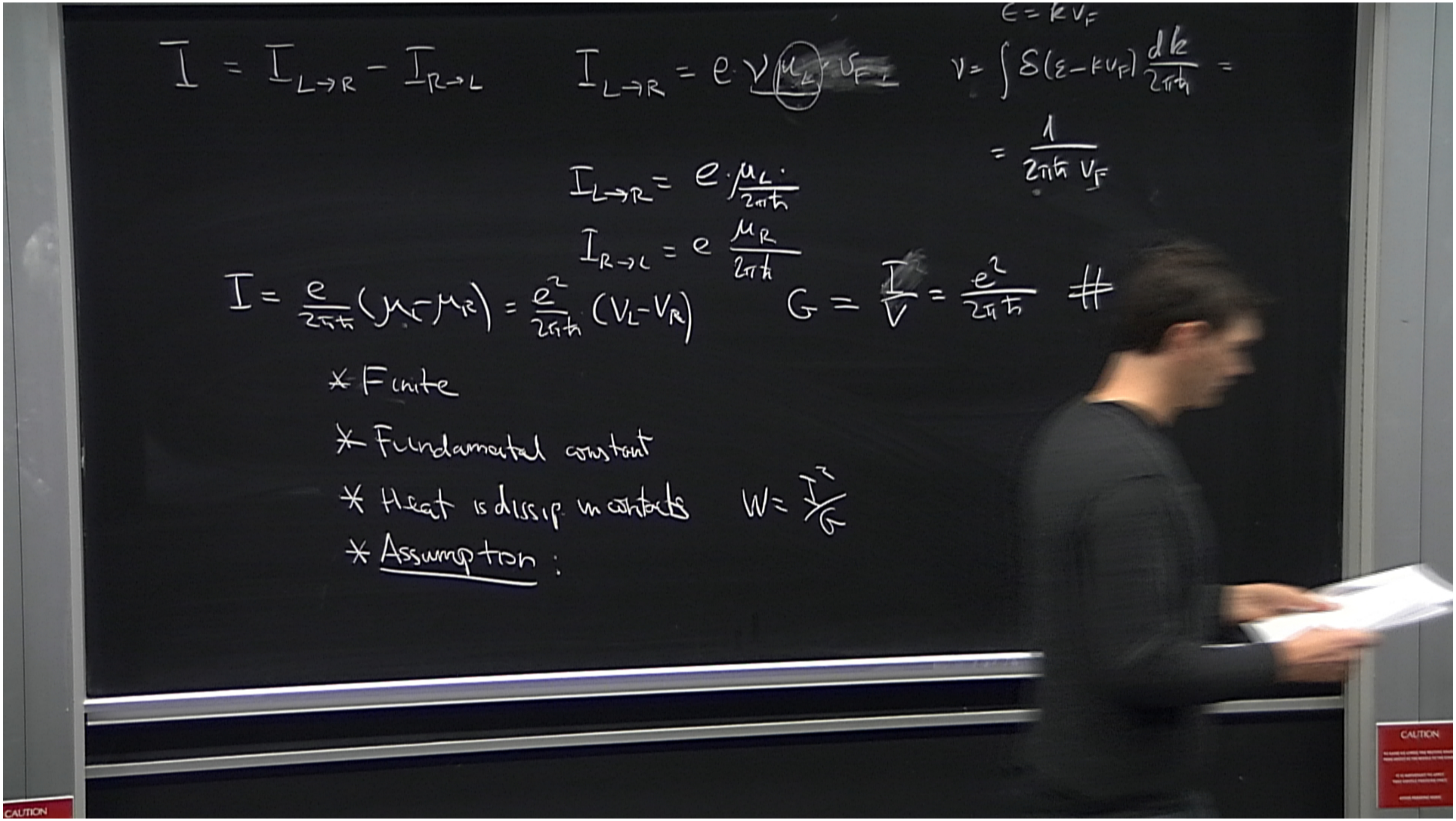
* Finite

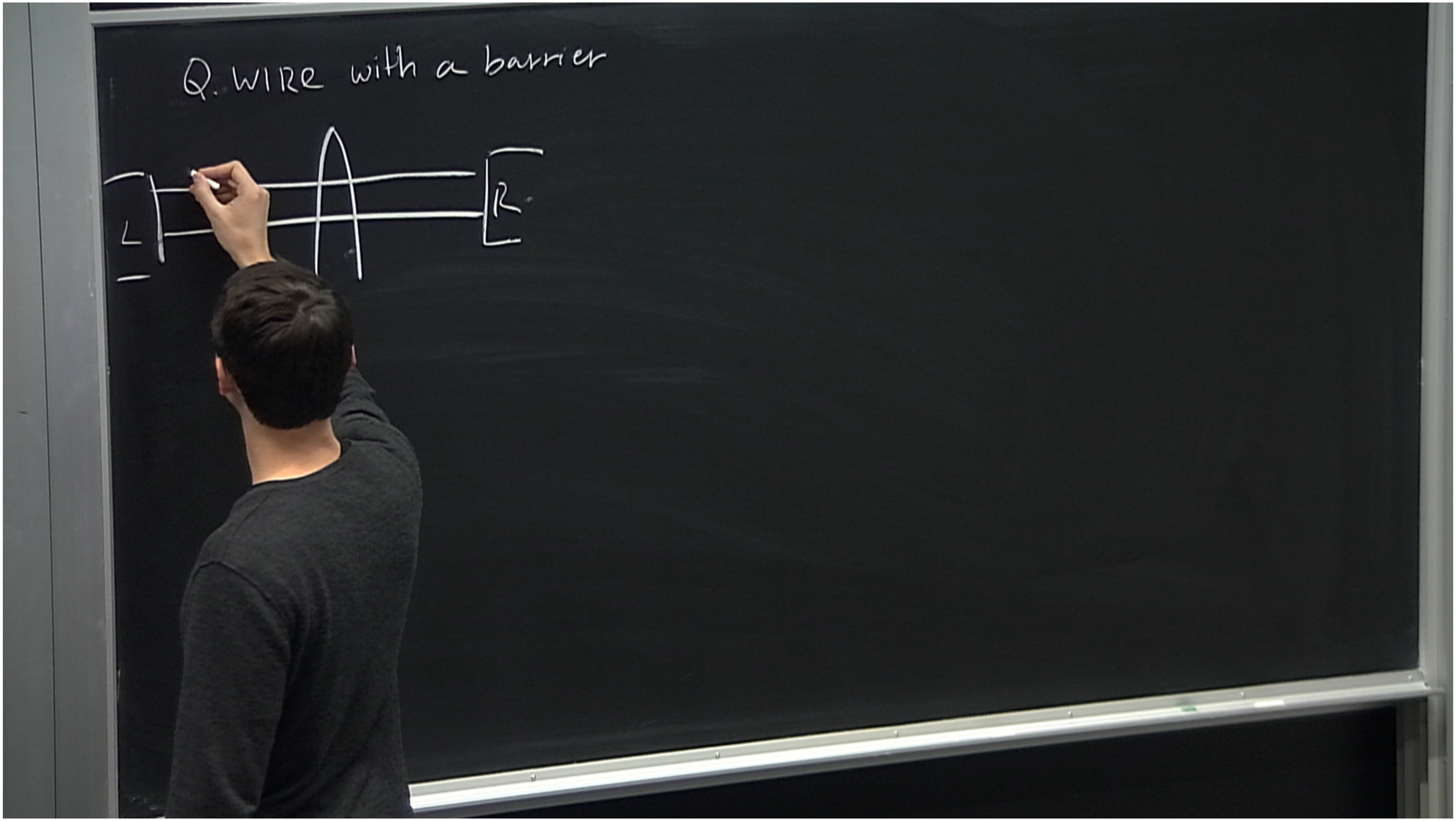
* Fundamental constant

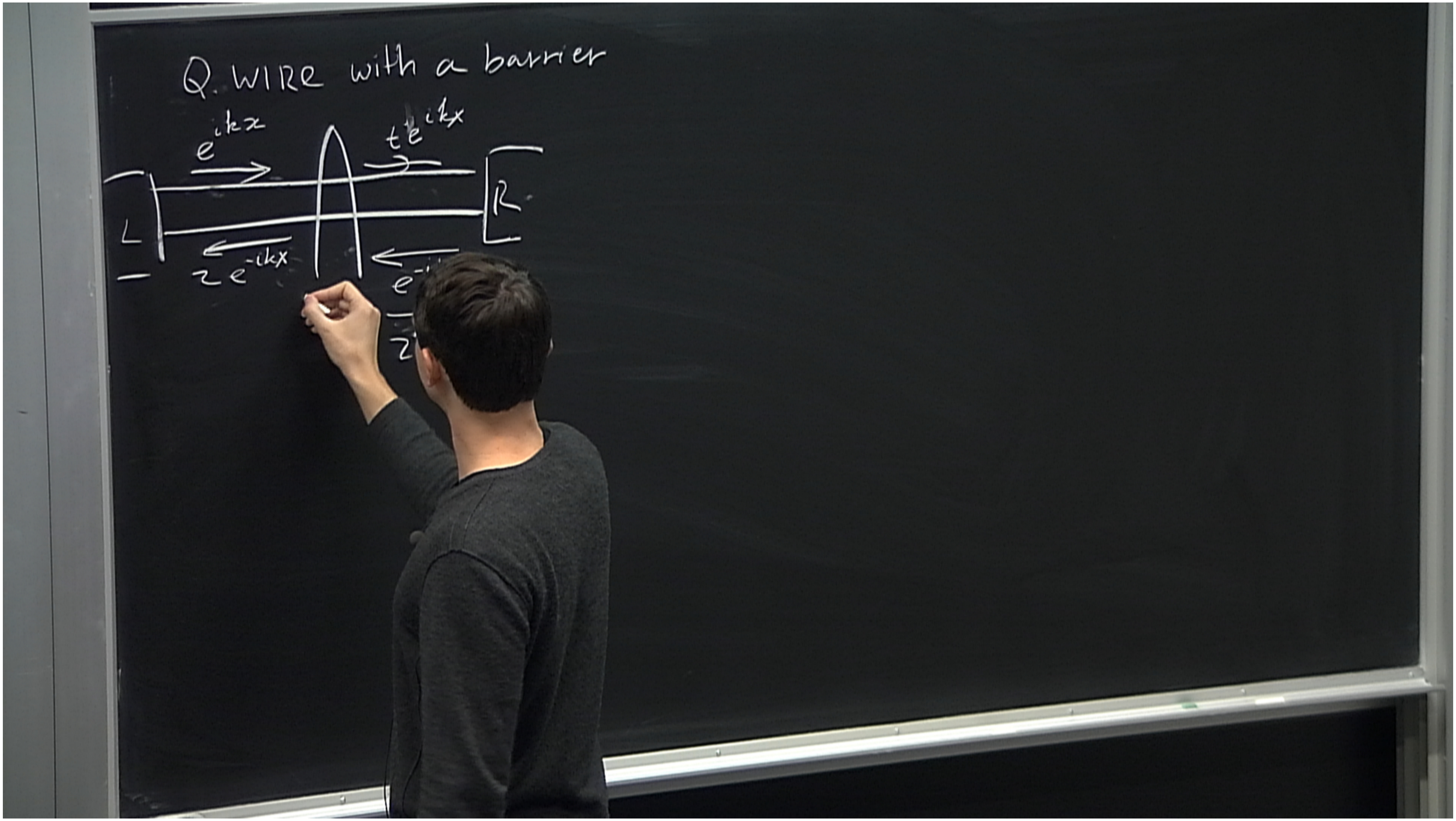
* Heat is dissip in contacts

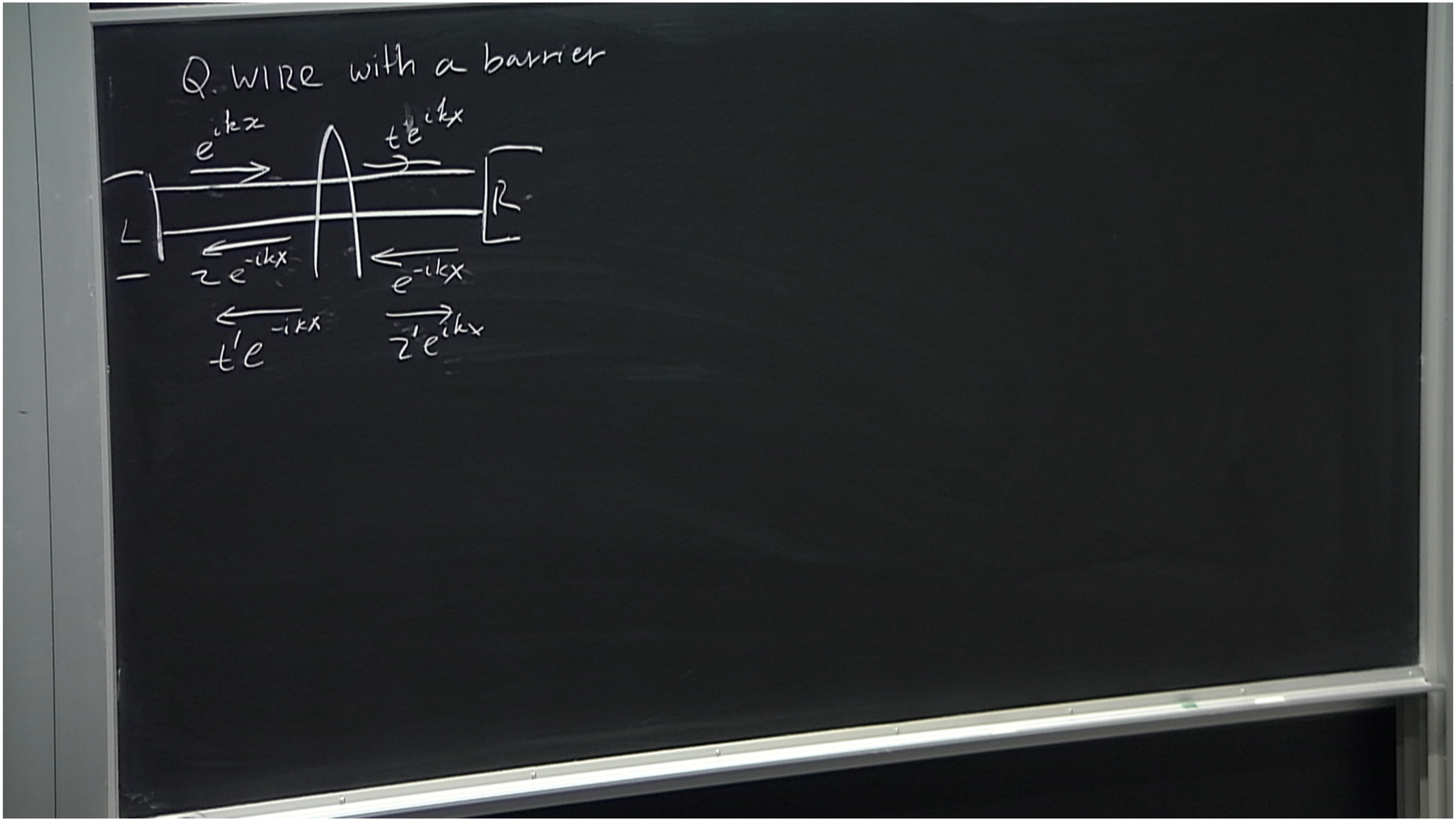

$I_{L\to R} = e \frac{\mu_L}{2\pi\hbar}$
$2\pi\hbar\, v_F$
$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$
$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R)$
$G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$ #
* Finite
* Fundamental constant
* Heat is dissip. in contacts $W = I^2/G$
CAUTION

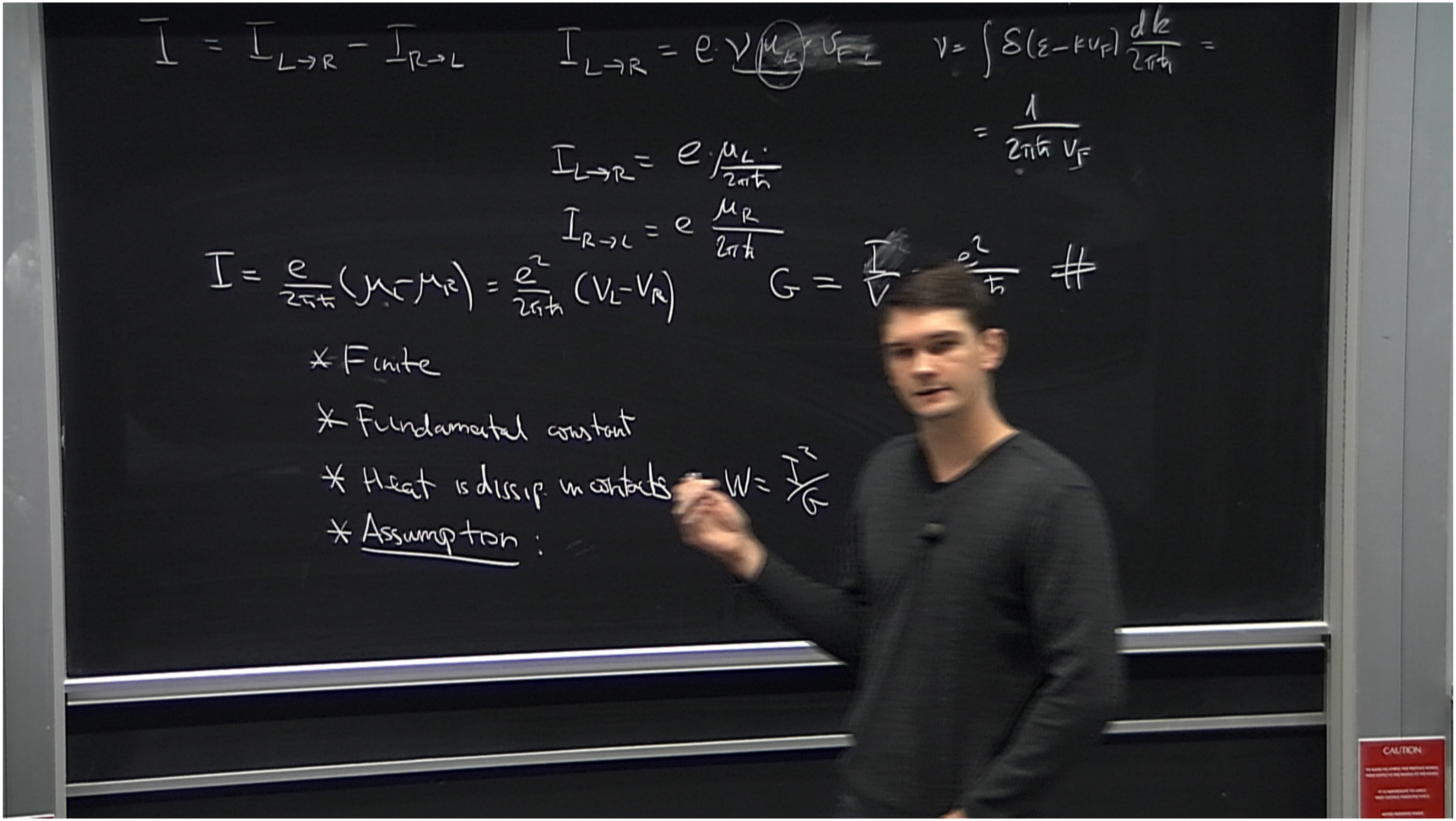

$2\pi\hbar v_F$
$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$
$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R)$
$G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$ #
* Finite
* Fundamental constant
* Heat is dissip. in contacts $W = I^2/G$
* Assumption :

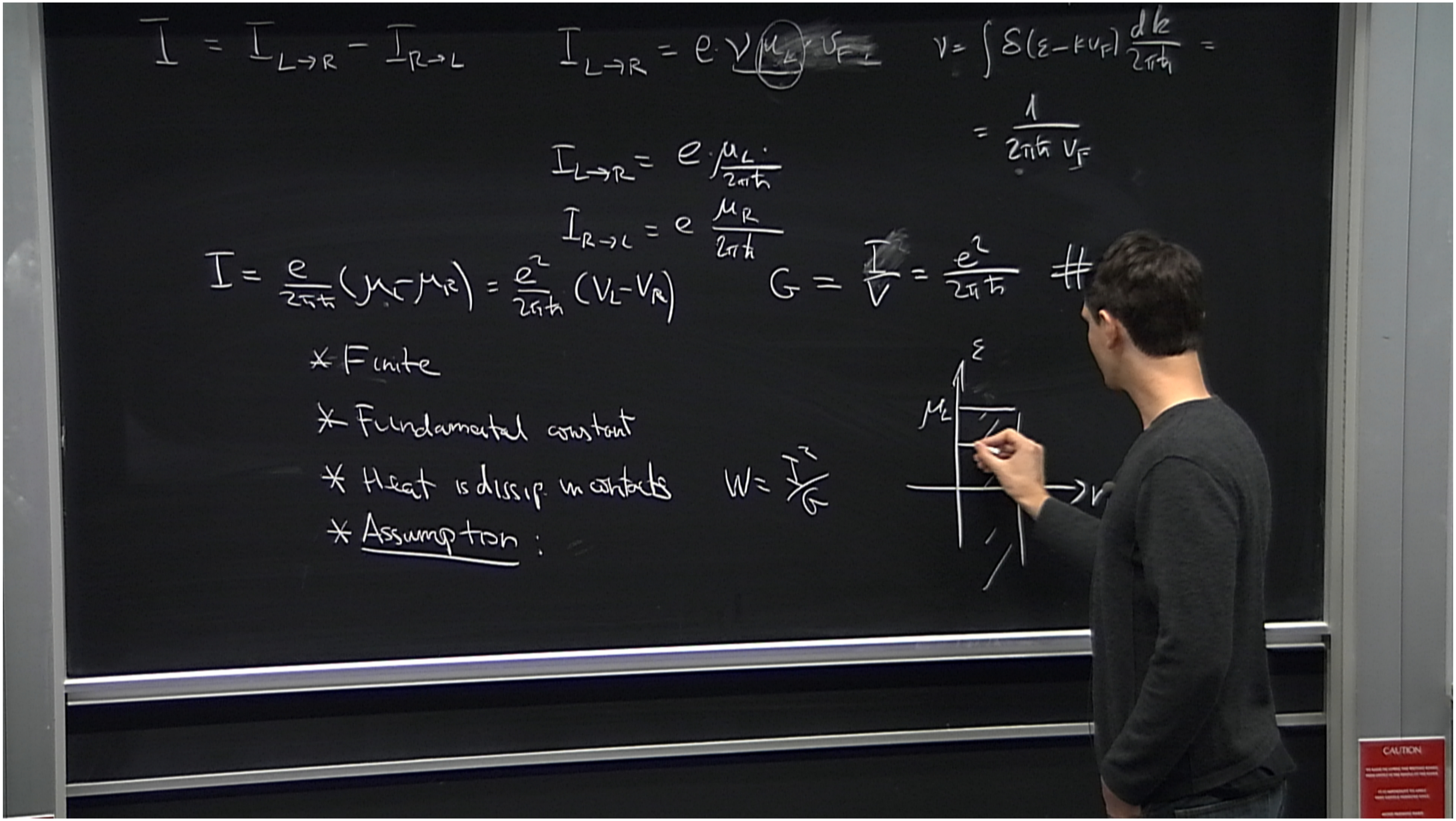

$\epsilon = k v_F$
$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e\,\nu\,\mu_L\,v_F$
$\nu = \int \delta(\varepsilon - k v_F)\frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$
$I_{L\to R} = e\cdot\frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e\,\frac{\mu_R}{2\pi\hbar}$
$I = \frac{e}{2\pi\hbar}(\mu_L-\mu_R) = \frac{e^2}{2\pi\hbar}(V_L-V_R)$
$G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$ #
* Finite
* Fundamental constant
* Heat is dissip. in contacts $W = I^2/G$
* Assumption:
CAUTION

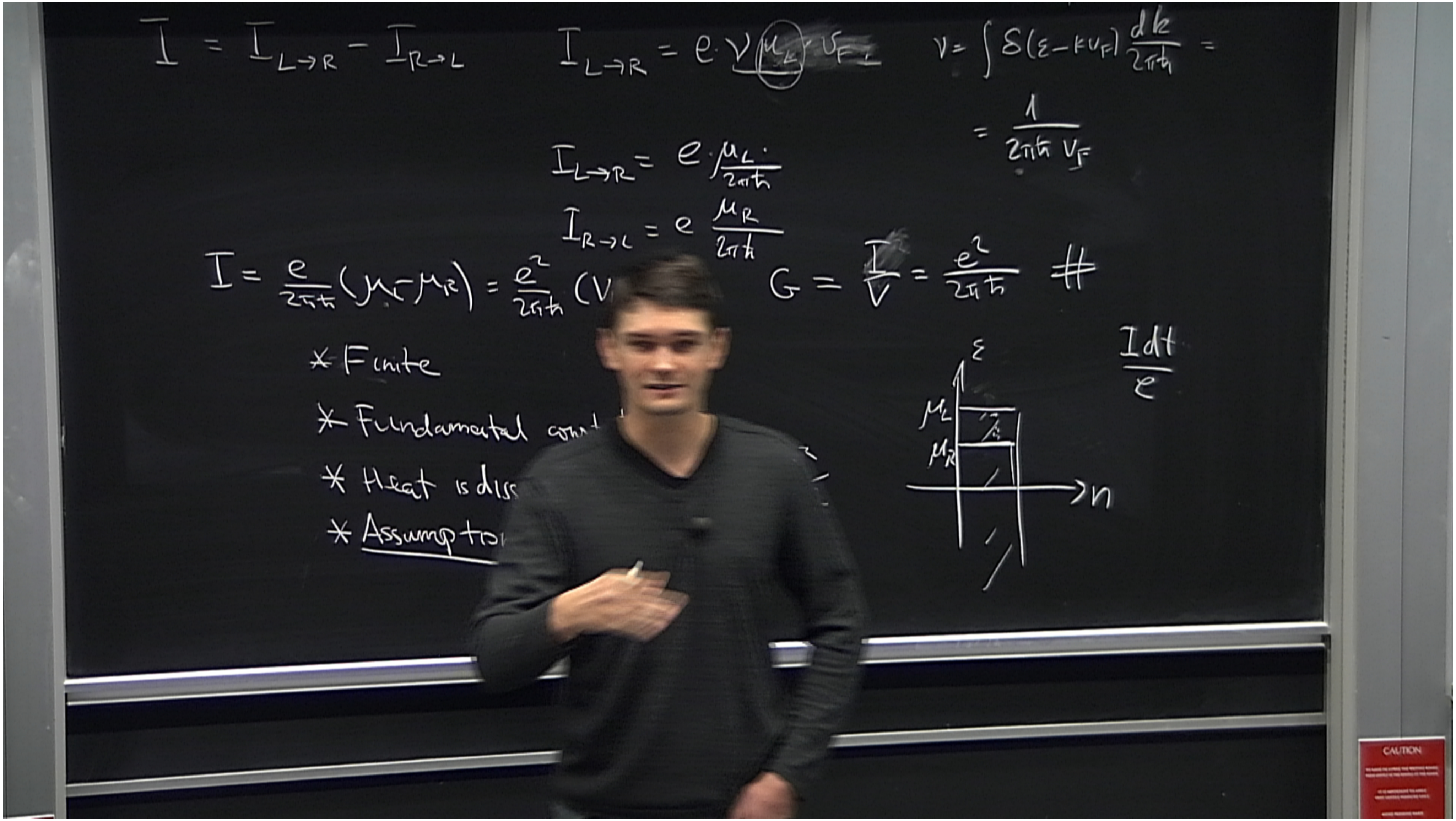

Q. WIRE with a barrier
L
R

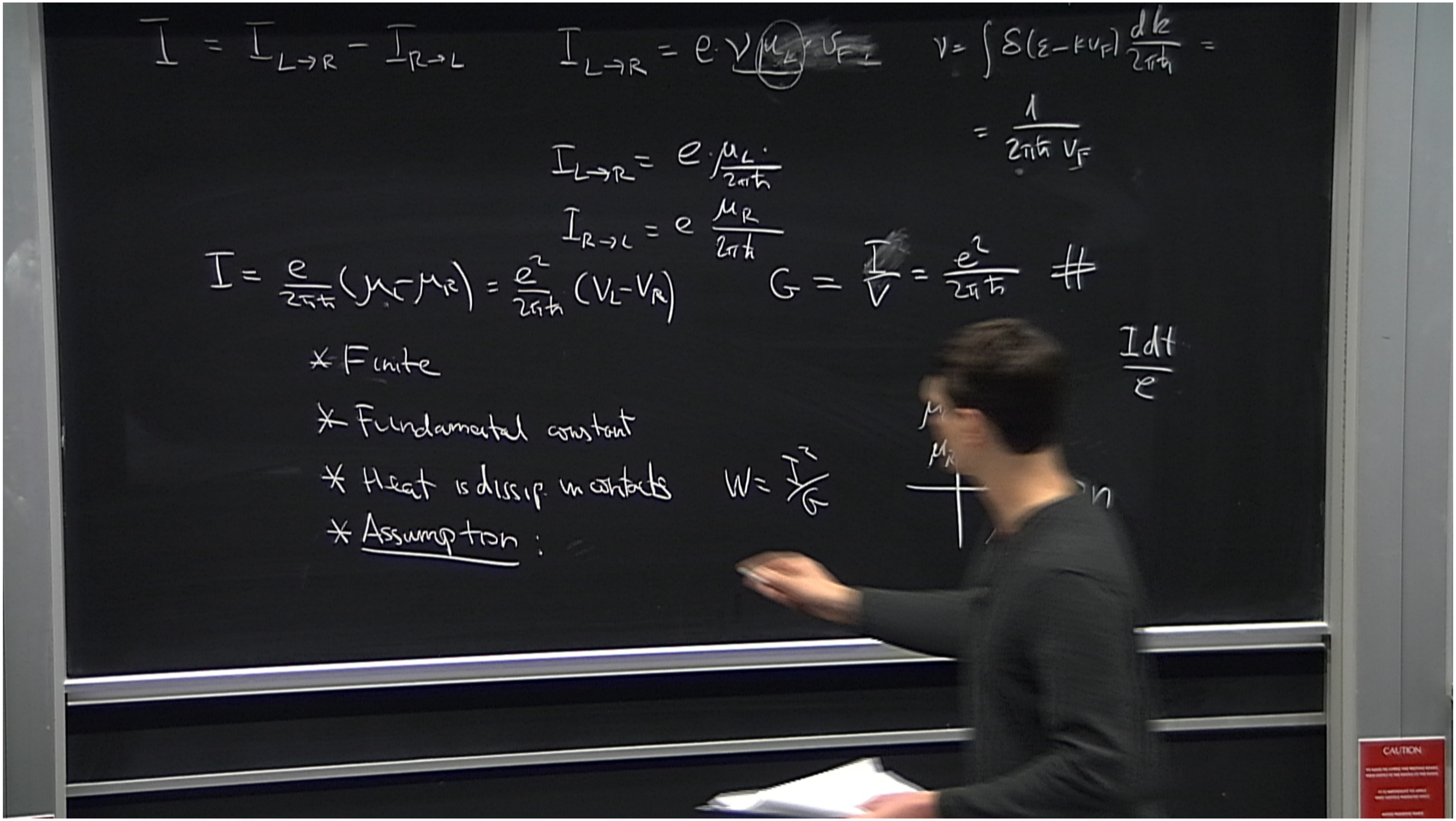

Q. WIRE with a barrier
e^{ikx}
te^{ikx}
L
R
re^{-ikx}


Q. WIRE with a barrier
e^{ikx}
te^{ikx}
L
R
re^{-ikx}
e^{-ikx}
t'e^{-ikx}
r'e^{ikx}


$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e\cdot \nu\, \mu_L\, v_F$
$\nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$
$I_{L\to R} = e \frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$
$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R)$
$G = \frac{I}{V}$ #
* Finite
* Fundamental constant
* Heat is dissip. in contacts $W = I^2/G$
* Assumption :


$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e \cdot \nu \, \mu_L \cdot v_F$
$\nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$
$I_{L\to R} = e \cdot \frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$
$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R)$
$G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$ #
* Finite
* Fundamental constant
* Heat is dissip. in contacts $W = I^2/G$
* Assumption :
ε
μ_L


$I = I_{L\to R} - I_{R\to L}$
$I_{L\to R} = e \cdot \nu \, \mu_L \cdot v_F$
$\nu = \int \delta(\varepsilon - k v_F) \frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar v_F}$
$I_{L\to R} = e \frac{\mu_L}{2\pi\hbar}$
$I_{R\to L} = e \frac{\mu_R}{2\pi\hbar}$
$I = \frac{e}{2\pi\hbar}(\mu_L - \mu_R) = \frac{e^2}{2\pi\hbar}(V$
$G = \frac{I}{V} = \frac{e^2}{2\pi\hbar}$ #
$\frac{I dt}{e}$
* Finite
* Fundamental const
* Heat is diss
* Assumptions
ε
μ_L
μ_R
n


I = I_{L→R} − I_{R→L}
I_{L→R} = e·ν μ_L v_F
ν = ∫ δ(ε − k v_F) dk/2πħ = 1/(2πħ v_F)
I_{L→R} = e μ_L/2πħ
I_{R→L} = e μ_R/2πħ
I = e/2πħ (μ_L − μ_R) = e²/2πħ (V_L − V_R)
G = I/V = e²/2πħ #
Idt/e
* Finite
* Fundamental constant
* Heat is dissip. in contacts
W = I²/G
* Assumption :

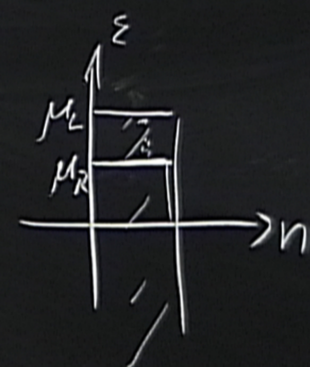
$$I = I_{L\to R} - I_{R\to L} \qquad I_{L\to R} = e\cdot \nu(\mu_L)\cdot v_F \qquad \nu = \int \delta(\varepsilon - k v_F)\frac{dk}{2\pi\hbar} = \frac{1}{2\pi\hbar\, v_F}$$

$$I_{L\to R} = e\cdot\frac{\mu_L}{2\pi\hbar}$$

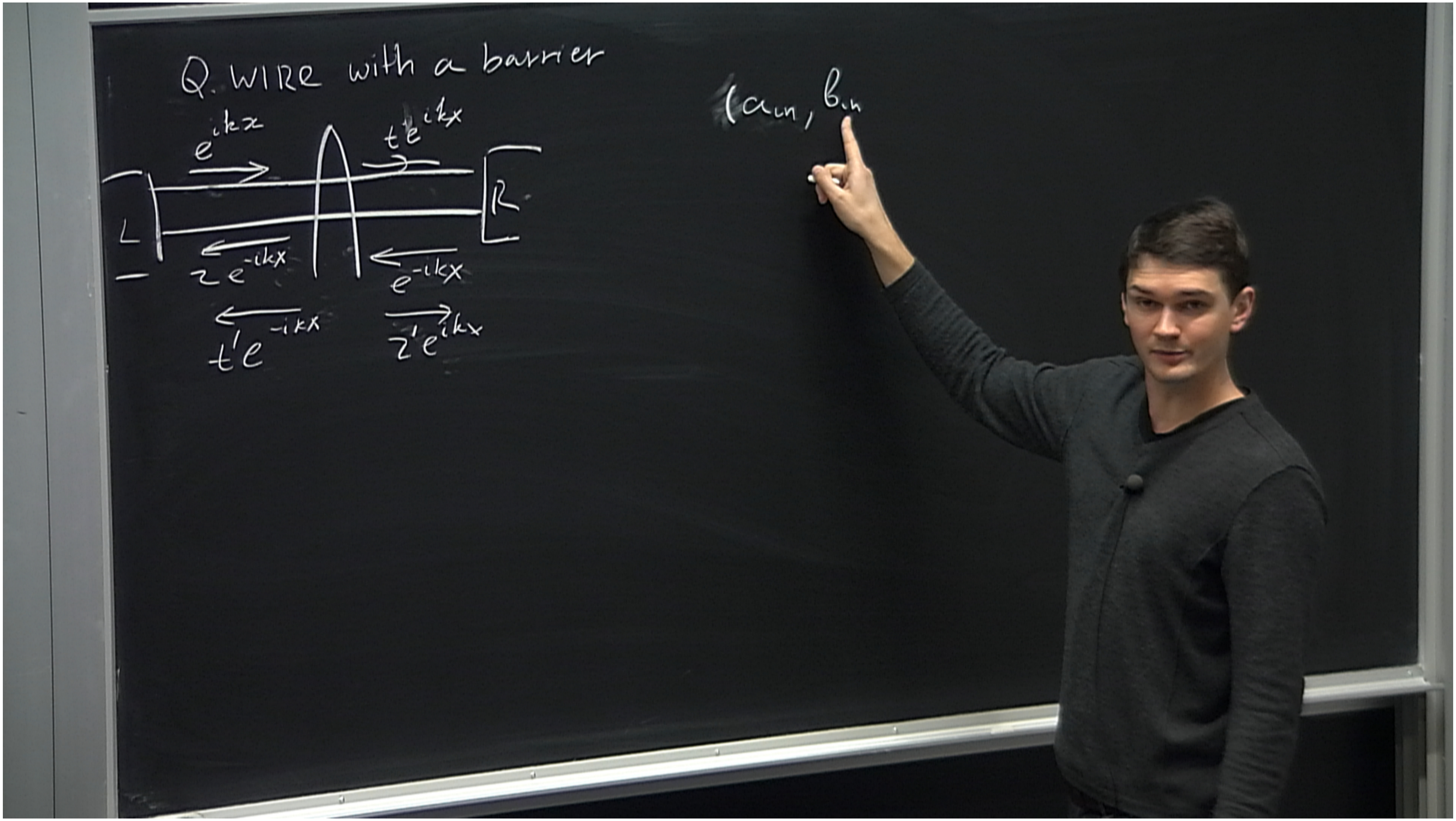
$$I_{R\to L} = e\,\frac{\mu_R}{2\pi\hbar}$$

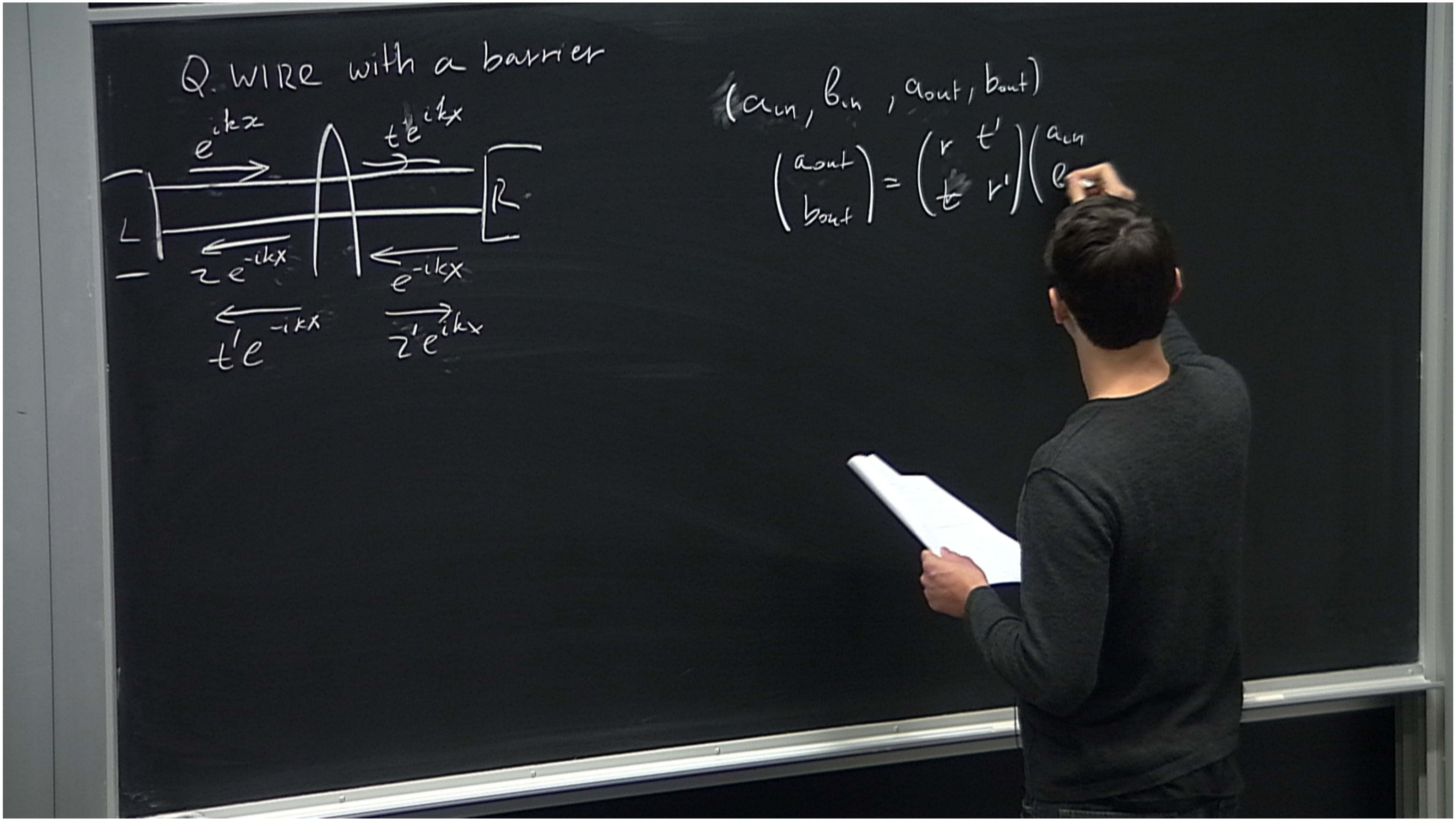
$$I = \frac{e}{2\pi\hbar}(\mu_L-\mu_R) = \frac{e^2}{2\pi\hbar}(V_L - V_R) \qquad G = \frac{I}{V} = \frac{e^2}{2\pi\hbar} \quad \#$$

* Finite
* Fundamental constant
* Heat is dissip. in contacts $\quad W = I^2/G$
* <u>Assumption</u>: equil. in contacts

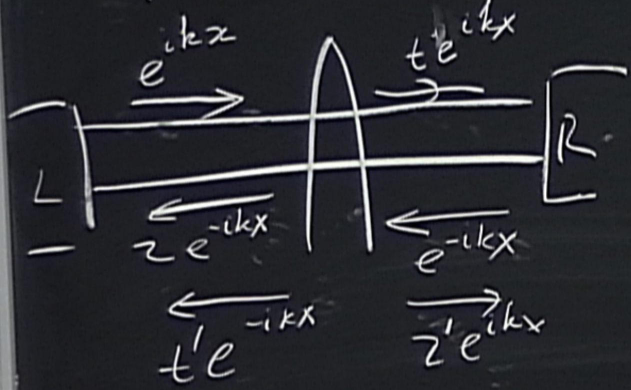


$$\frac{I\,dt}{e}$$


Q. WIRE with a barrier
e^{ikx}
te^{ikx}
L
R
re^{-ikx}
e^{-ikx}
t'e^{-ikx}
r'e^{ikx}
(a_in, b_in


Q. WIRE with a barrier
e^{ikx}
te^{ikx}
L
R
re^{-ikx}
e^{-ikx}
$t'e^{-ikx}$
$r'e^{ikx}$
$(a_{in}, b_{in}, a_{out}, b_{out})$
$\begin{pmatrix} a_{out} \\ b_{out} \end{pmatrix} = \begin{pmatrix} r & t' \\ t & r' \end{pmatrix}$

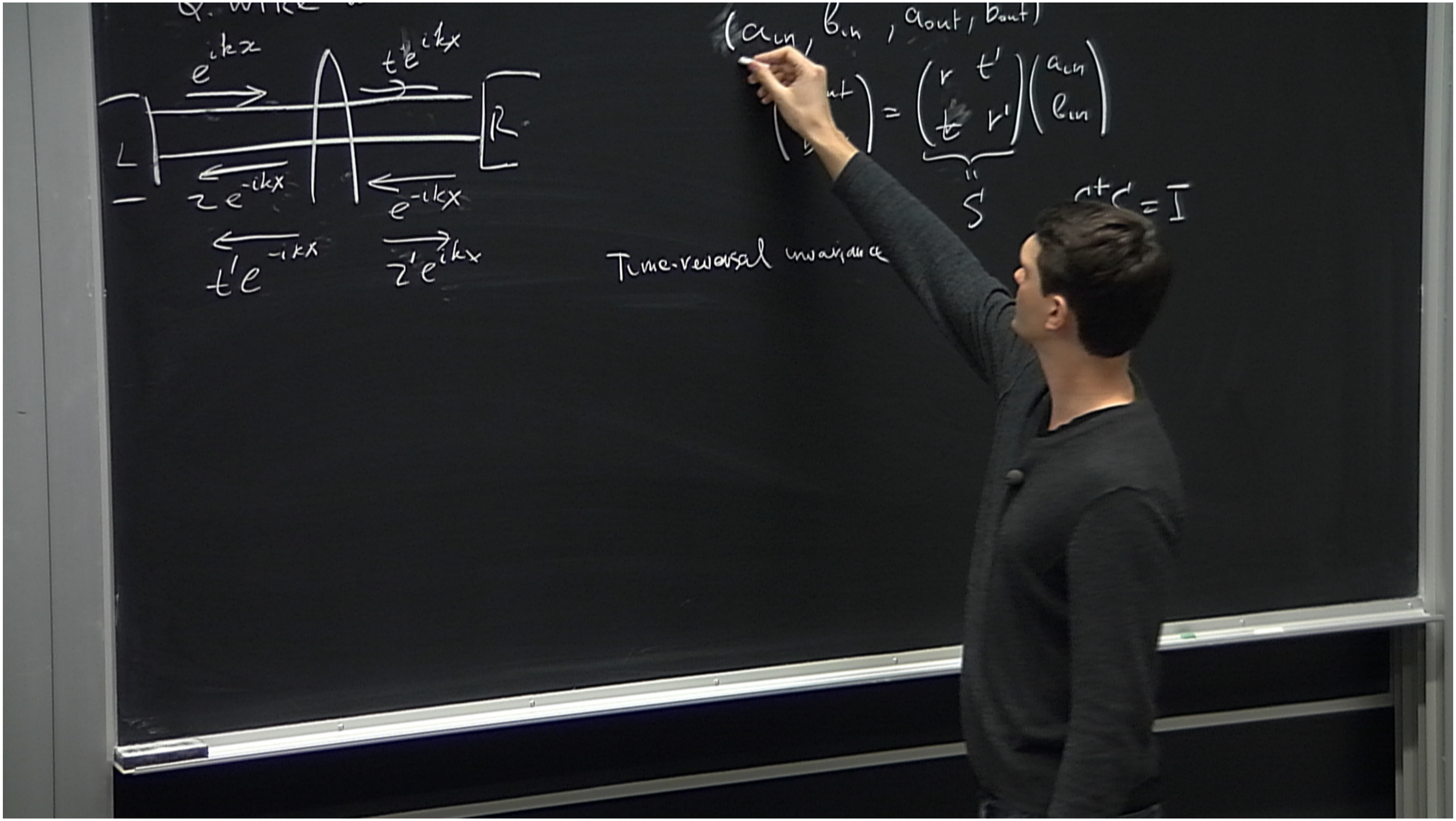
Q. WIRE with a barrier



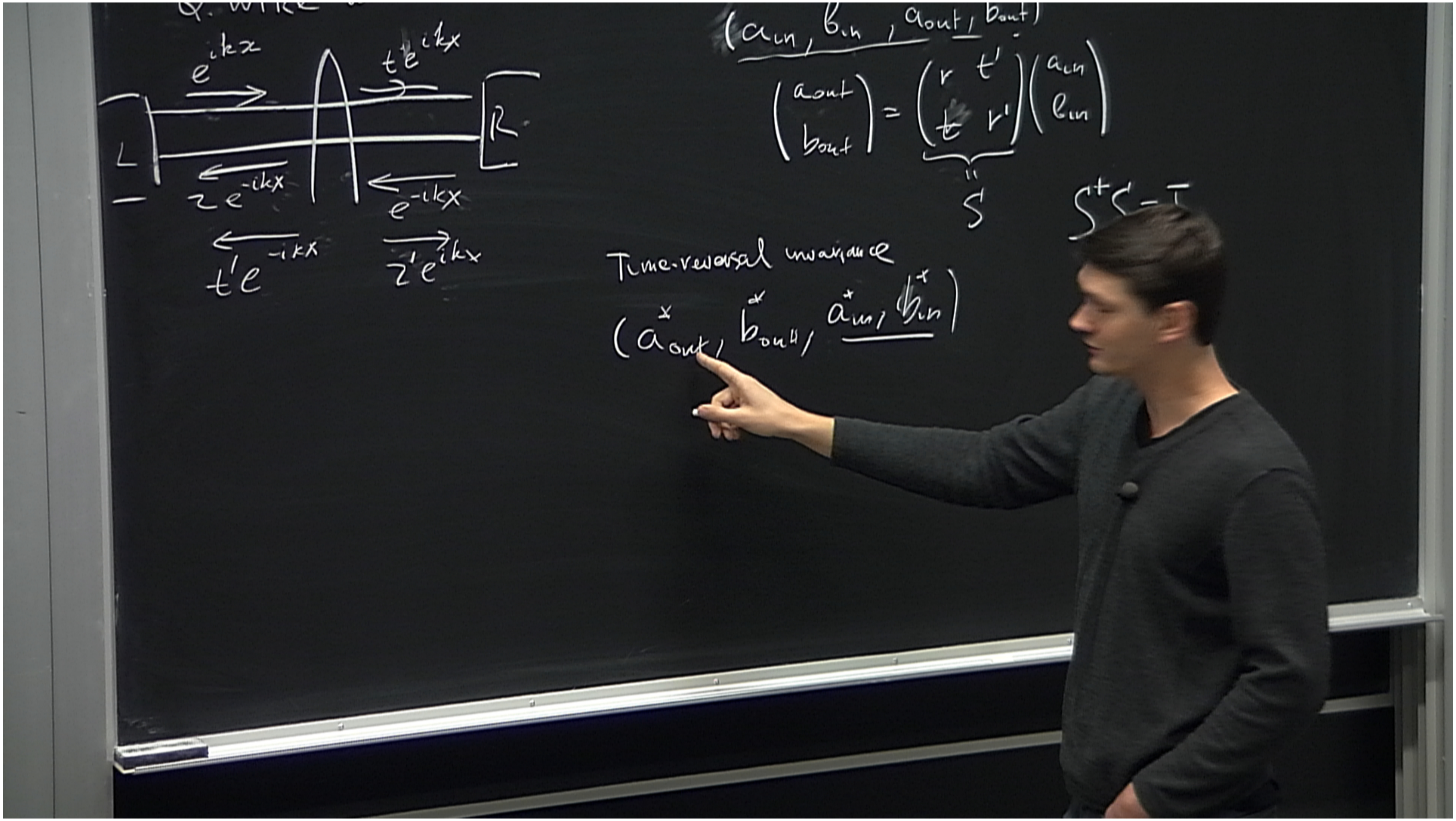
$(a_{in}, b_{in}, a_{out}, b_{out})$

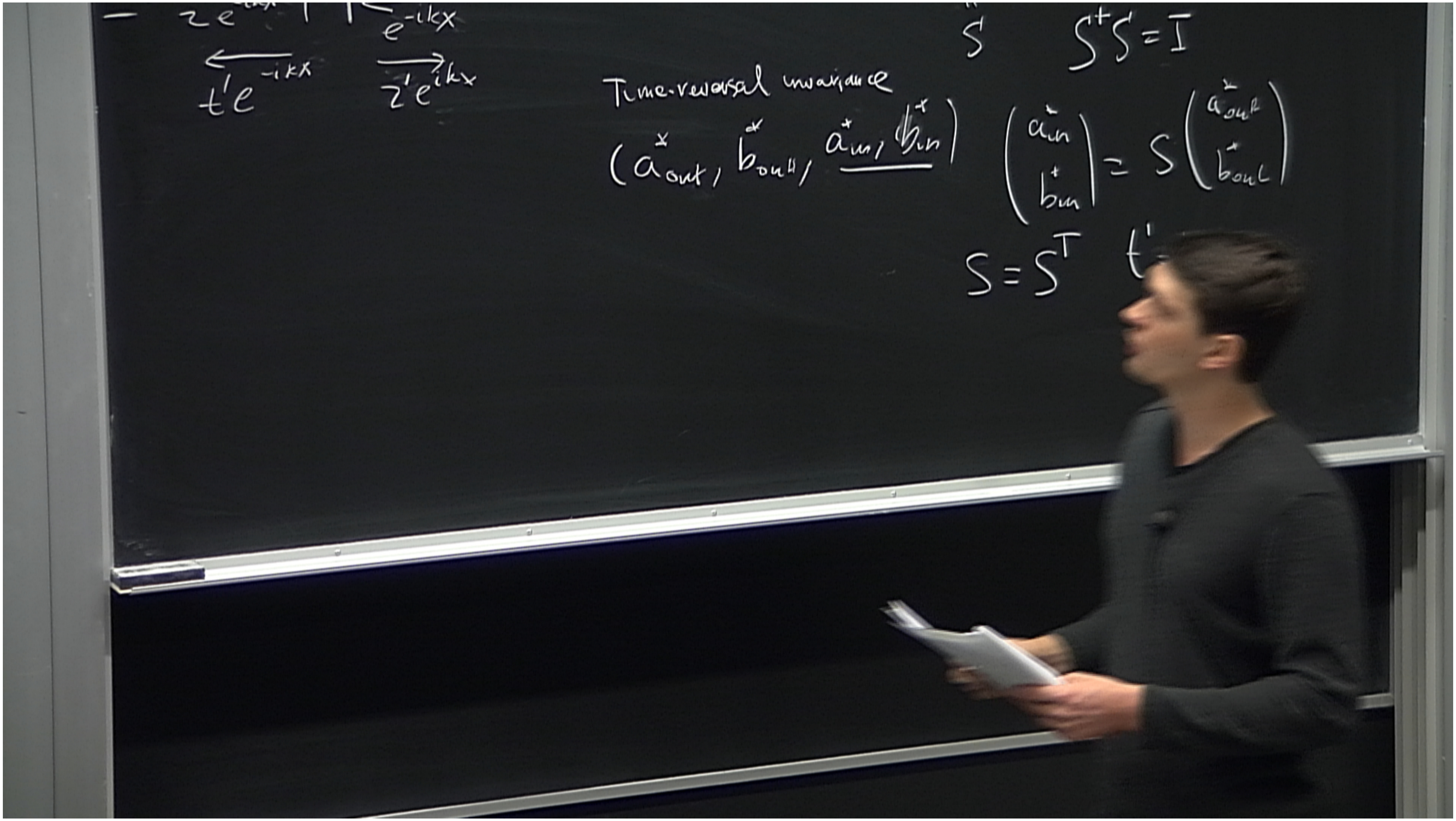
$$\begin{pmatrix} a_{out} \\ b_{out} \end{pmatrix} = \underbrace{\begin{pmatrix} r & t' \\ t & r' \end{pmatrix}}_{= S} \begin{pmatrix} a_{in} \\ b_{in} \end{pmatrix}$$

$$S^{\dagger} S = I$$

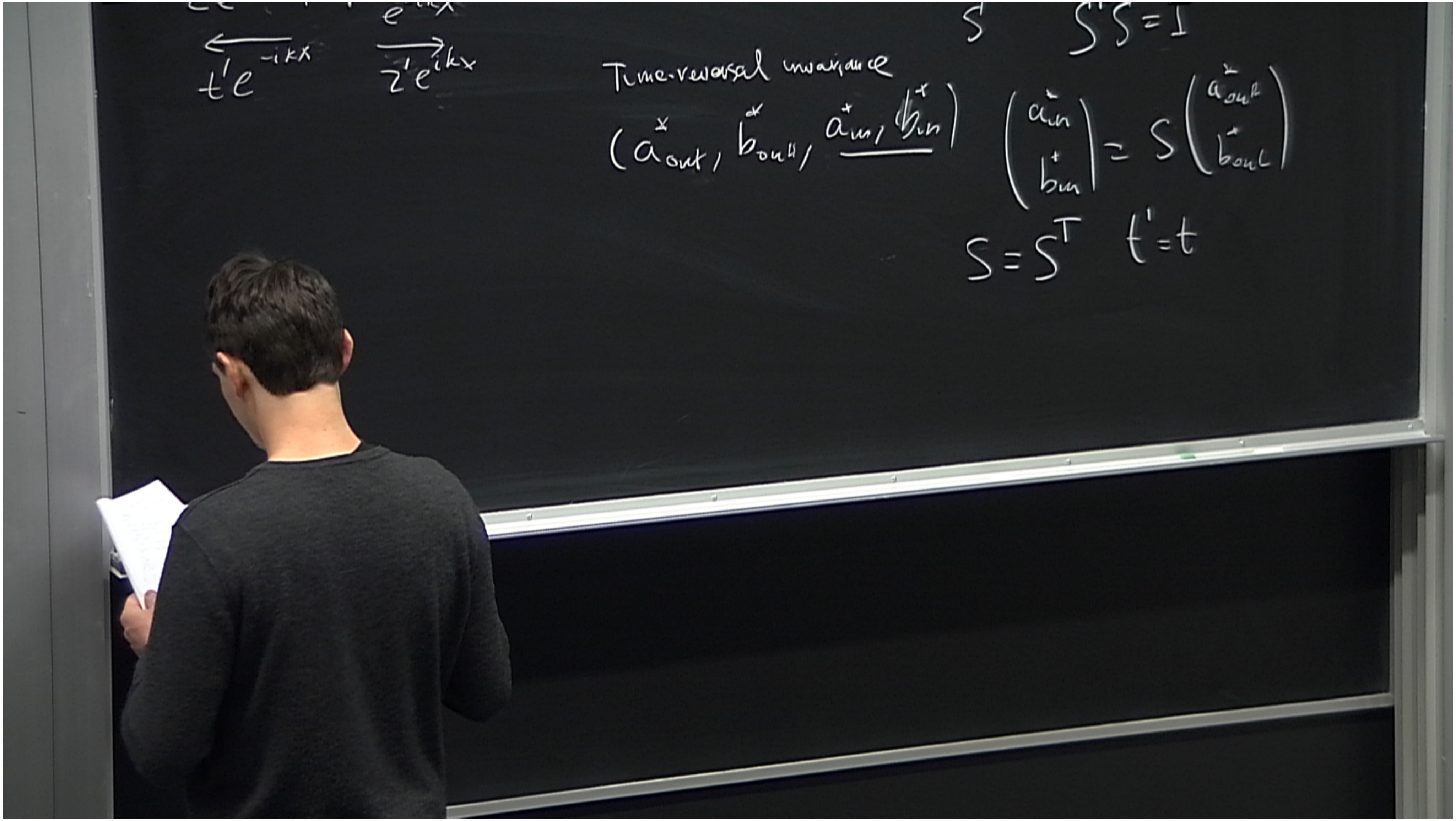


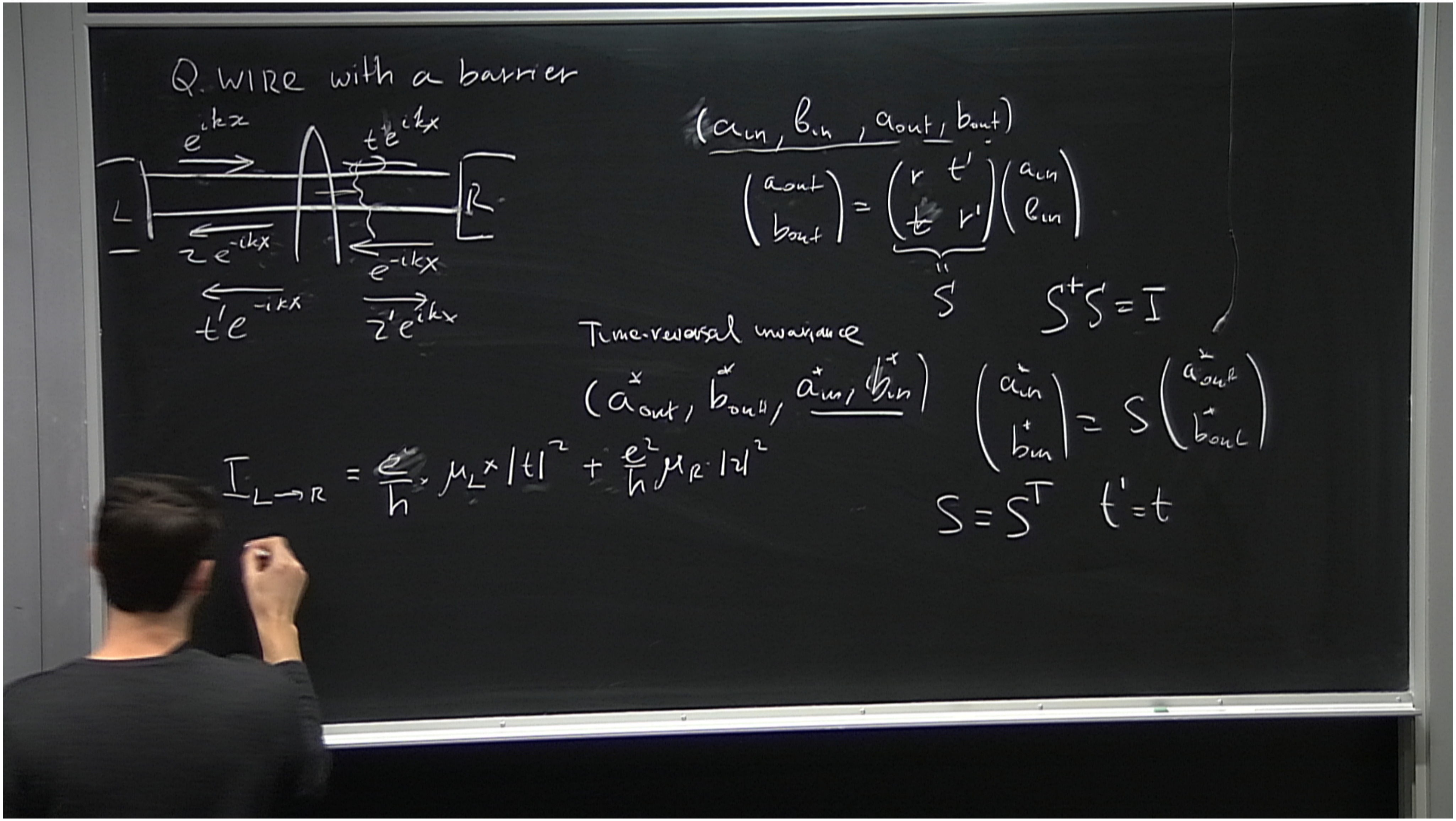
(a_in, b_in, a_out, b_out)
e^ikx
te^ikx
re^-ikx
e^-ikx
t'e^-ikx
r'e^ikx
L
R
r t'
t r'
a_in
b_in
S
S†S = I
Time-reversal invariance

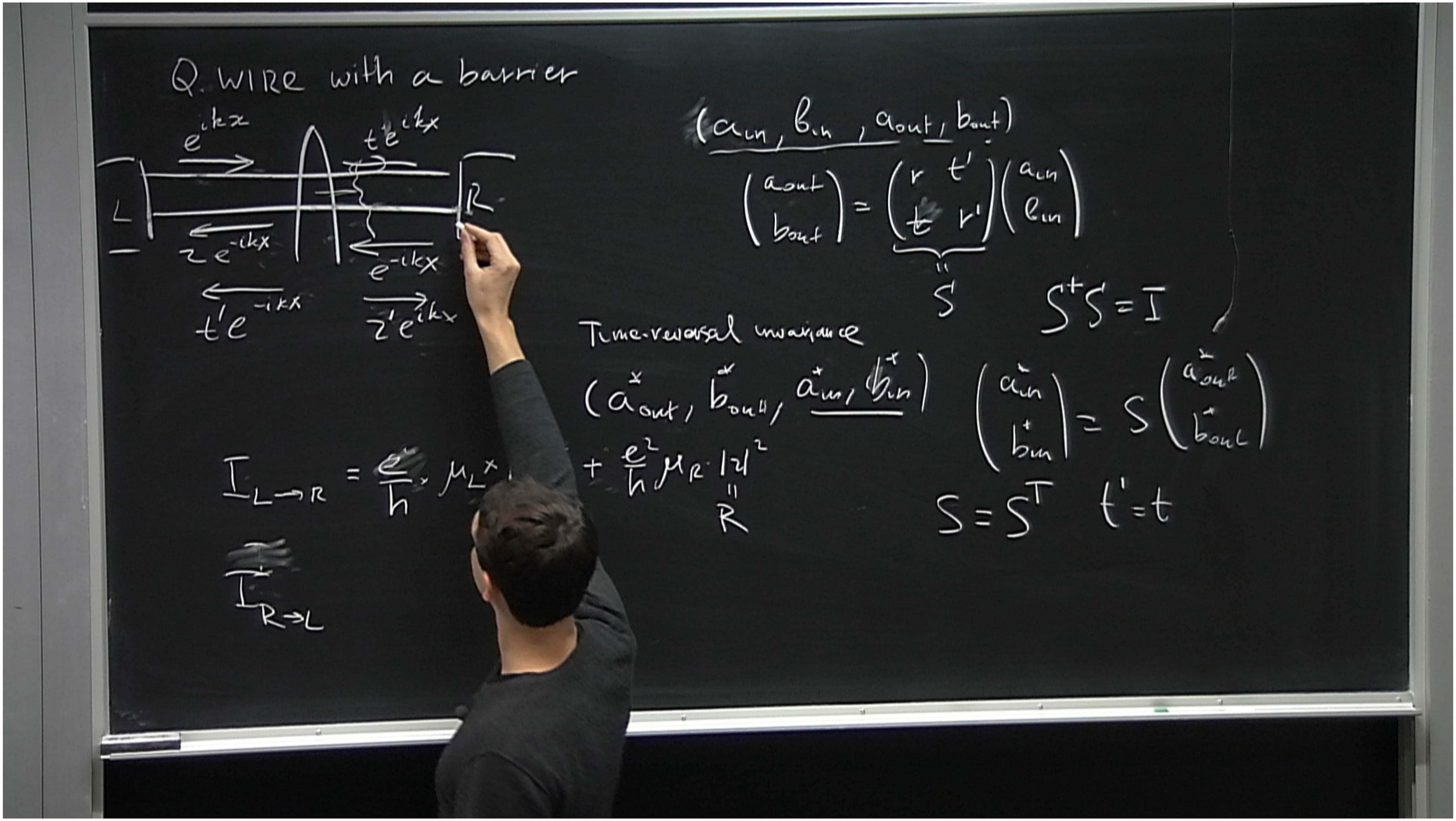

L
R
Time-reversal invariance

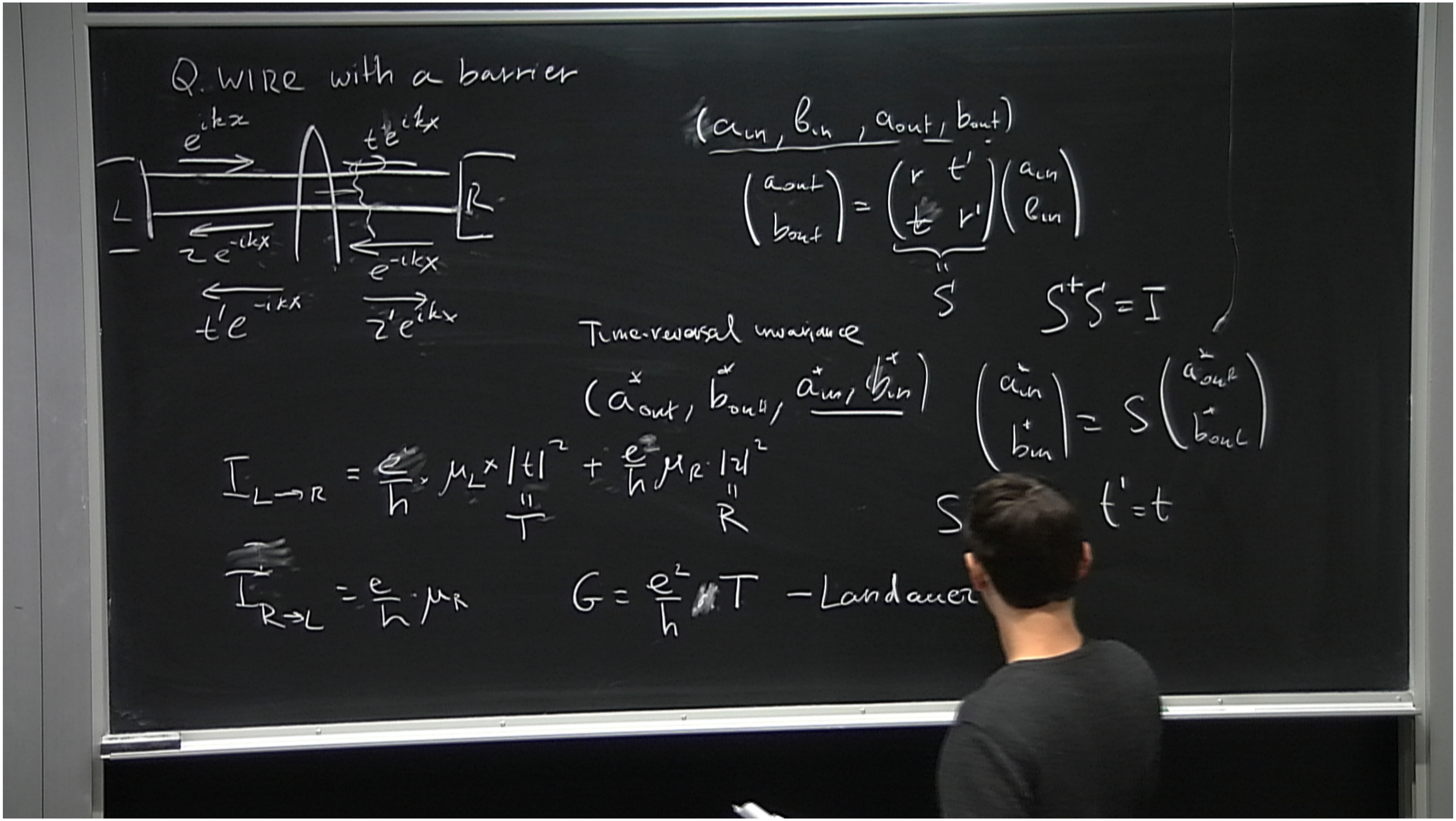


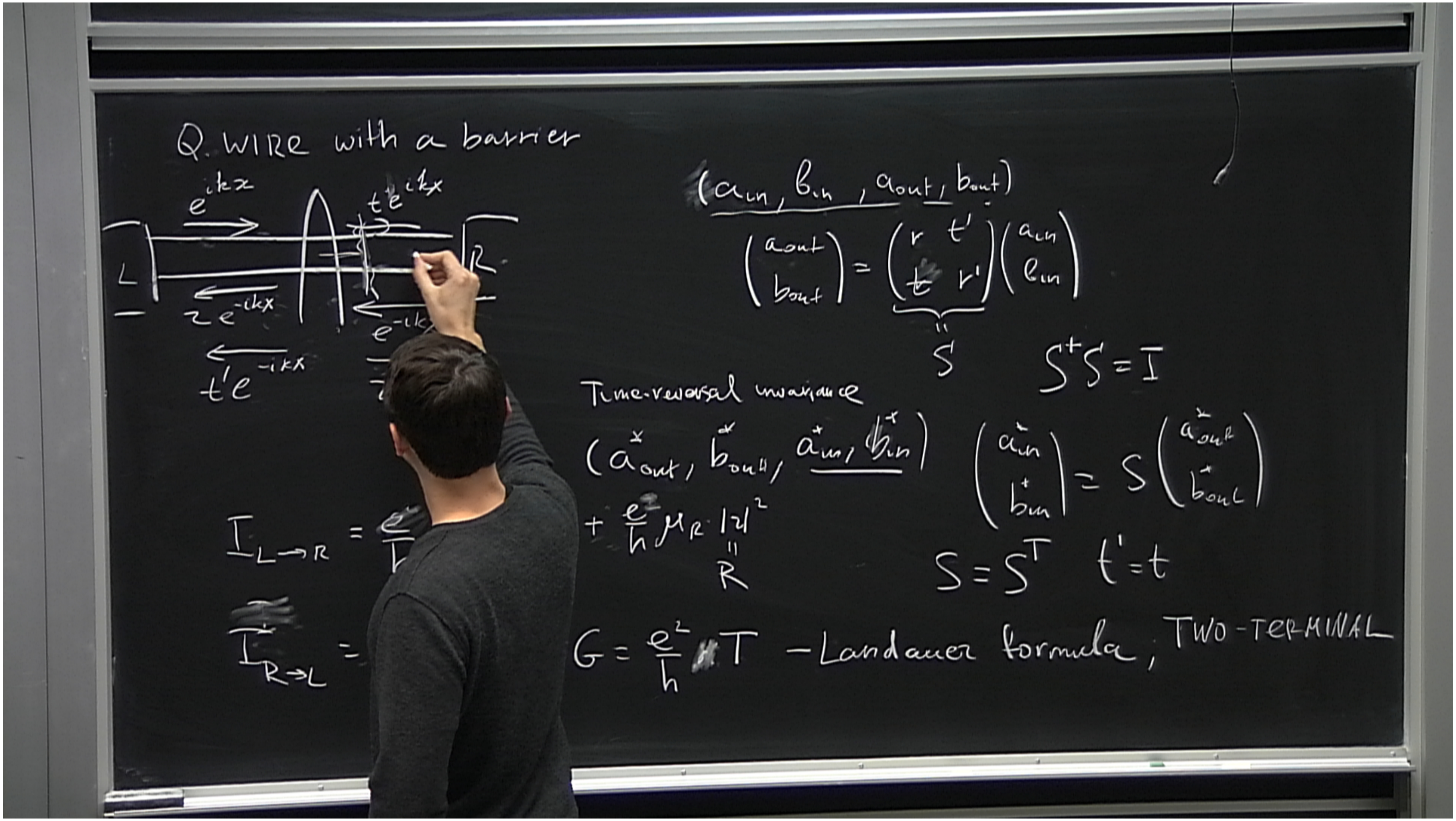
$t'e^{-ikx}$
$r'e^{ikx}$
Time-reversal invariance
$(a^*_{out}, b^*_{out}, a^*_{in}, b^*_{in})$
$S^\dagger S = I$
$\begin{pmatrix} a^*_{in} \\ b^*_{in} \end{pmatrix} = S \begin{pmatrix} a^*_{out} \\ b^*_{out} \end{pmatrix}$
$S = S^T$

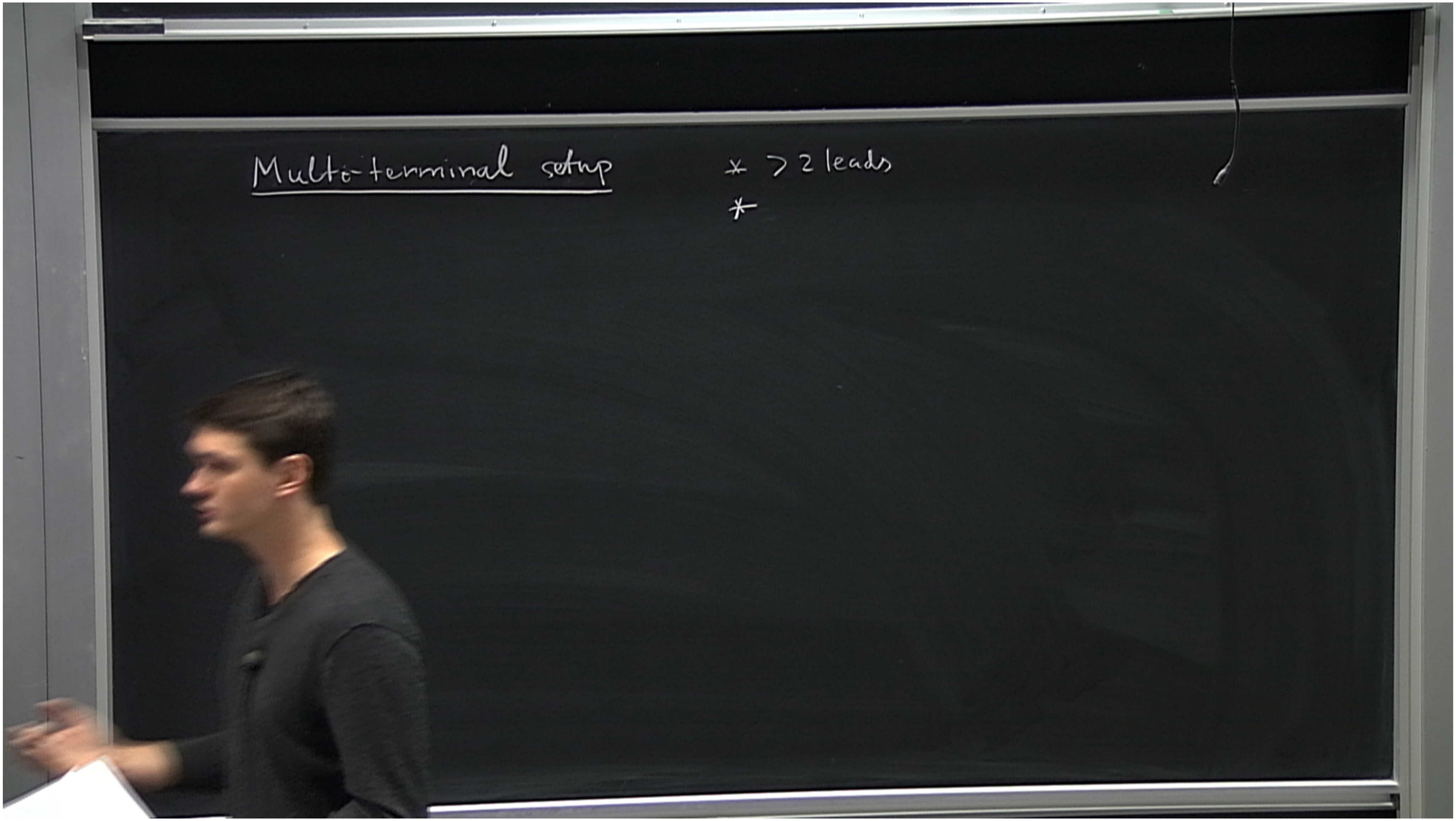

t'e^{-ikx}
r'e^{ikx}
Time-reversal invariance
S=S^T
t'=t

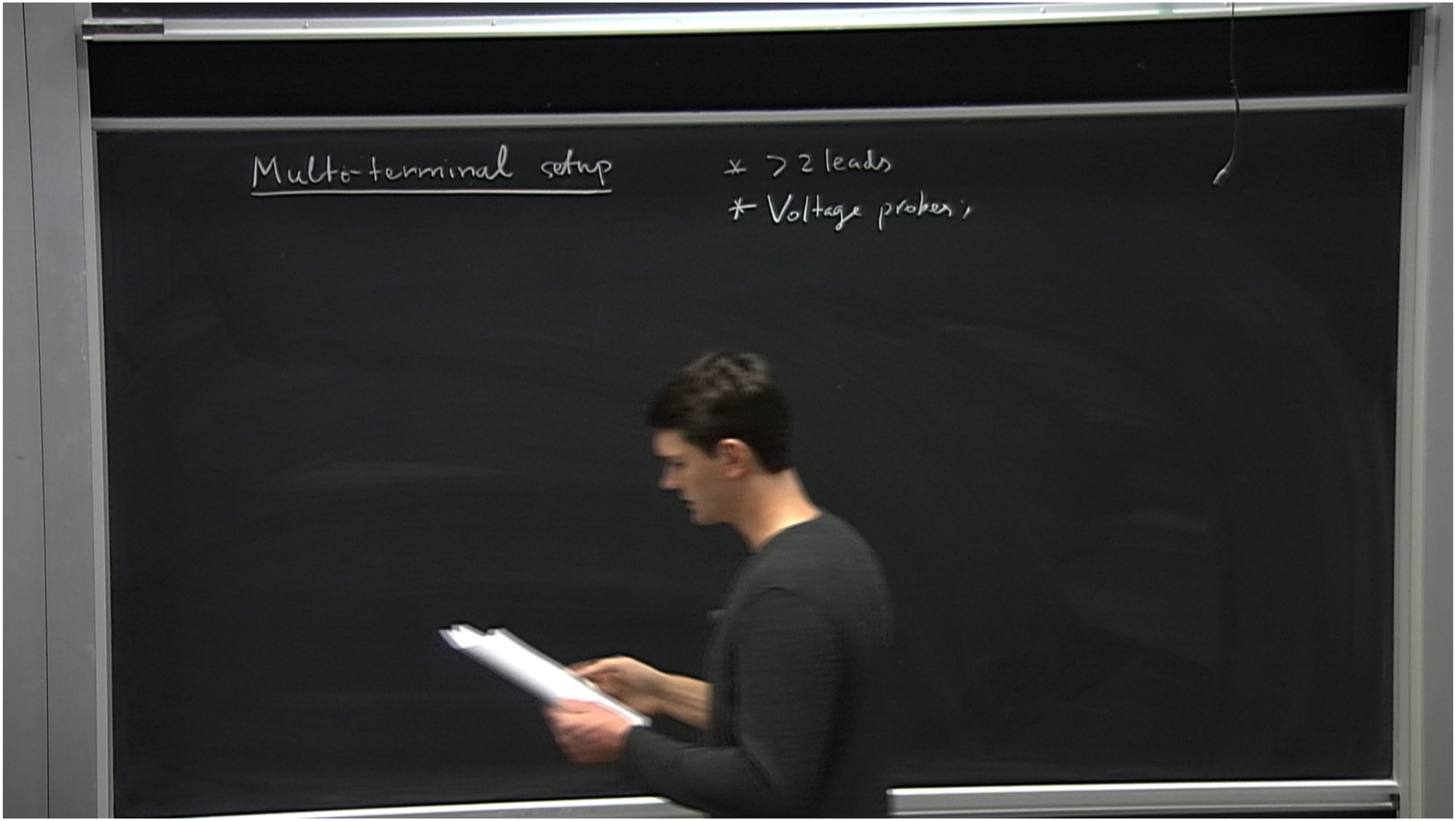

Q. WIRE with a barrier
e^{ikx}
te^{ikx}
re^{-ikx}
e^{-ikx}
$t'e^{-ikx}$
$r'e^{ikx}$
L
R
$(a_{in}, b_{in}, a_{out}, b_{out})$
$\begin{pmatrix} a_{out} \\ b_{out} \end{pmatrix} = \underbrace{\begin{pmatrix} r & t' \\ t & r' \end{pmatrix}}_{= S} \begin{pmatrix} a_{in} \\ b_{in} \end{pmatrix}$
$S^{+}S = I$
Time-reversal invariance
$(a^{*}_{out}, b^{*}_{out}, a^{*}_{in}, b^{*}_{in})$
$\begin{pmatrix} a^{*}_{in} \\ b^{*}_{in} \end{pmatrix} = S \begin{pmatrix} a^{*}_{out} \\ b^{*}_{out} \end{pmatrix}$
$I_{L\to R} = \frac{e}{h} \mu_L \times |t|^2 + \frac{e^2}{h} \mu_R |r|^2$
$S = S^T \quad t' = t$

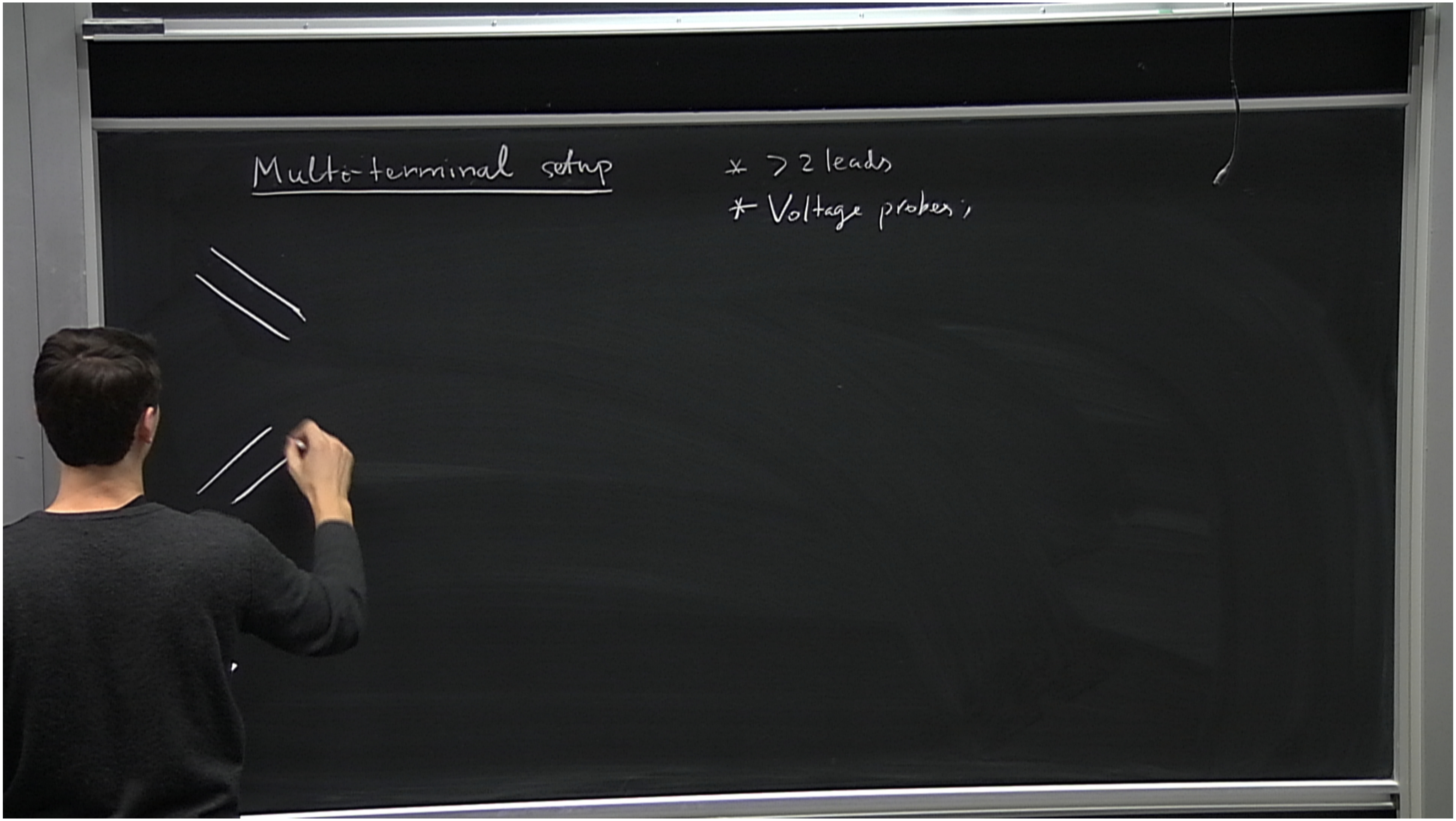

Q. WIRE with a barrier
e^{ikx}
t e^{ikx}
L
R
r e^{-ikx}
e^{-ikx}
t' e^{-ikx}
r' e^{ikx}
(a_in, b_in, a_out, b_out)
(a_out b_out) = (r t' ; t r') (a_in b_in)
S
S^+ S = I
Time-reversal invariance
(a*_out, b*_out, a*_in, b*_in)
(a*_in b*_in) = S (a*_out b*_out)
S = S^T   t' = t
I_{L→R} = e²/h μ_L
+ e²/h μ_R |r|²
R
I_{R→L}

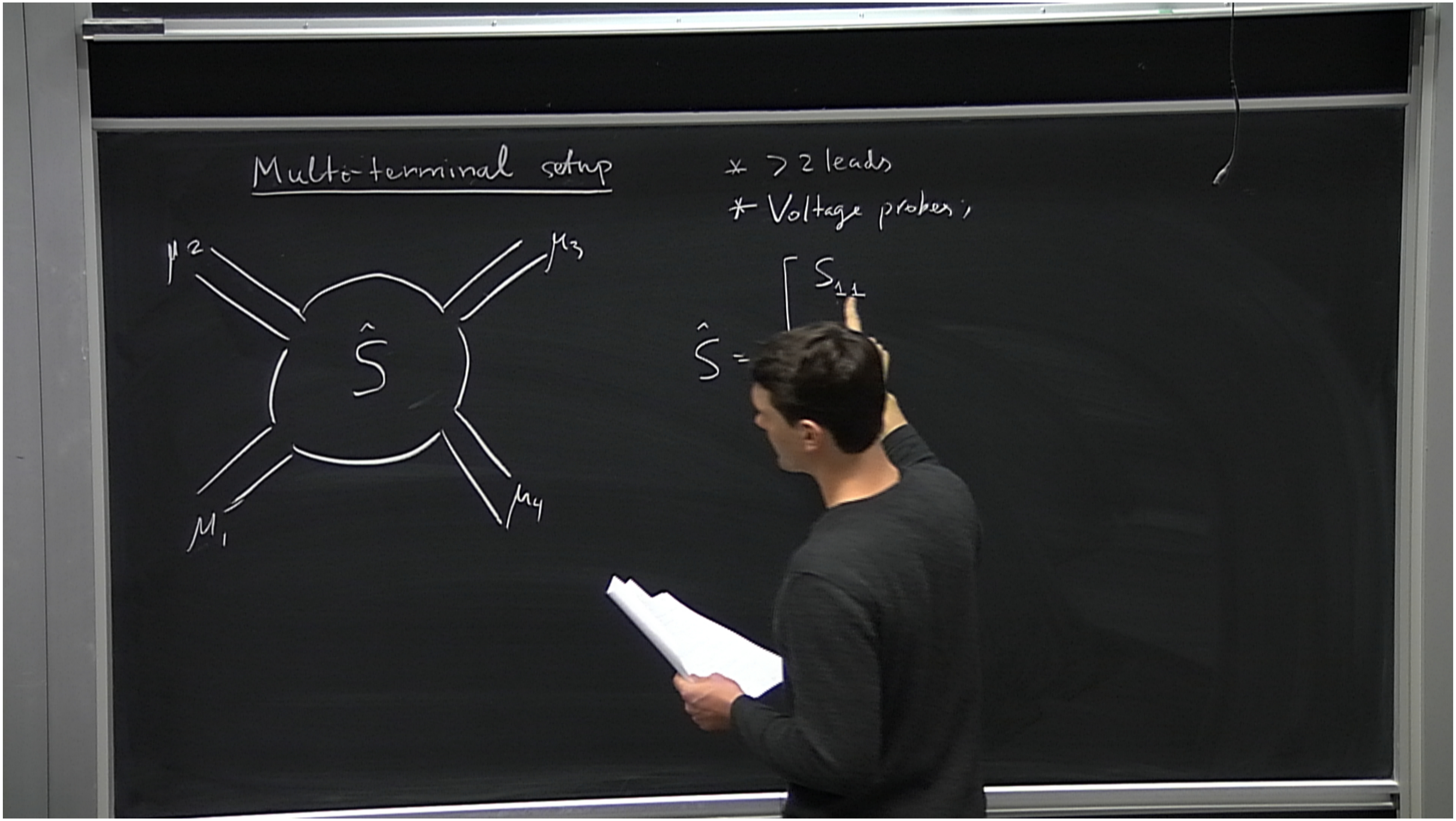

Q. WIRE with a barrier
e^{ikx}
t e^{ikx}
L
R
r e^{-ikx}
e^{-ikx}
t' e^{-ikx}
r' e^{ikx}
(a_in, b_in, a_out, b_out)
(a_out, b_out) = (r t' ; t r') (a_in, b_in)
S
S† S = I
Time-reversal invariance
(a*_out, b*_out, a*_in, b*_in)
(a*_in, b*_in) = S (a*_out, b*_out)
I_{L→R} = e/h · μ_L × |t|² + e/h μ_R · |r|²
T
R
I_{R→L} = e/h · μ_R
G = e²/h T — Landauer
S
t' = t

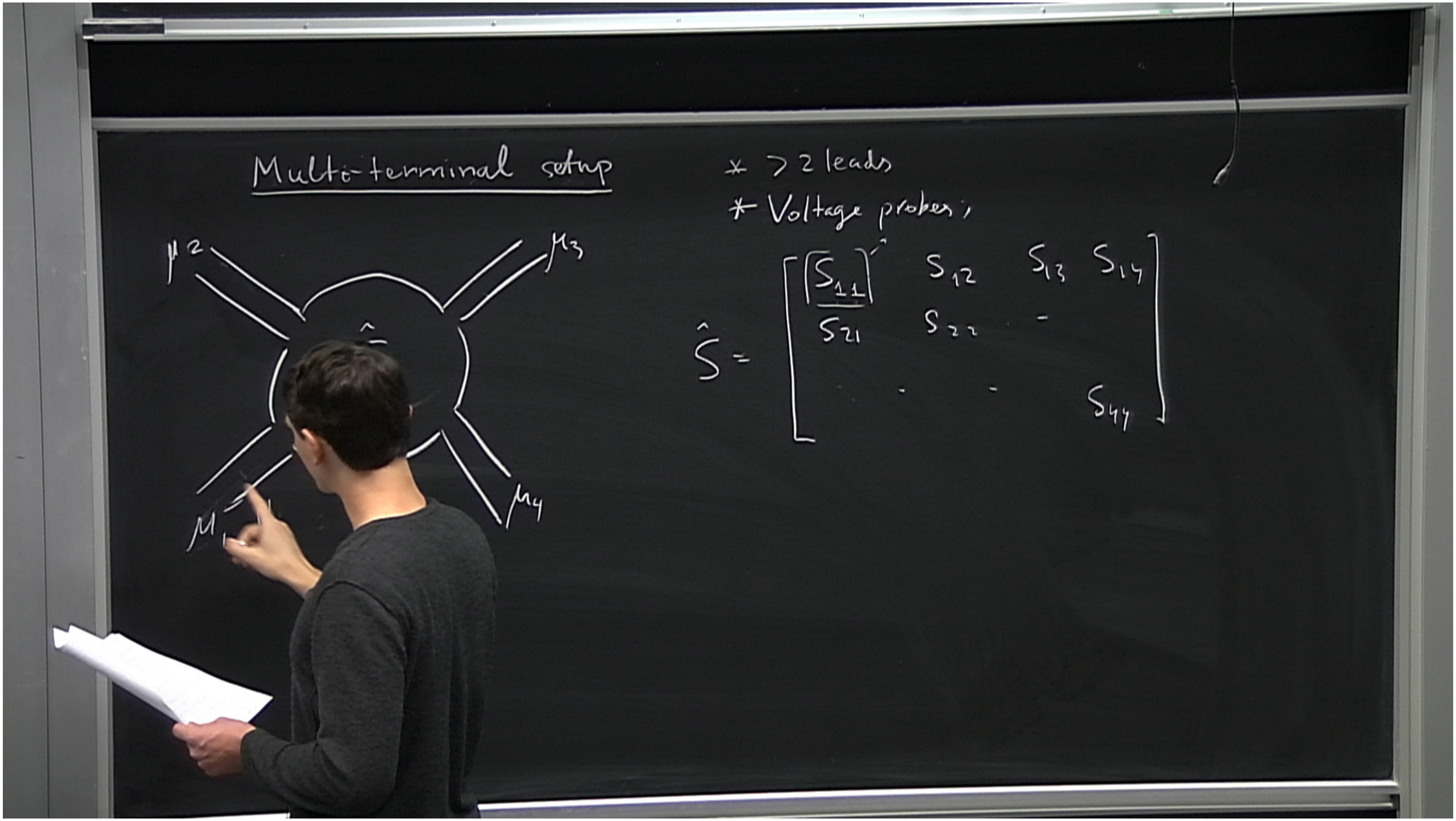

Q. WIRE with a barrier
e^{ikx}
te^{ikx}
L
R
re^{-ikx}
e^{-ikx}
$t'e^{-ikx}$
$(a_{in}, b_{in}, a_{out}, b_{out})$
$\begin{pmatrix} a_{out} \\ b_{out} \end{pmatrix} = \underbrace{\begin{pmatrix} r & t' \\ t & r' \end{pmatrix}}_{S} \begin{pmatrix} a_{in} \\ b_{in} \end{pmatrix}$
$S^{+}S = I$
Time-reversal invariance
$(a^{*}_{out}, b^{*}_{out}, a^{*}_{in}, b^{*}_{in})$
$\begin{pmatrix} a^{*}_{in} \\ b^{*}_{in} \end{pmatrix} = S \begin{pmatrix} a^{*}_{out} \\ b^{*}_{out} \end{pmatrix}$
$S = S^{T} \quad t' = t$
$I_{L\to R} = \frac{e}{h} \ldots + \frac{e}{h}\mu_R |r|^2 = R$
$I_{R\to L} =$
$G = \frac{e^2}{h} T$ – Landauer formula, TWO-TERMINAL

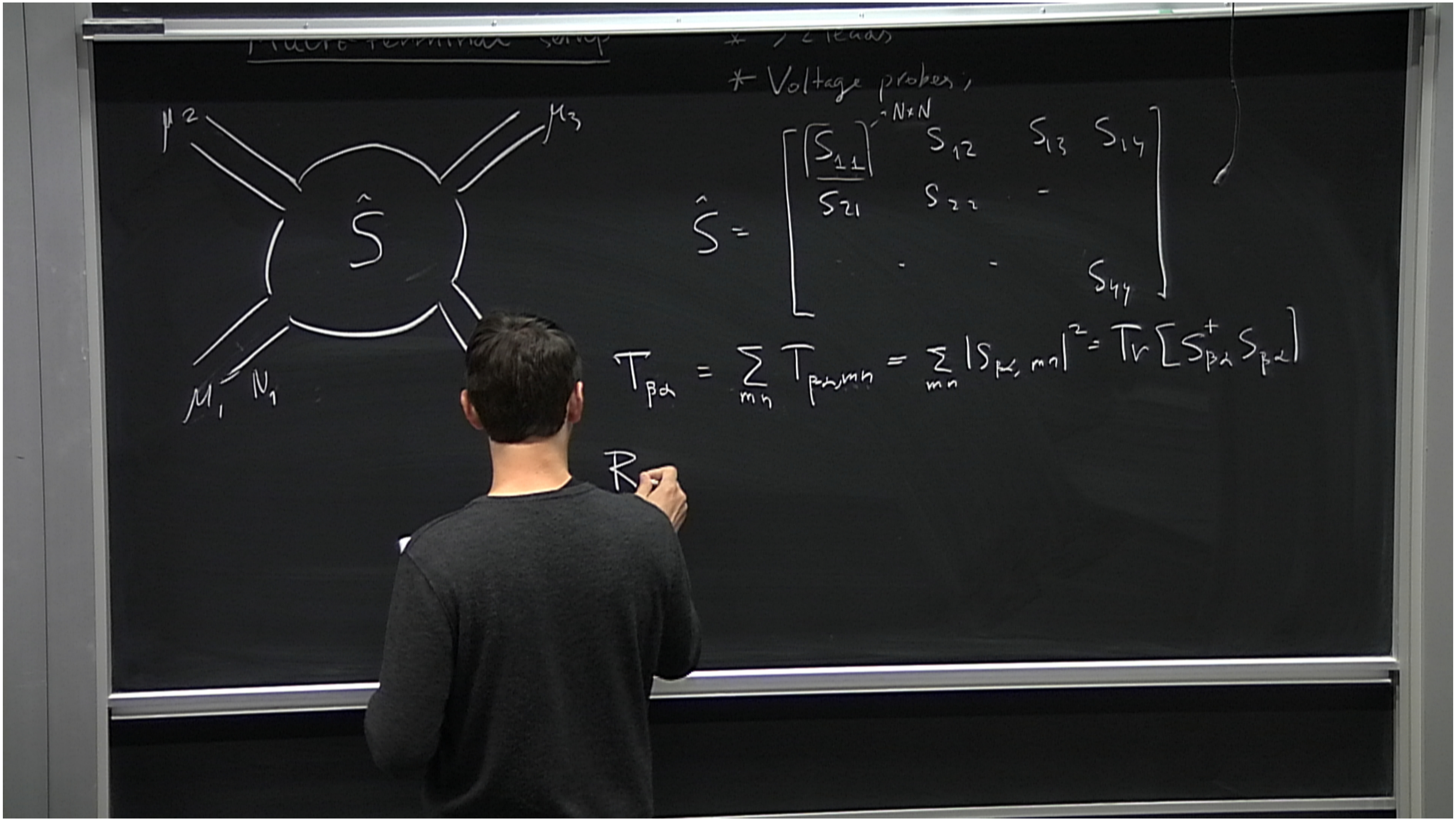

Multi-terminal setup
* > 2 leads
*

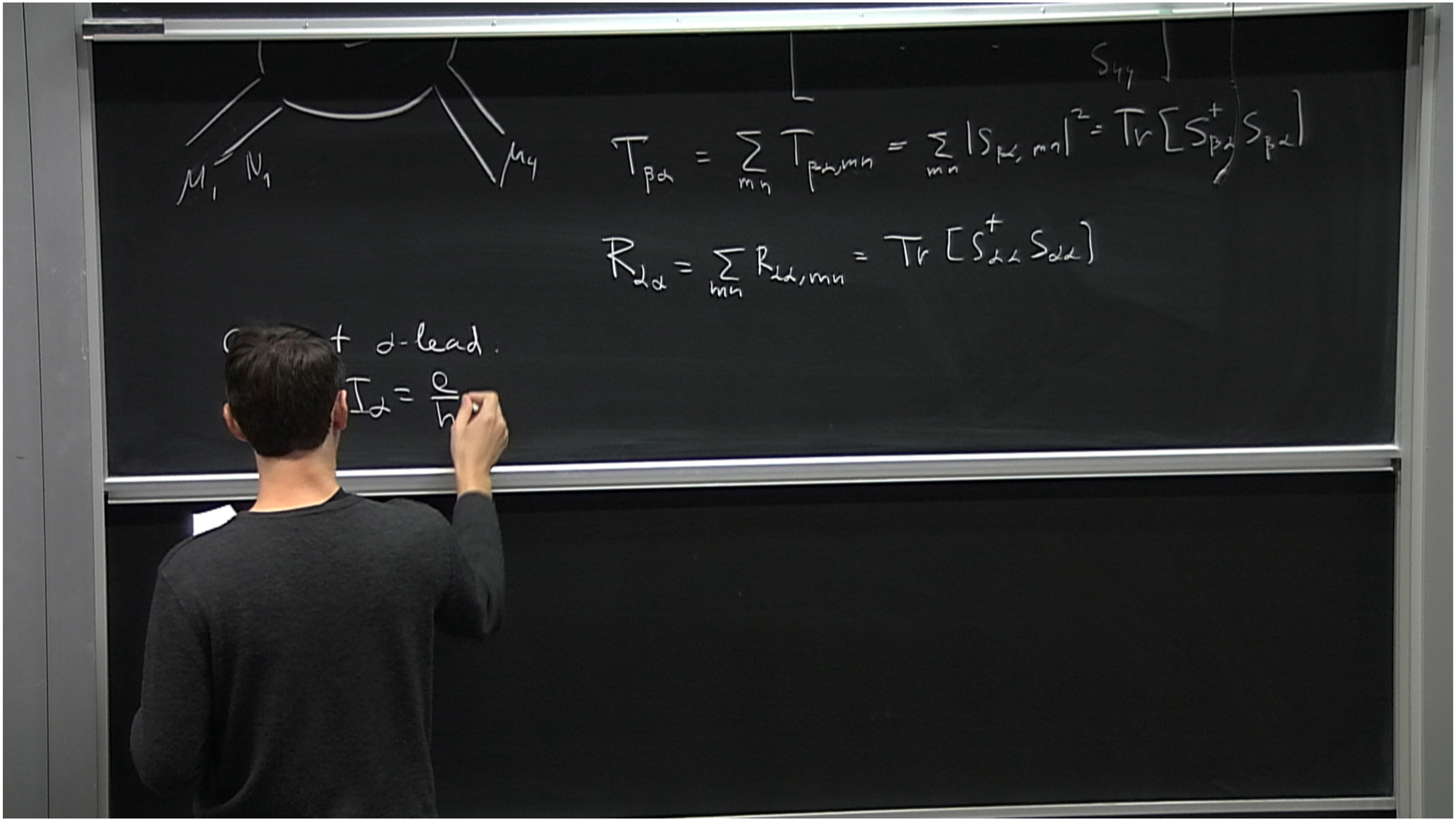

Multi-terminal setup
* > 2 leads
* Voltage probes;


Multi-terminal setup
* > 2 leads
* Voltage probes;


Multi-terminal setup
* > 2 leads
* Voltage probes ;
μ2
μ3
Ŝ
μ1
μ4
Ŝ =
S11


Multi-terminal setup
* > 2 leads
* Voltage probes;
μ2
μ3
μ4
Ŝ =
S11 S12 S13 S14
S21 S22
S44


* Voltage probes;
N×N
$\hat{S} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & \cdot & \\ & \cdot & \cdot & S_{44} \end{bmatrix}$
$\hat{S}$
μ_2
μ_3
μ_1
N_1
$T_{\beta\alpha} = \sum_{mn} T_{\beta\alpha,mn} = \sum_{mn} |S_{\beta\alpha,mn}|^2 = \mathrm{Tr}[S^\dagger_{\beta\alpha} S_{\beta\alpha}]$
R


S_{44}
μ_1 N_1
μ_4
$T_{\beta\alpha} = \sum_{mn} T_{\beta\alpha,mn} = \sum_{mn} |S_{\beta\alpha,mn}|^2 = \mathrm{Tr}[S^{\dagger}_{\beta\alpha} S_{\beta\alpha}]$
$R_{\alpha\alpha} = \sum_{mn} R_{\alpha\alpha,mn} = \mathrm{Tr}[S^{\dagger}_{\alpha\alpha} S_{\alpha\alpha}]$
t α-lead:
$I_\alpha = \frac{e}{h}$

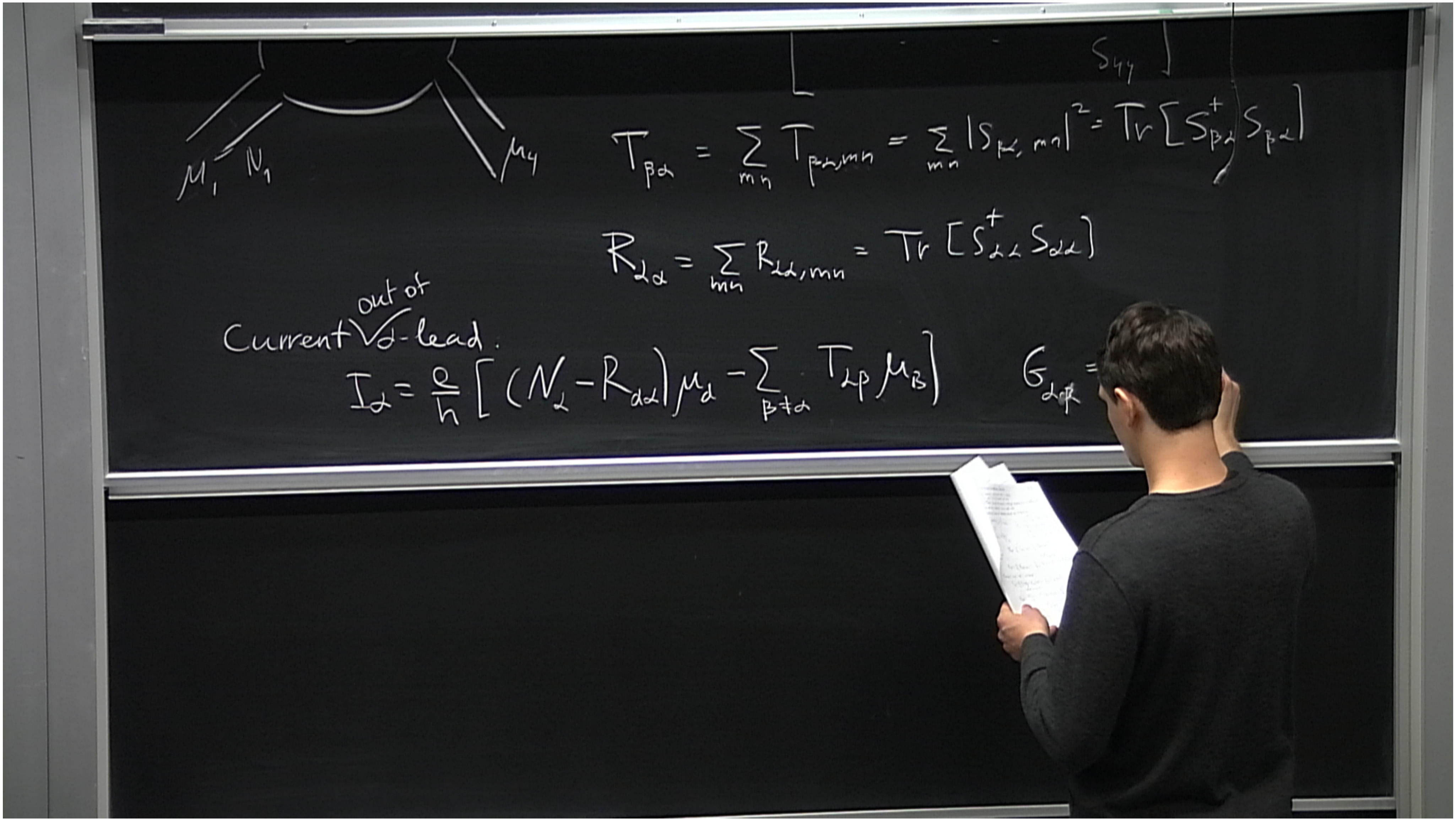
$$\left[\quad \cdots \quad S_{44} \right]$$

$$T_{\beta\alpha} = \sum_{mn} T_{\beta\alpha,mn} = \sum_{mn} |S_{\beta\alpha,mn}|^2 = \mathrm{Tr}\left[S^{\dagger}_{\beta\alpha} S_{\beta\alpha}\right]$$

$$R_{\alpha\alpha} = \sum_{mn} R_{\alpha\alpha,mn} = \mathrm{Tr}\left[S^{\dagger}_{\alpha\alpha} S_{\alpha\alpha}\right]$$

Current out of α-lead.

$$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$$

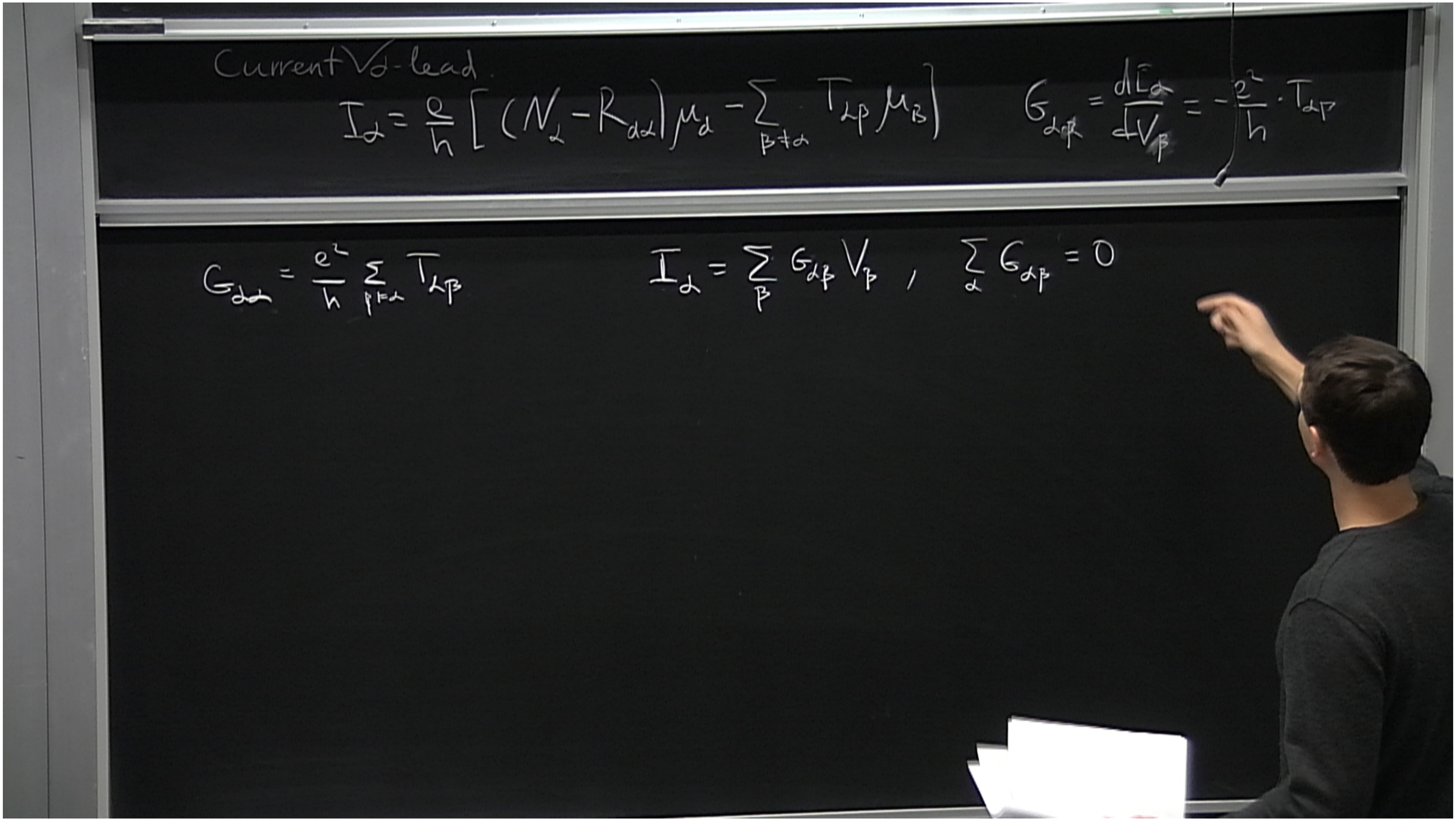

S_{44}
μ_1 N_1 μ_4
$T_{\beta\alpha} = \sum_{mn} T_{\beta\alpha,mn} = \sum_{mn} |S_{\beta\alpha,mn}|^2 = Tr[S^\dagger_{\beta\alpha} S_{\beta\alpha}]$
$R_{\alpha\alpha} = \sum_{mn} R_{\alpha\alpha,mn} = Tr[S^\dagger_{\alpha\alpha} S_{\alpha\alpha}]$
Current out of α-lead.
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\right]$
$G_{\alpha\beta} =$

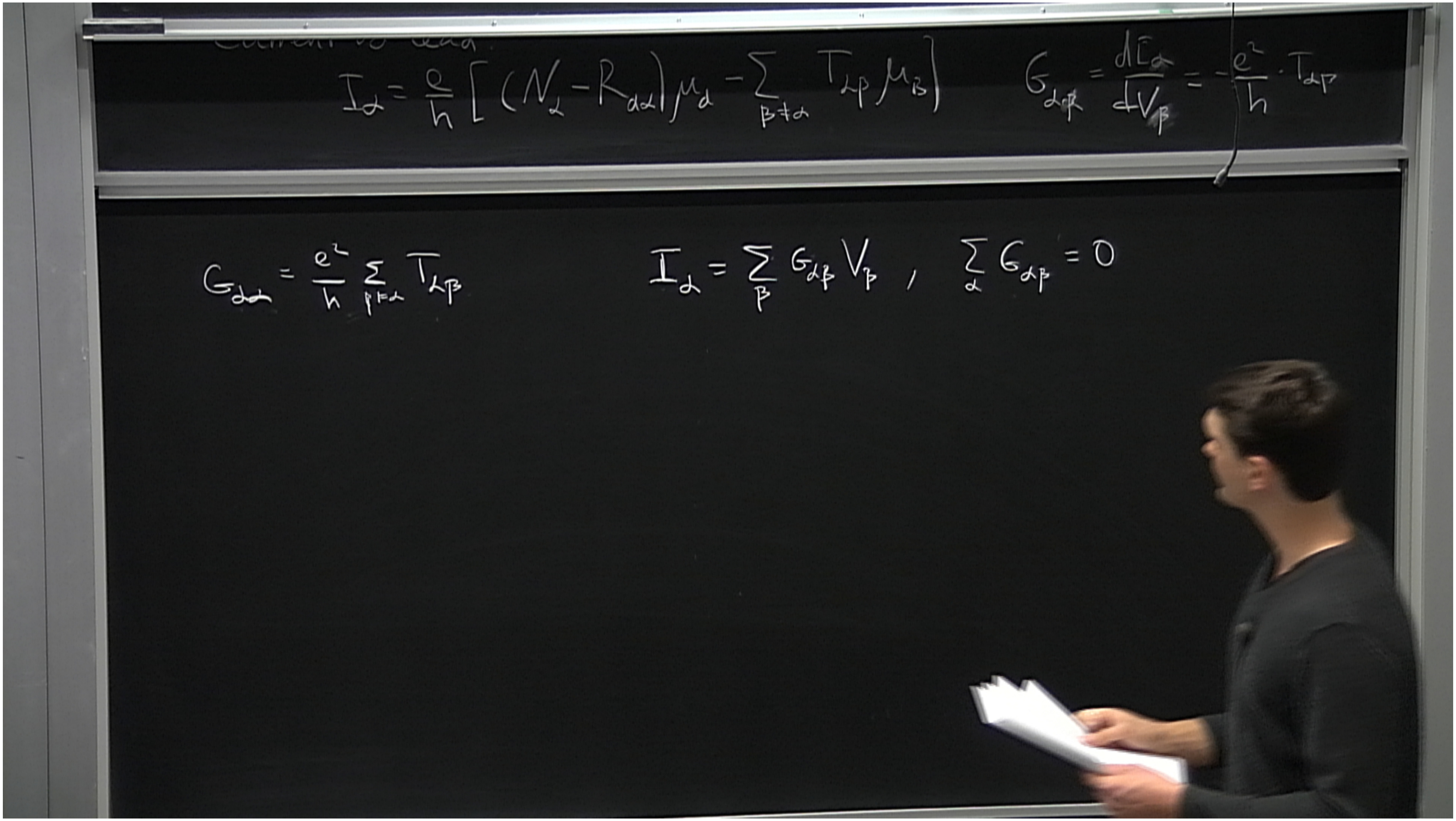
Current $\forall\alpha$-lead.

$$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\right]$$

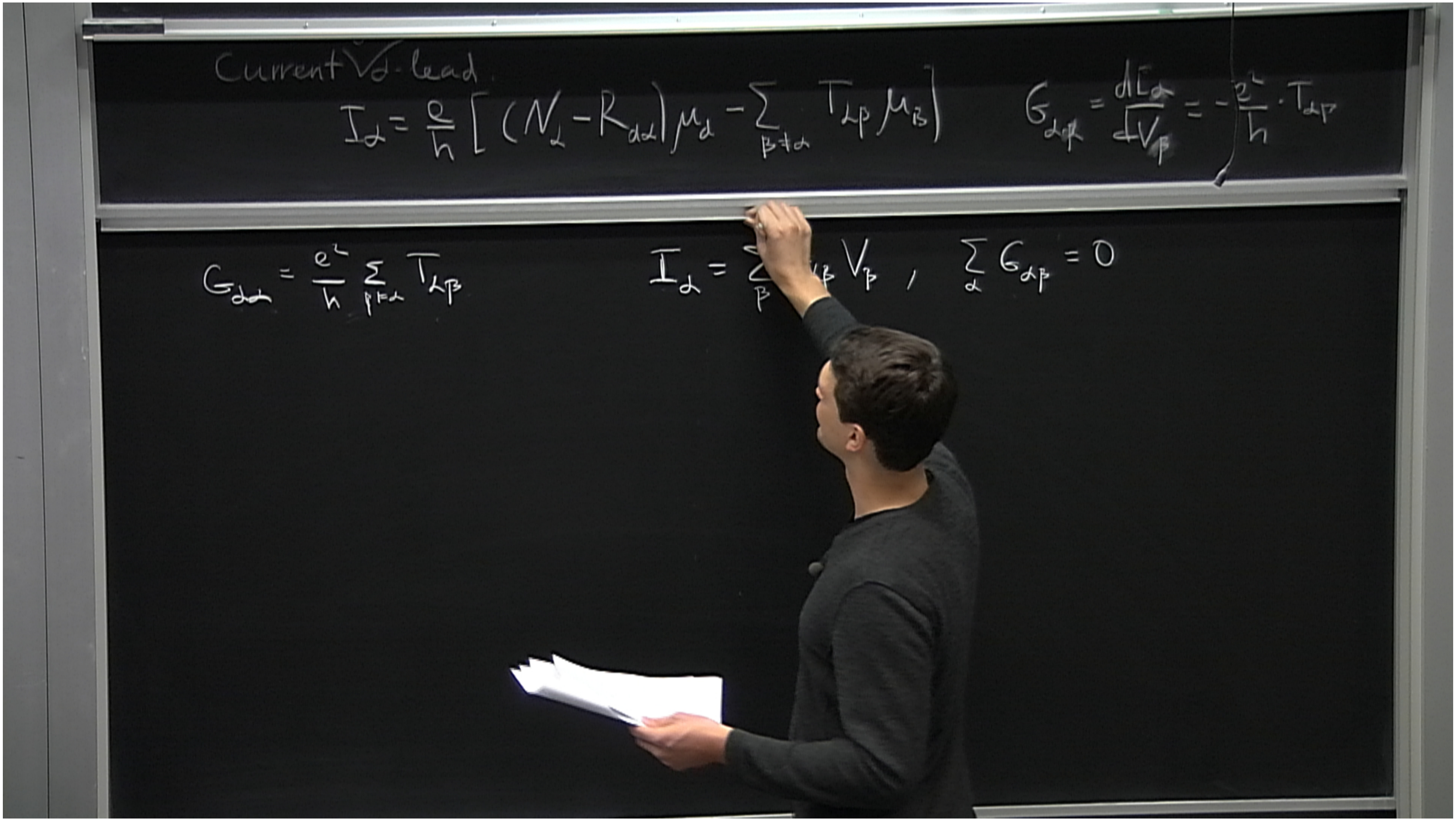
$$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$$

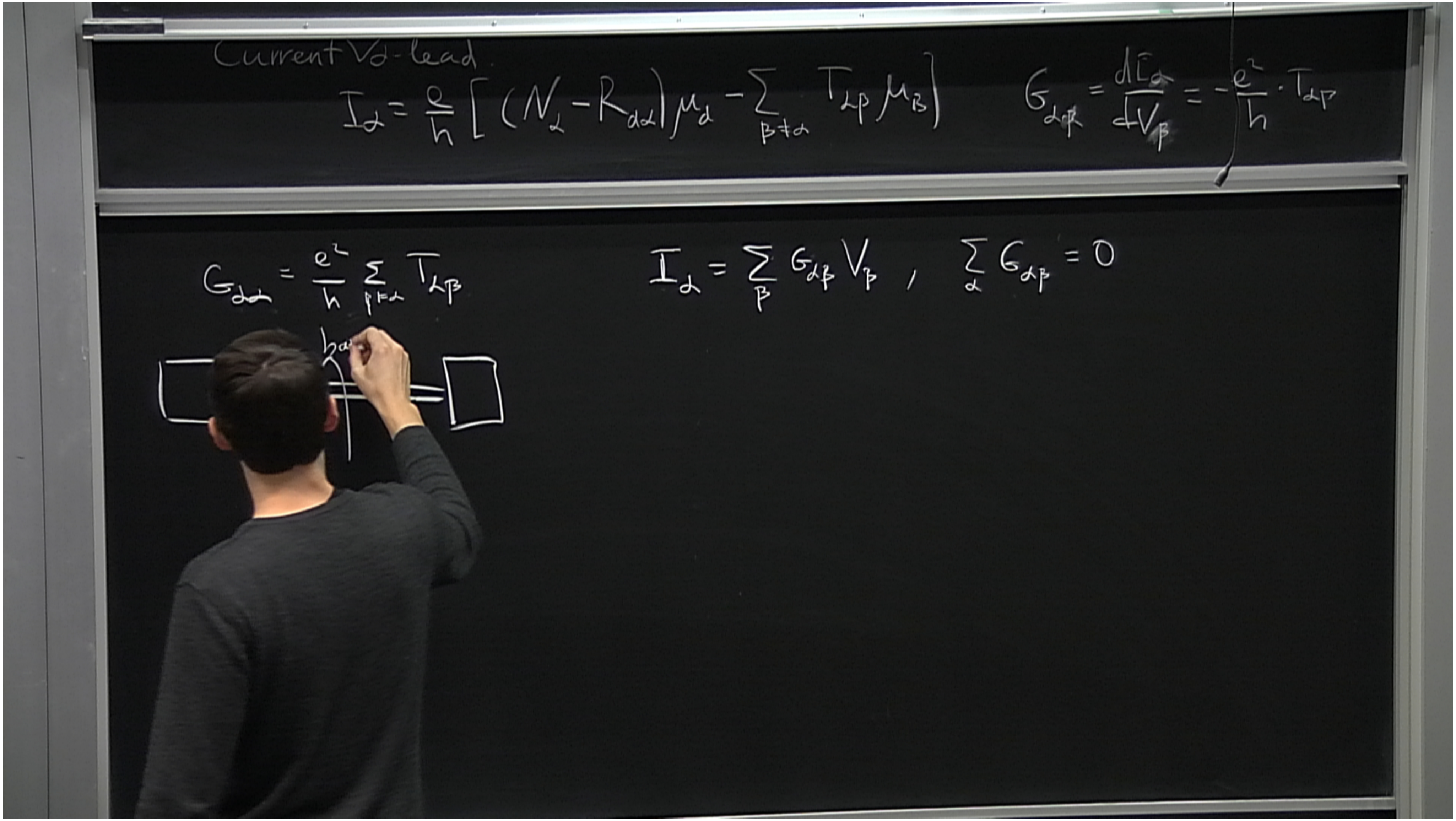
$$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$$

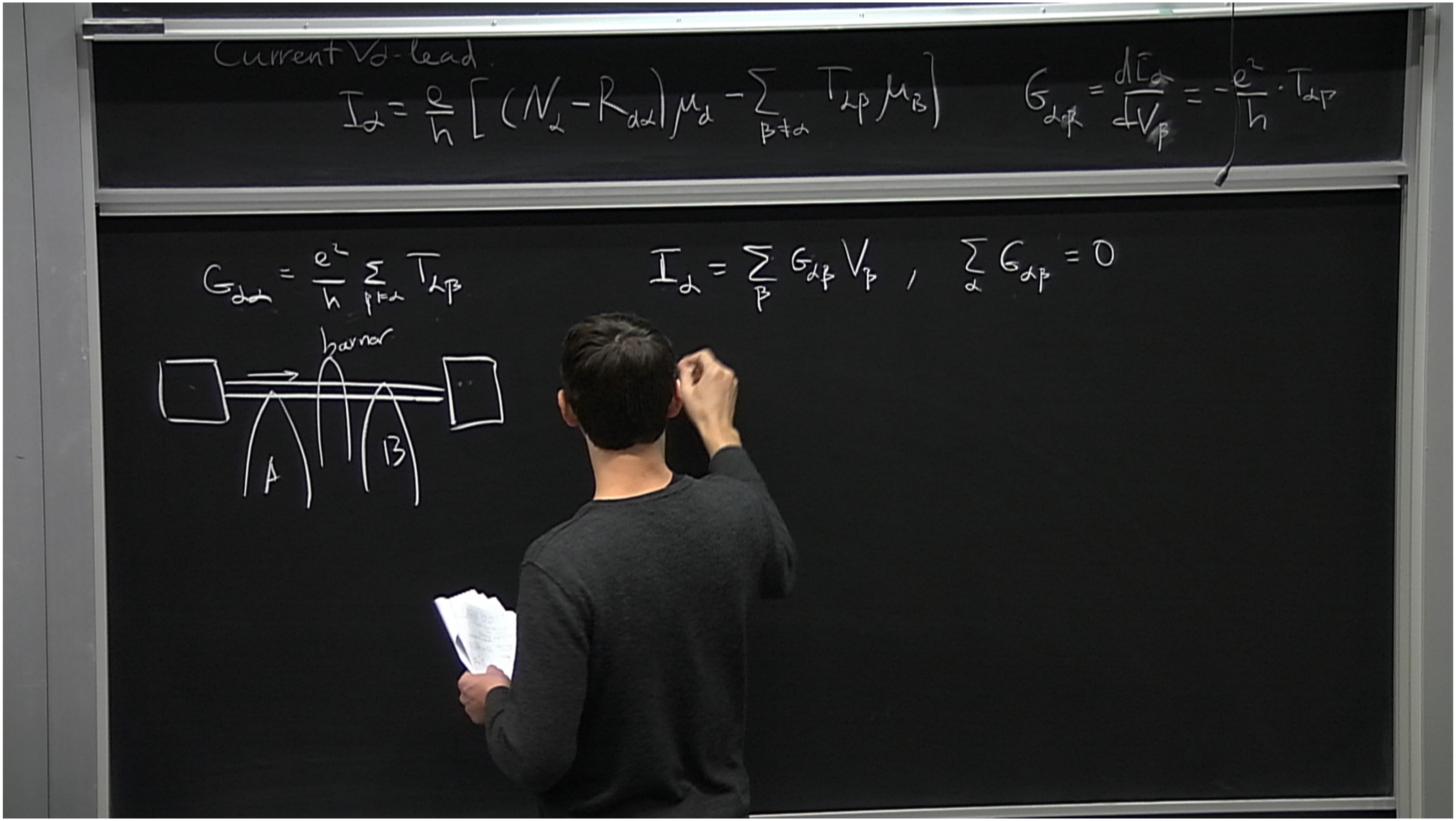

Current $\forall\alpha$-lead
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta$, $\sum_\alpha G_{\alpha\beta} = 0$

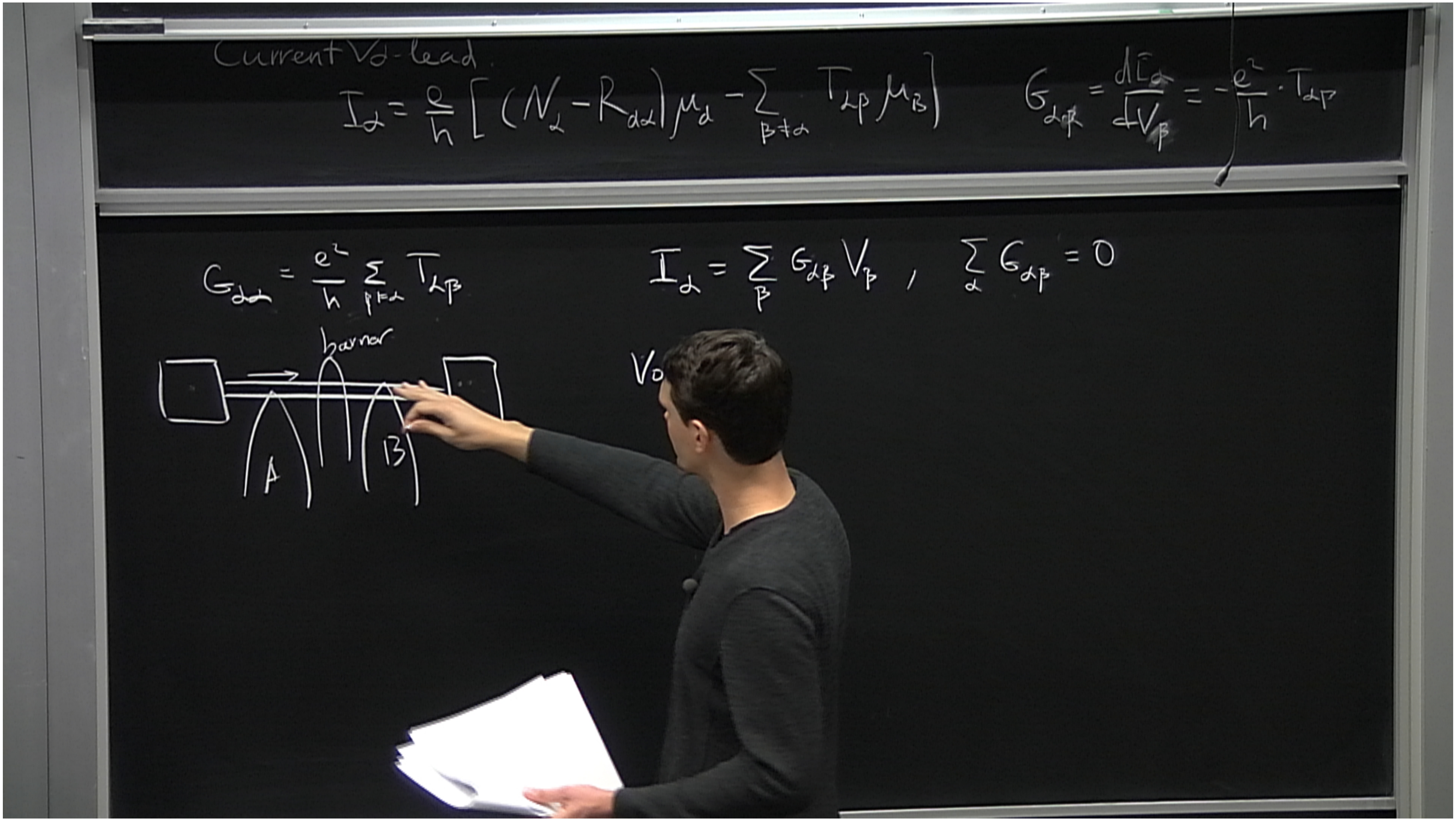


$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \ , \quad \sum_\alpha G_{\alpha\beta} = 0$


Current α-lead
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta$ $_{\alpha\beta} V_\beta$, $\sum_\alpha G_{\alpha\beta} = 0$


Current $\forall\alpha$-lead.
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \,,\quad \sum_\alpha G_{\alpha\beta} = 0$

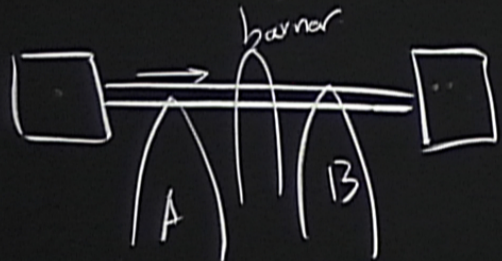

Current to α-lead
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \; , \; \sum_\alpha G_{\alpha\beta} = 0$
barrier
A
B


Current Vα-lead
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta$, $\sum_\alpha G_{\alpha\beta} = 0$
barrier
A
B
Vo

Current to α-lead.

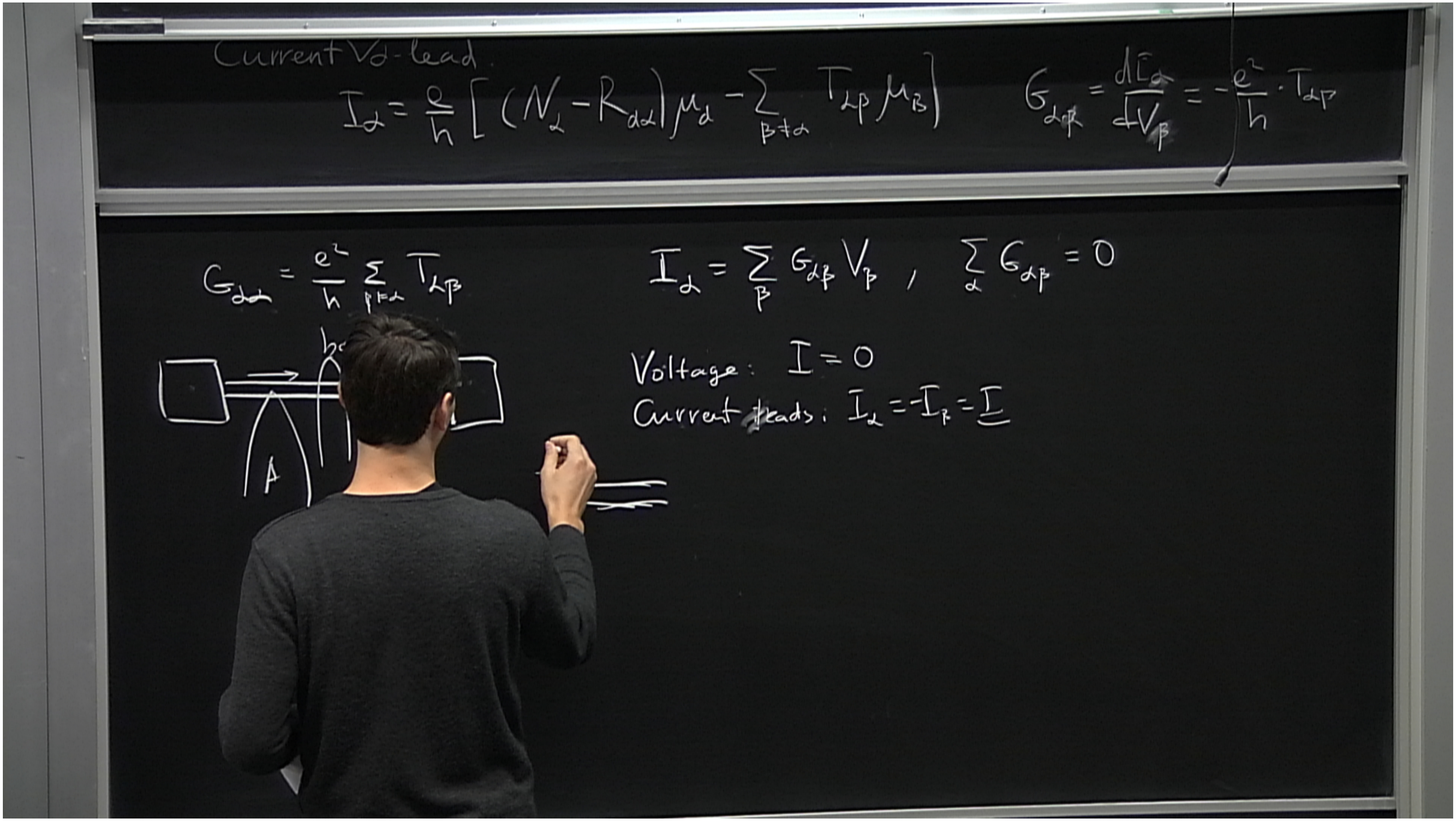
$$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\right] \qquad G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$$

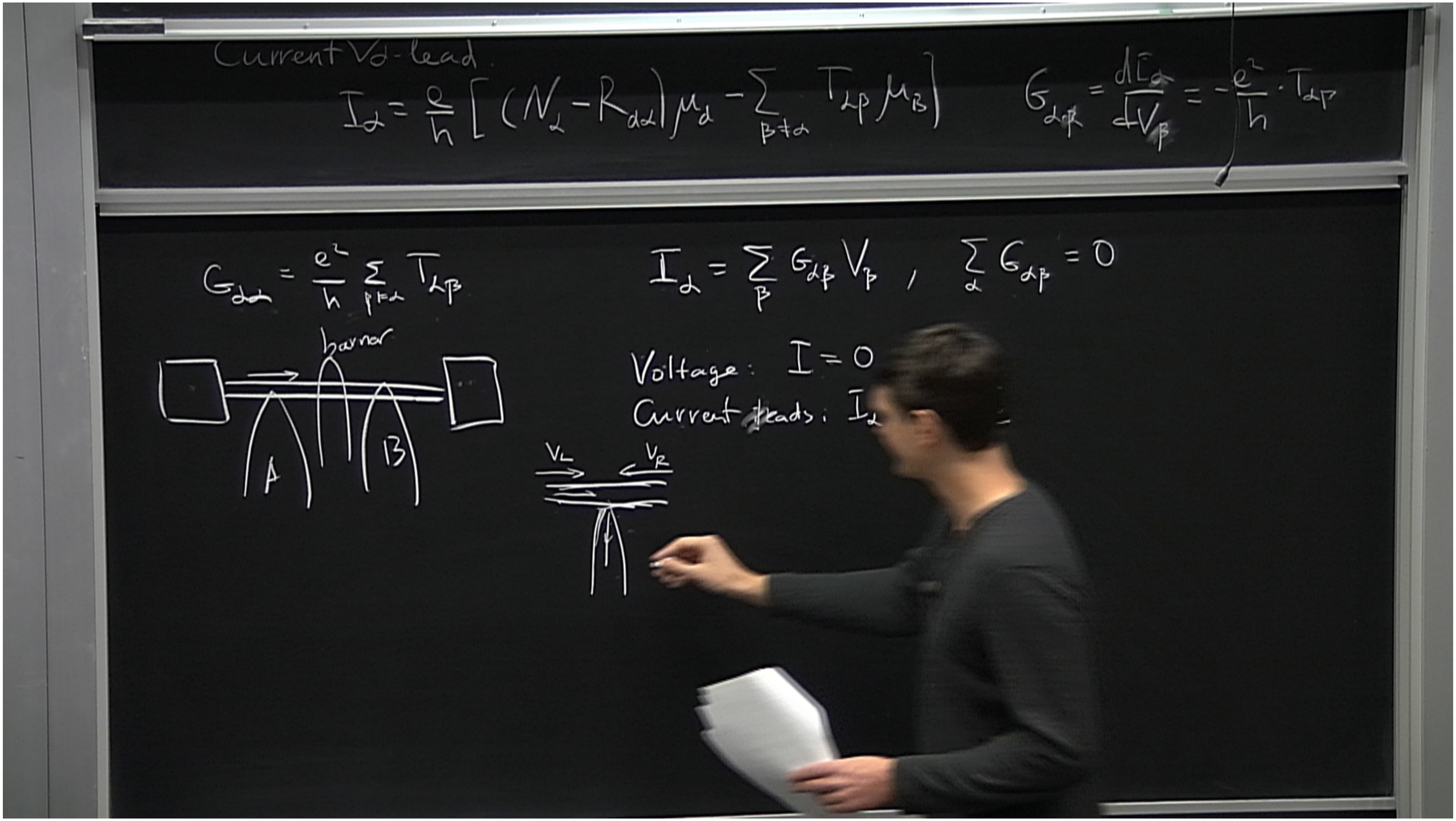
$$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta} \qquad I_\alpha = \sum_\beta G_{\alpha\beta}V_\beta\,, \quad \sum_\alpha G_{\alpha\beta} = 0$$

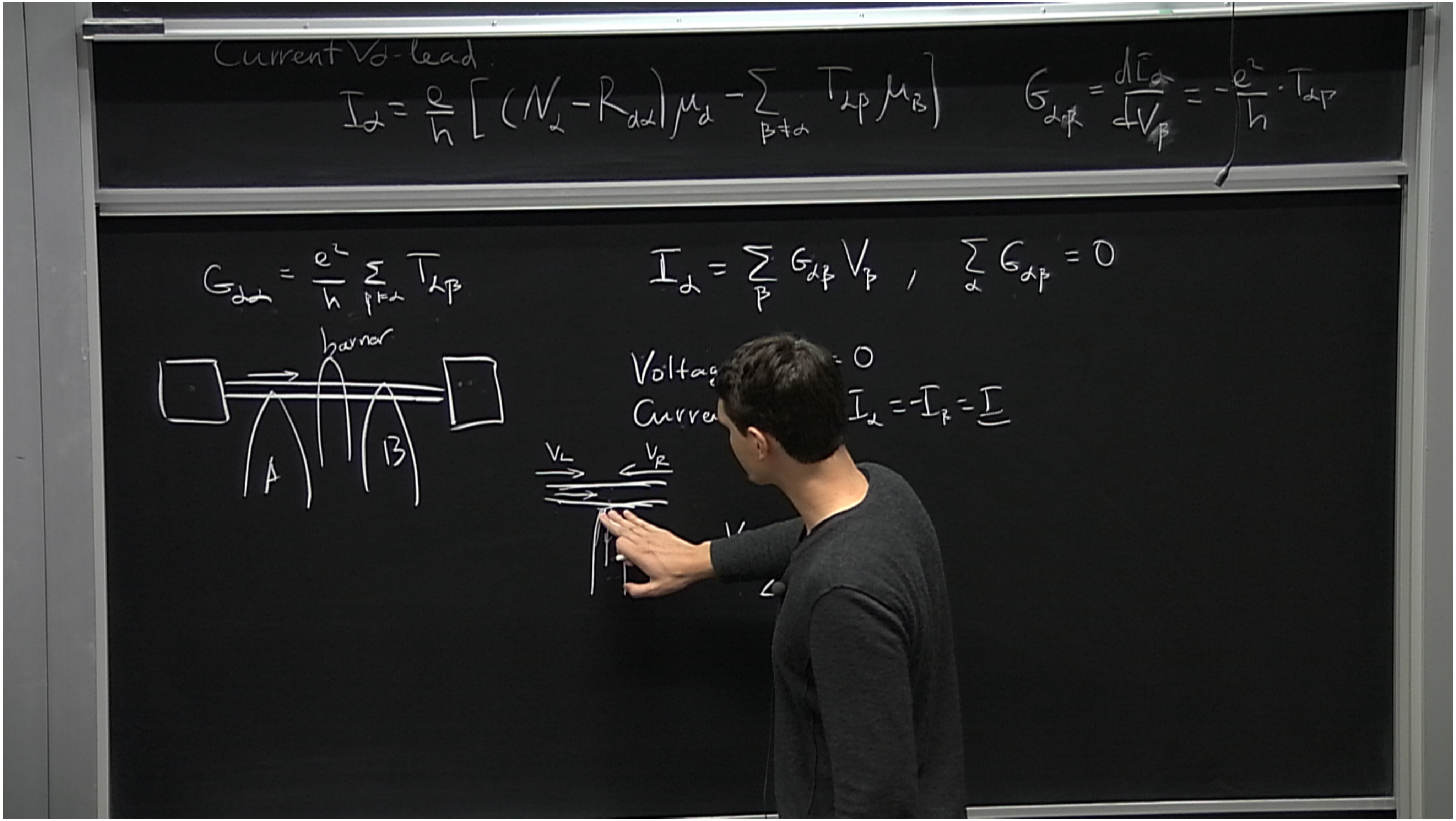


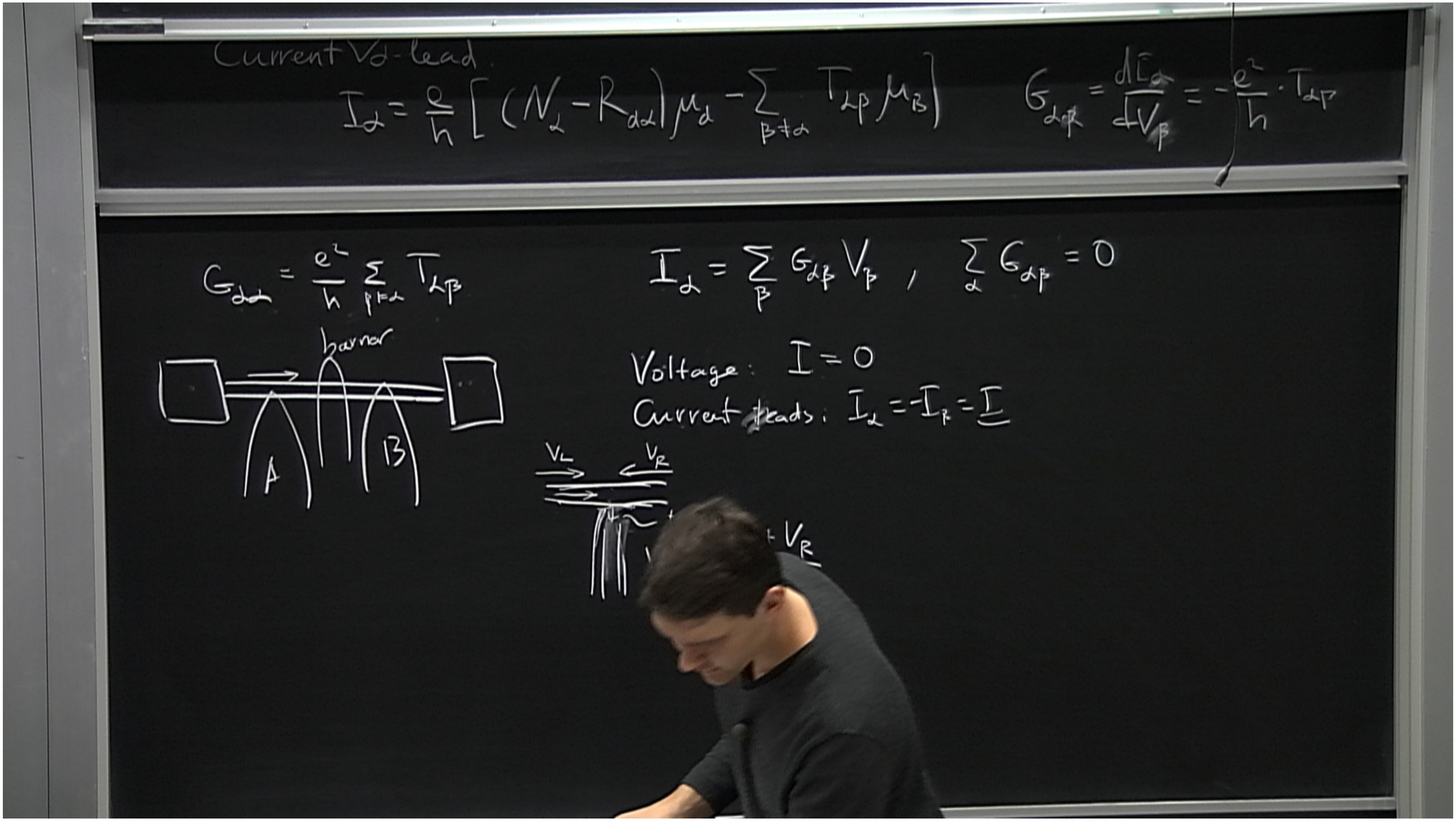
Voltage: $I = 0$

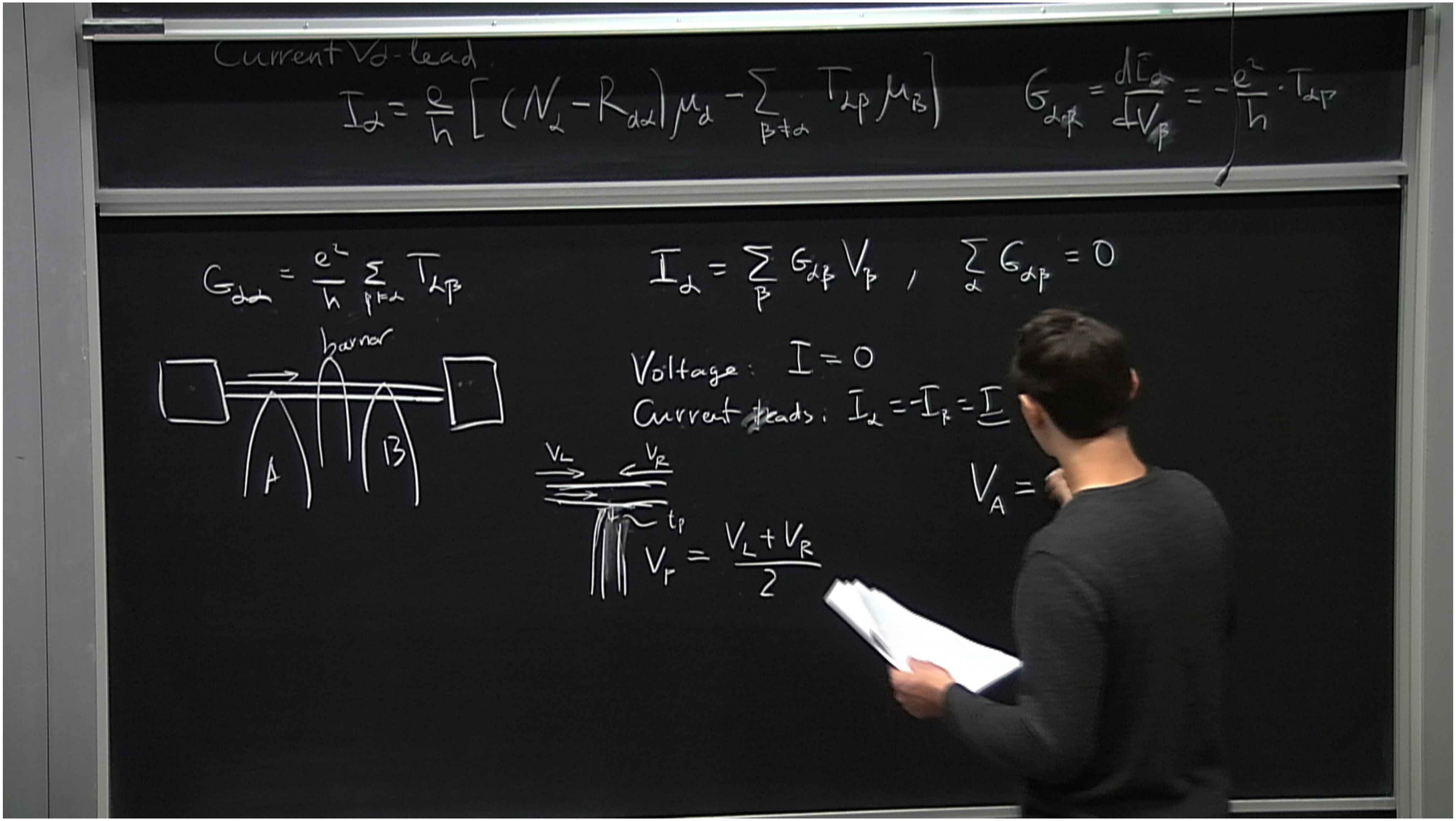
Current leads: $I_\alpha = -I_\beta = I$

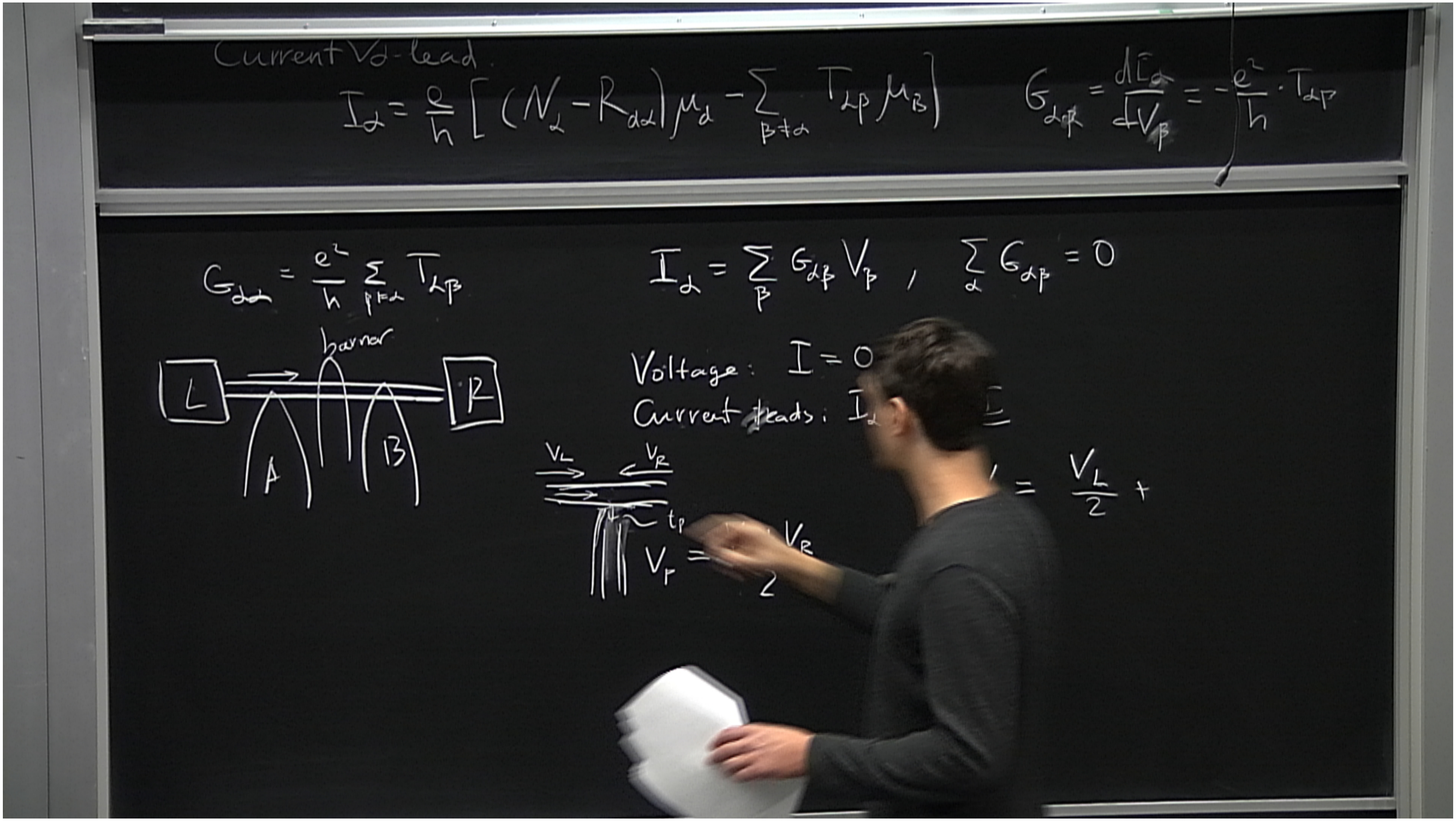

Current Vα-lead.
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \ , \ \sum_\alpha G_{\alpha\beta} = 0$
Voltage: $I = 0$
Current leads: $I_\alpha = -I_\beta = I$


Current to α-lead.
I_α = e/h [(N_α − R_αα) μ_α − Σ_{β≠α} T_αβ μ_β]
G_αβ = dI_α/dV_β = −e²/h · T_αβ
G_αα = e²/h Σ_{β≠α} T_αβ
I_α = Σ_β G_αβ V_β , Σ_α G_αβ = 0
barrier
A
B
Voltage: I = 0
Current leads: I_α
V_L
V_R


Current Vα-lead.
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta}V_\beta \,,\quad \sum_\alpha G_{\alpha\beta} = 0$
barrier
A
B
$I_\alpha = -I_\beta = I$
V_L
V_R


Current to α-lead
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \quad , \quad \sum_\alpha G_{\alpha\beta} = 0$
barrier
A
B
Voltage: I = 0
Current leads: $I_\alpha = -I_\beta = I$
V_L
V_R


Current Vα-lead
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \,, \quad \sum_\alpha G_{\alpha\beta} = 0$
barrier
A
B
Voltage: $I = 0$
Current leads: $I_\alpha = -I_\beta = I$
V_L
V_R
t_p
$V_p = \frac{V_L + V_R}{2}$
$V_A =$

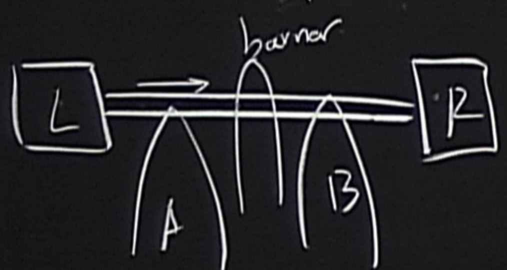

Current Vα-lead.
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h} \cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \ , \ \sum_\alpha G_{\alpha\beta} = 0$
barrier
L
R
A
B
Voltage: I = 0
Current leads:
V_L
V_R
t_p
$V_p =$
$\frac{V_L}{2} +$

Current V_α-lead.

$$I_\alpha = \frac{e}{h}\Big[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta\Big] \qquad G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$$

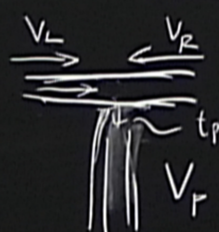
$$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$$

$$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \,, \quad \sum_\alpha G_{\alpha\beta} = 0$$



Voltage: $I = 0$

Current leads: $I_L = -I_R = \underline{I}$

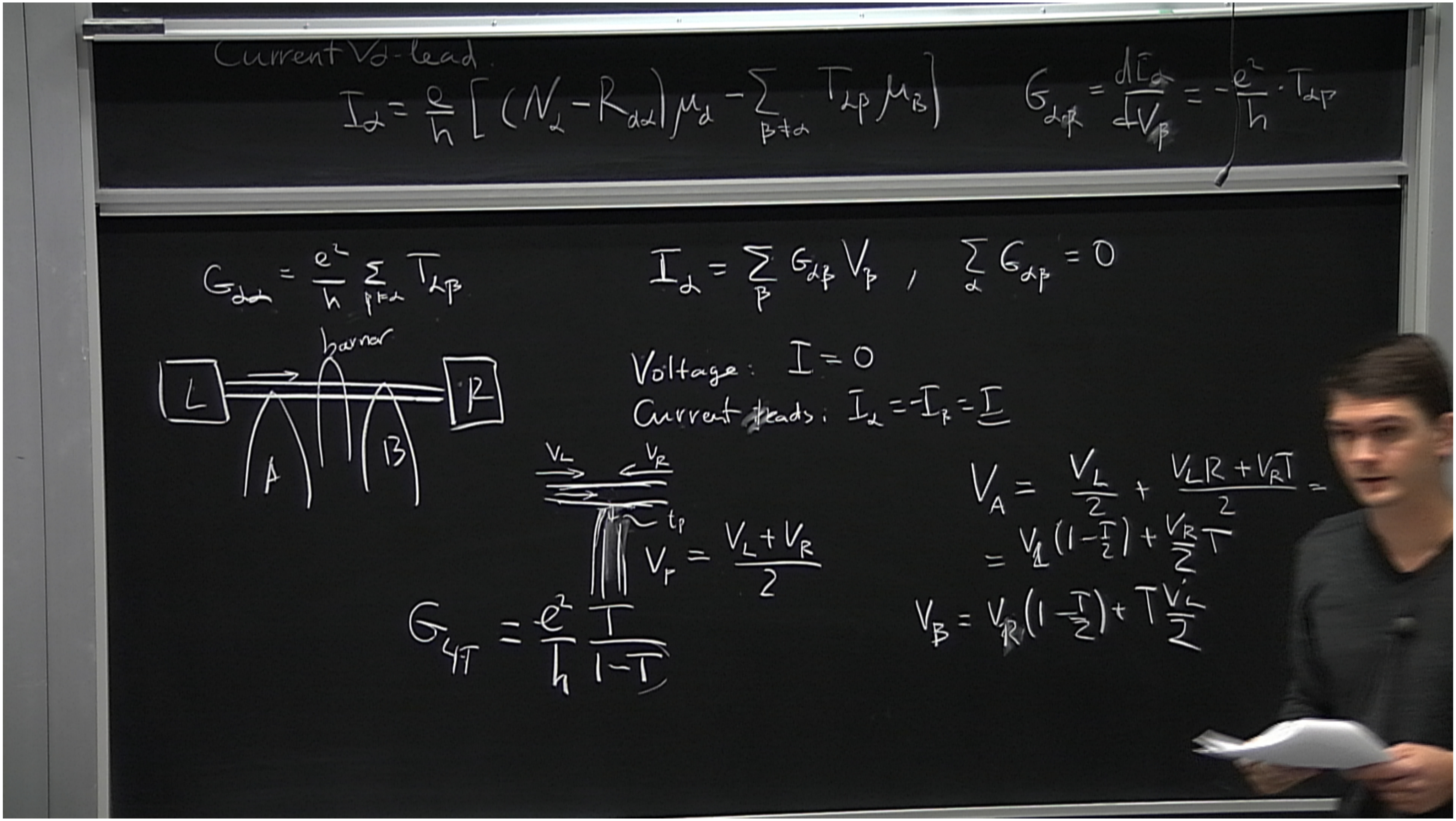


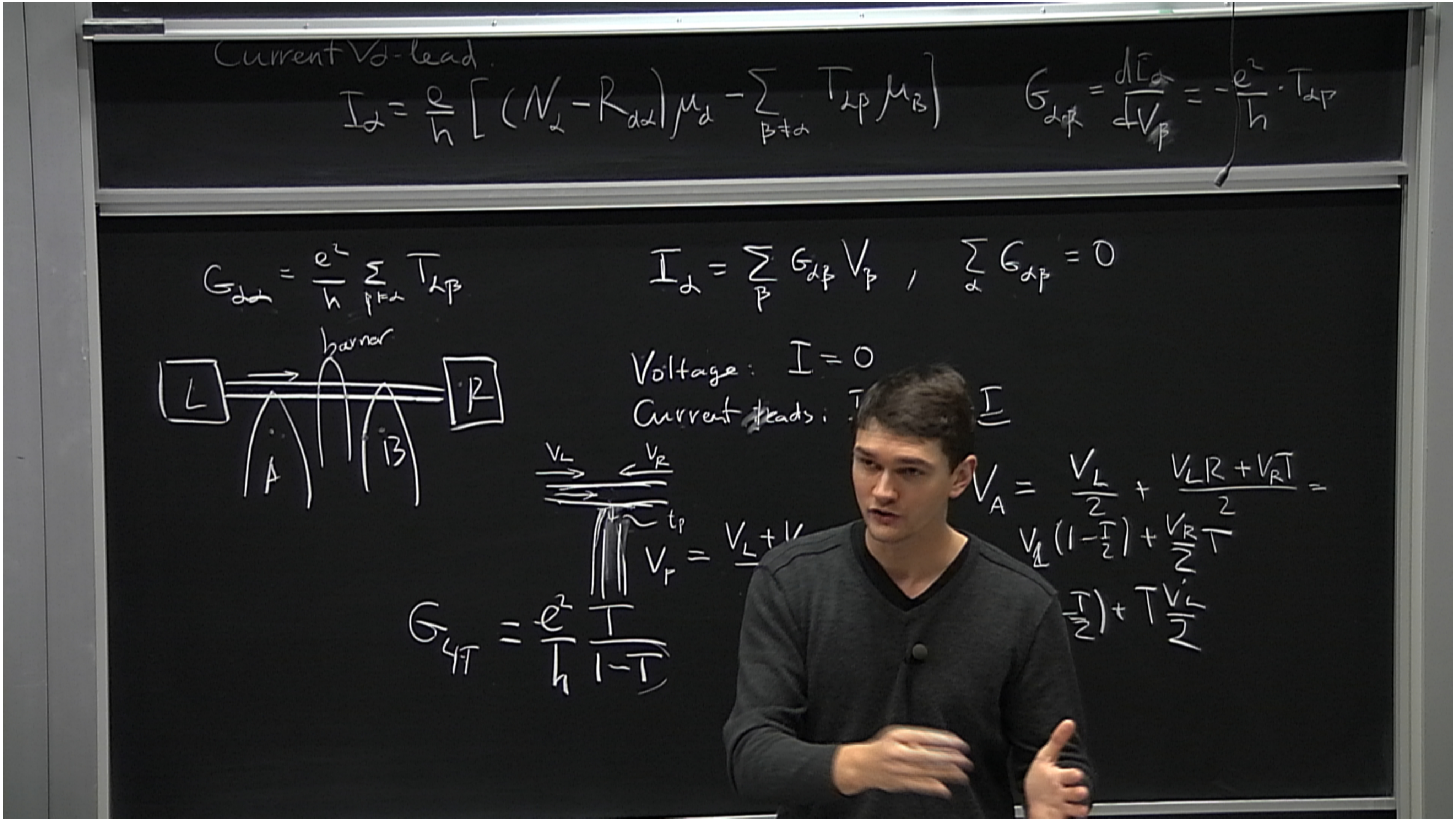
$$V_P = \frac{V_L + V_R}{2}$$

$$V_A = \frac{V_L}{2} + \frac{V_L}{\ldots}$$

$$= V_L\left(1 - \frac{T}{2}\right) + \frac{V_R}{2}T$$

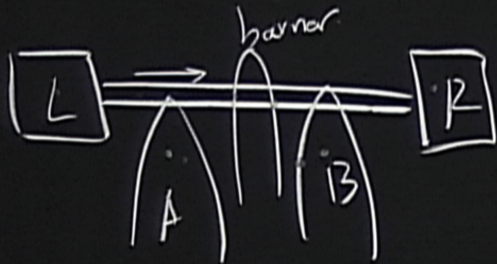
$$V_B = V_R\left(1 - \frac{T}{2}\right) + T\frac{V_L}{2}$$


Current Vα-lead.
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h}\cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h}\sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \;,\; \sum_\alpha G_{\alpha\beta} = 0$
barrier
L
R
A
B
Voltage: $I = 0$
Current leads: $I_\alpha = -I_\beta = I$
V_L
V_R
t_p
$V_p = \frac{V_L + V_R}{2}$
$G_{4T} = \frac{e^2}{h}\frac{T}{1-T}$
$V_A = \frac{V_L}{2} + \frac{V_L R + V_R T}{2} =$
$= V_L\left(1 - \frac{T}{2}\right) + \frac{V_R}{2}T$
$V_B = V_R\left(1 - \frac{T}{2}\right) + T\frac{V_L}{2}$


Current to α-lead.
$I_\alpha = \frac{e}{h}\left[(N_\alpha - R_{\alpha\alpha})\mu_\alpha - \sum_{\beta\neq\alpha} T_{\alpha\beta}\mu_\beta \right]$
$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta} = -\frac{e^2}{h} \cdot T_{\alpha\beta}$
$G_{\alpha\alpha} = \frac{e^2}{h} \sum_{\beta\neq\alpha} T_{\alpha\beta}$
$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \;, \quad \sum_\alpha G_{\alpha\beta} = 0$
barrier
L
R
A
B
Voltage: $I = 0$
Current leads:
V_L
V_R
t_p
$G_{4T} = \frac{e^2}{h}\frac{T}{1-T}$

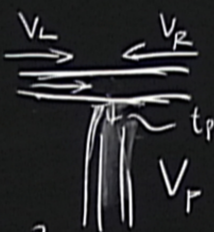
$$G_{\alpha\alpha} = \frac{e^2}{h} \sum_{\beta \neq \alpha} T_{\alpha\beta}$$

$$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta \,, \quad \sum_\alpha G_{\alpha\beta} = 0$$



Voltage: $I = 0$

Current leads: $I_\alpha = -I_\beta = I$



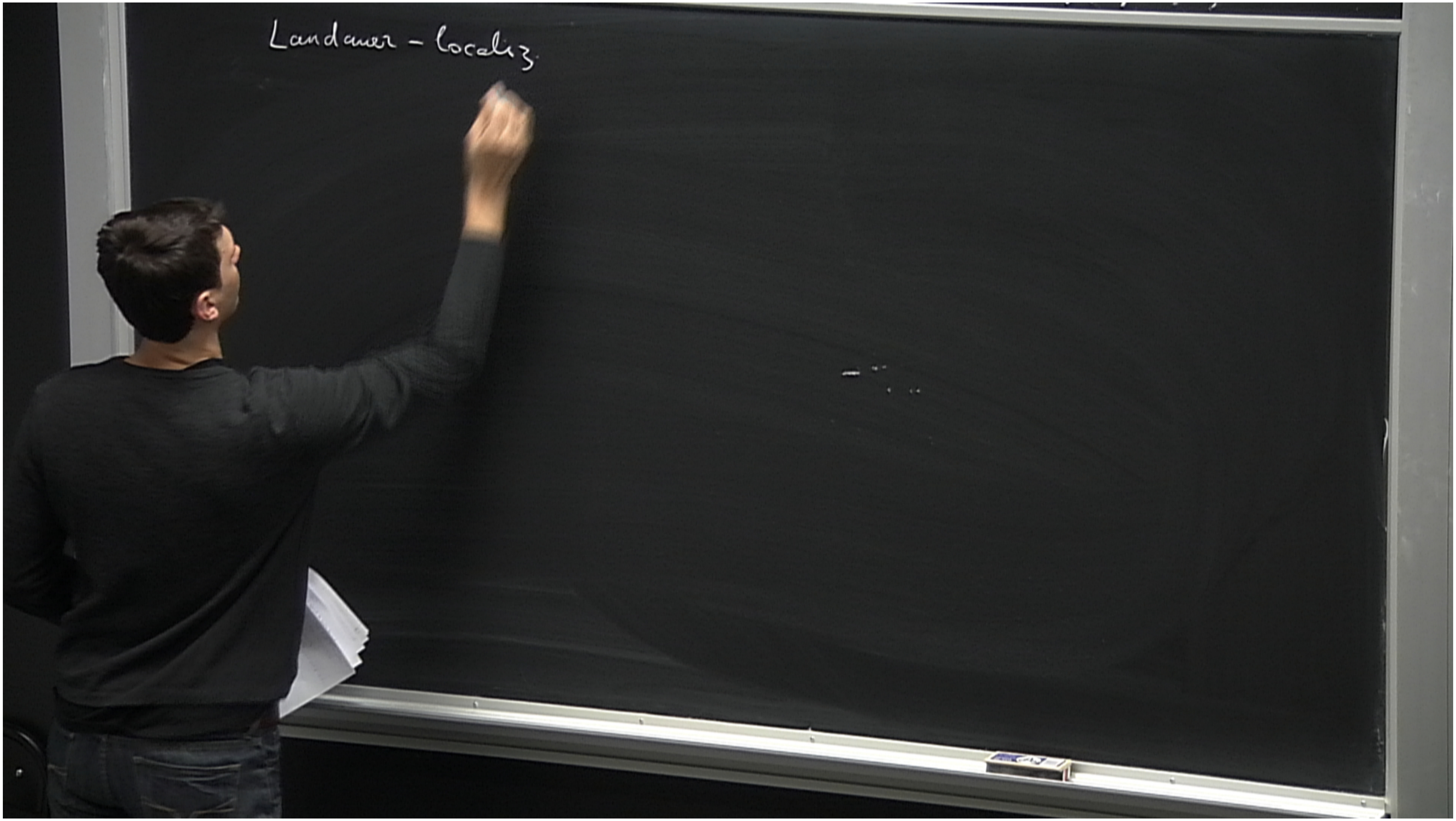
$$V_r = \frac{V_L + V_R}{2}$$

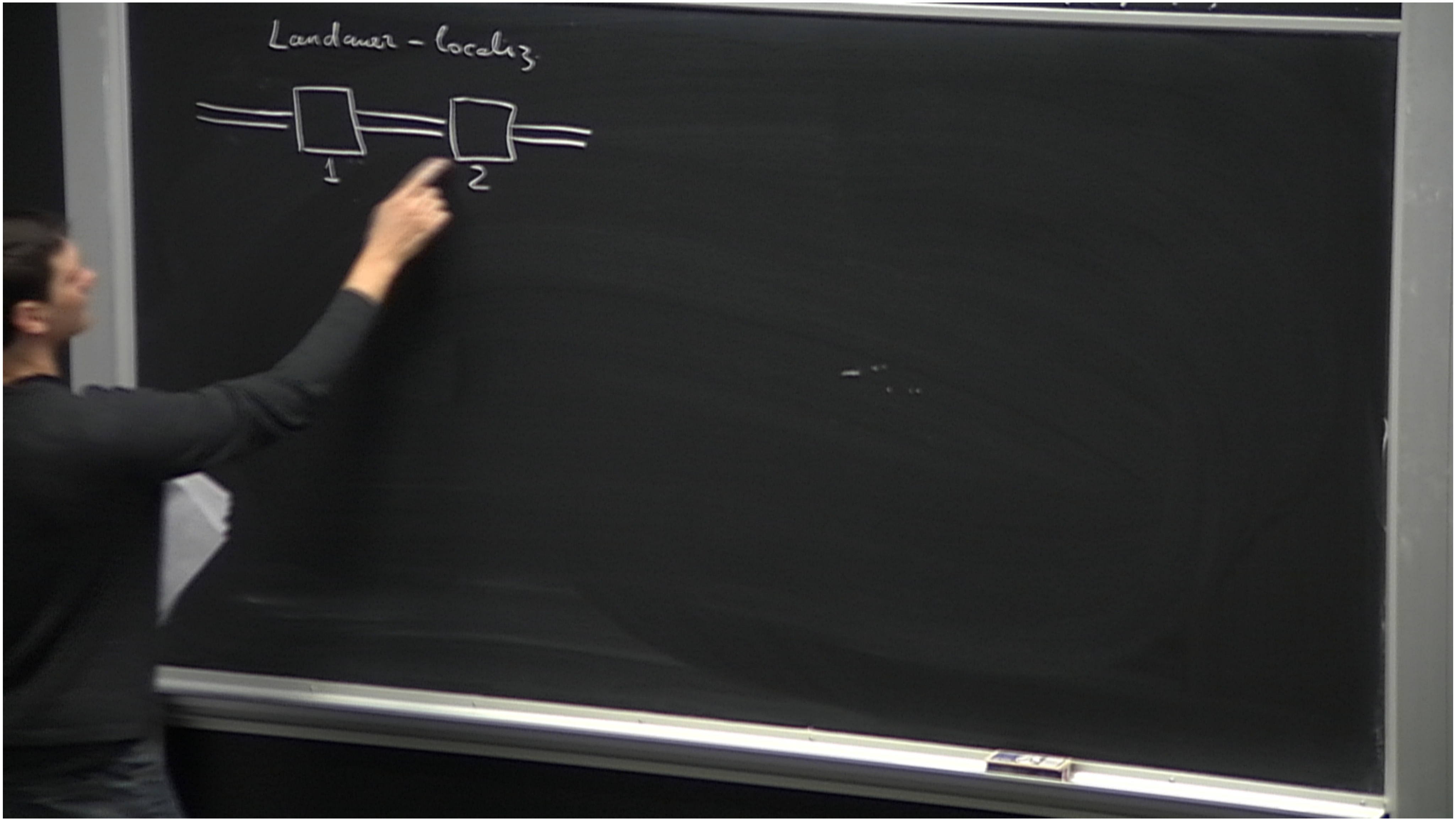
$$G_{4T} = \frac{e^2}{h} \frac{T}{1-T} > G_{2T}$$

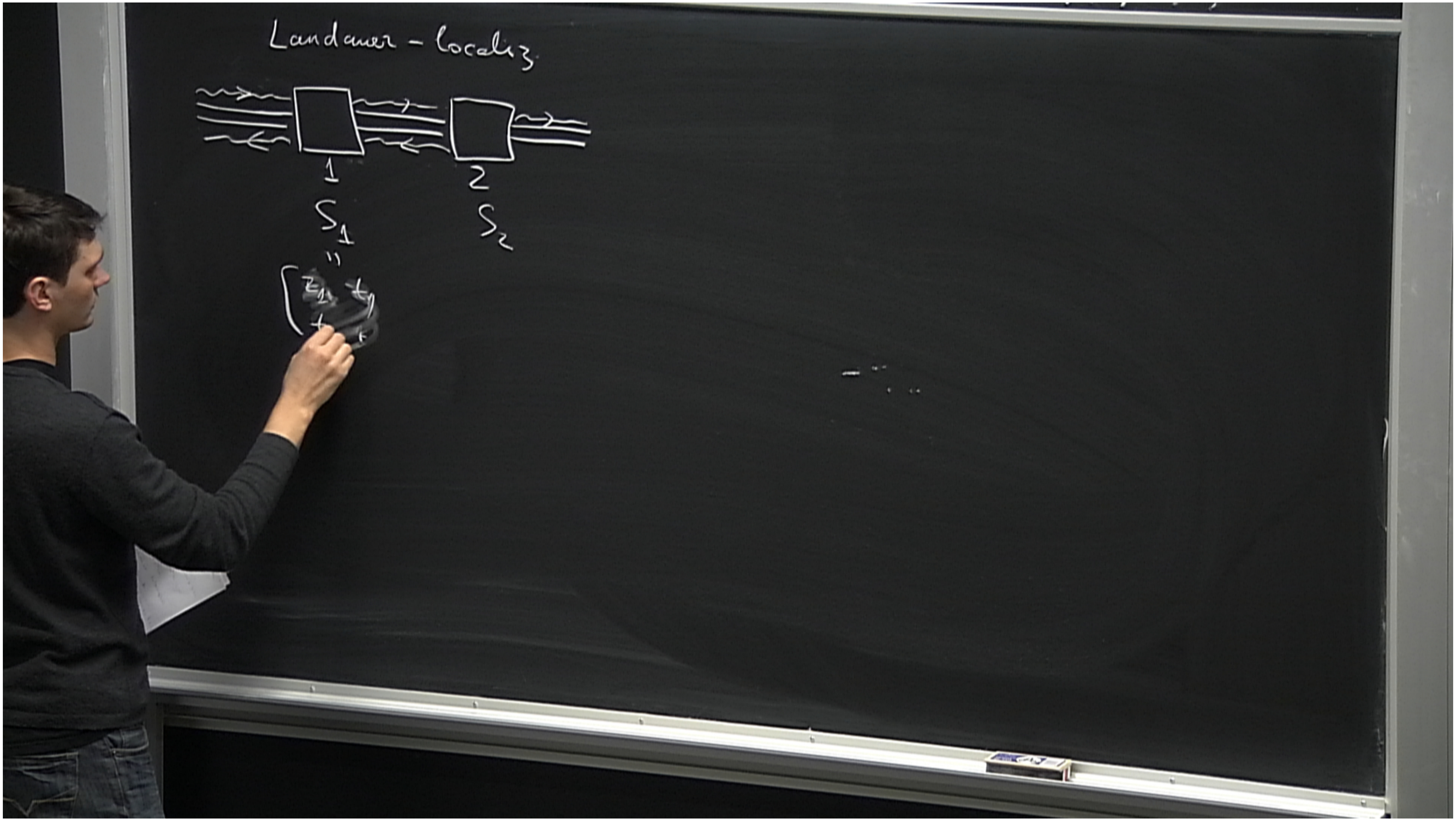
$$V_A = \frac{V_L}{2} + \frac{V_L R + V_R T}{2} =$$

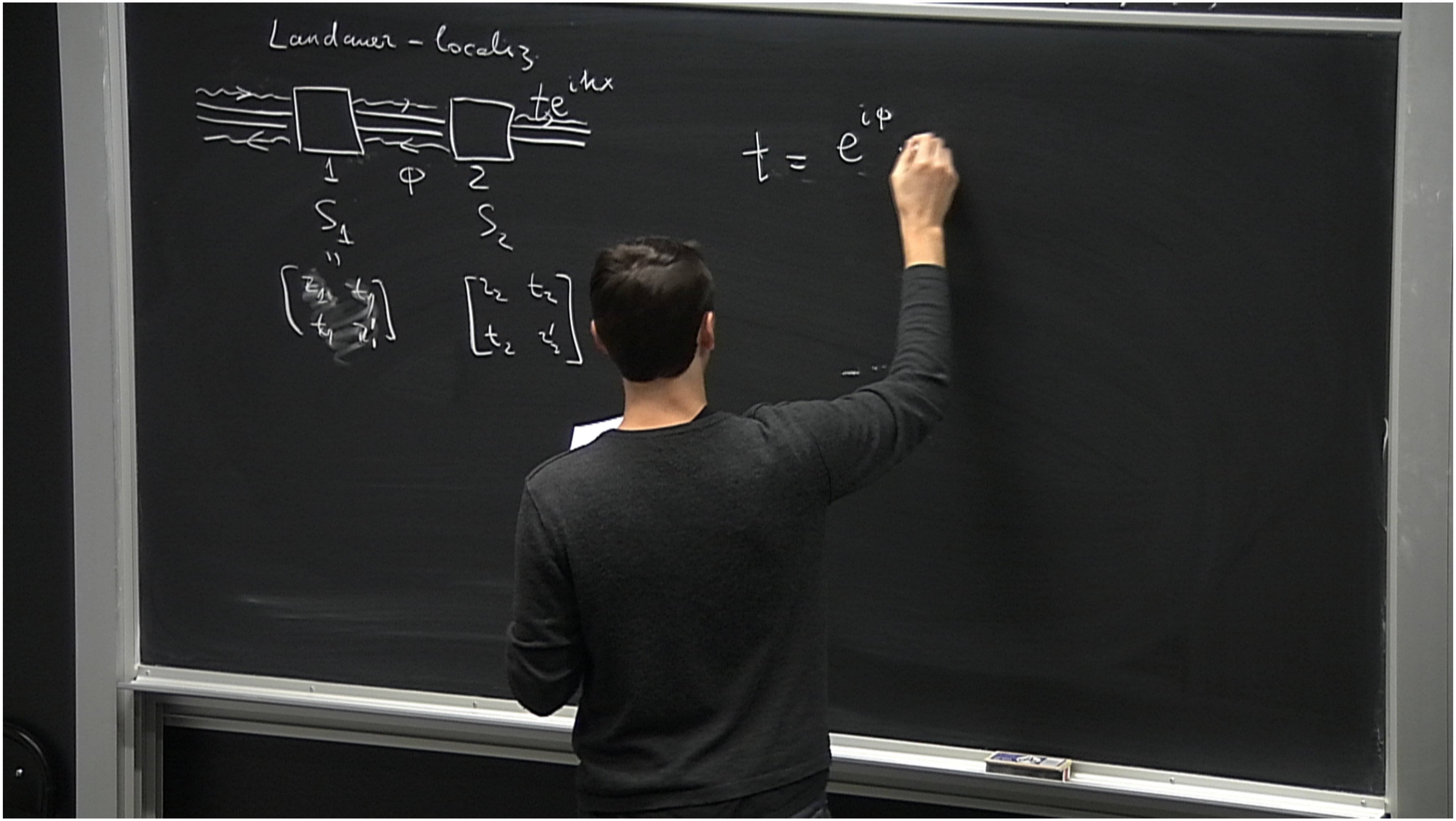
$$= V_L\left(1 - \frac{T}{2}\right) + \frac{V_R}{2} T$$

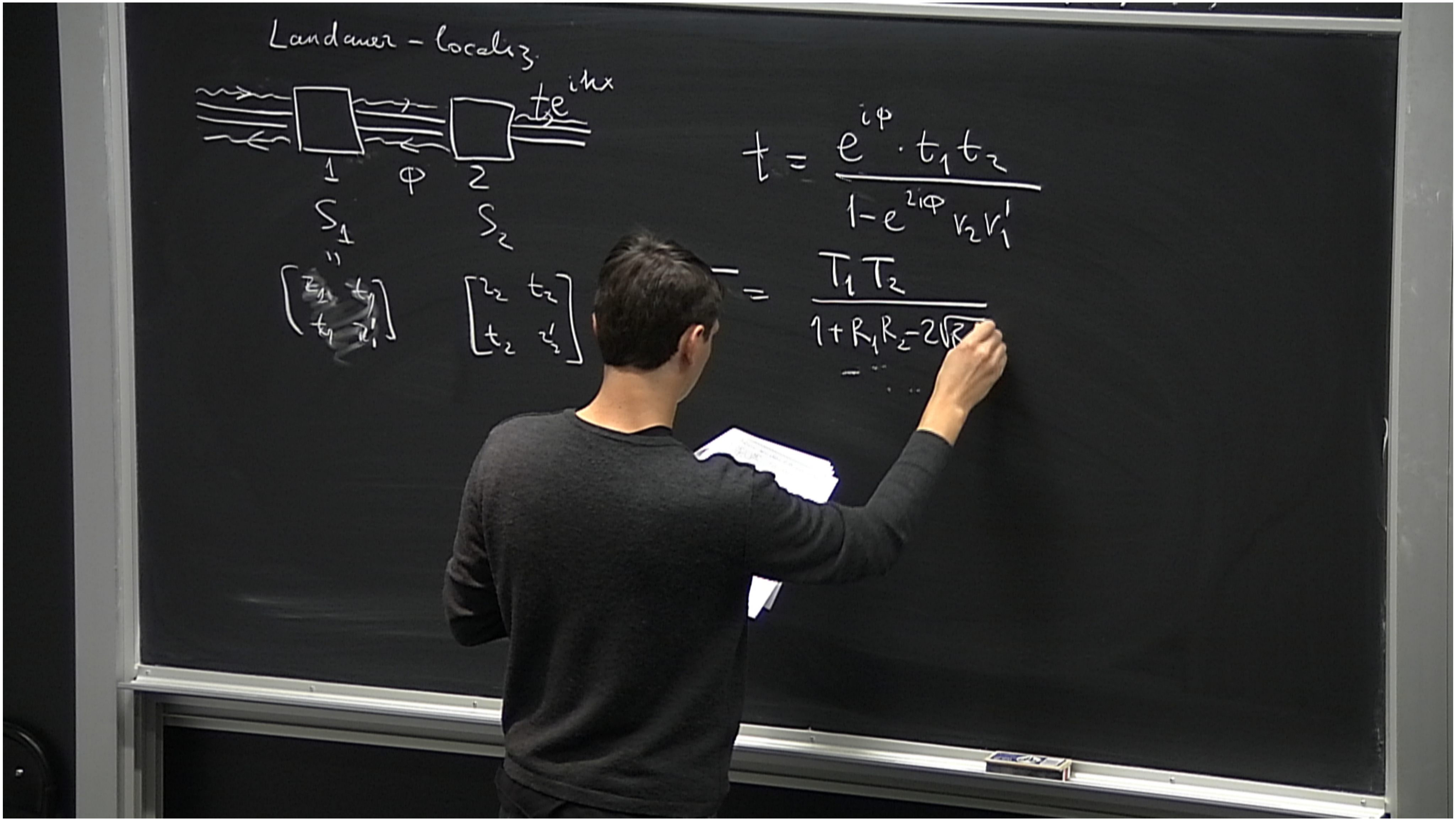
$$V_B = V_R\left(1 - \frac{T}{2}\right) + T \frac{V_L}{2}$$


Landauer – localiz.

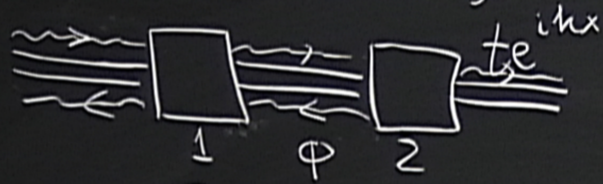

Landauer - localiz.
1
2


Landauer - localiz
1
2
S_1
S_2


Landauer - localiz.
1
φ
2
S1
S2
t = e^{iφ}


Landauer – localiz.
1
φ
2
S_1
S_2
$t = \frac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r_1'}$
$T_1 T_2$

Landauer – localiz.

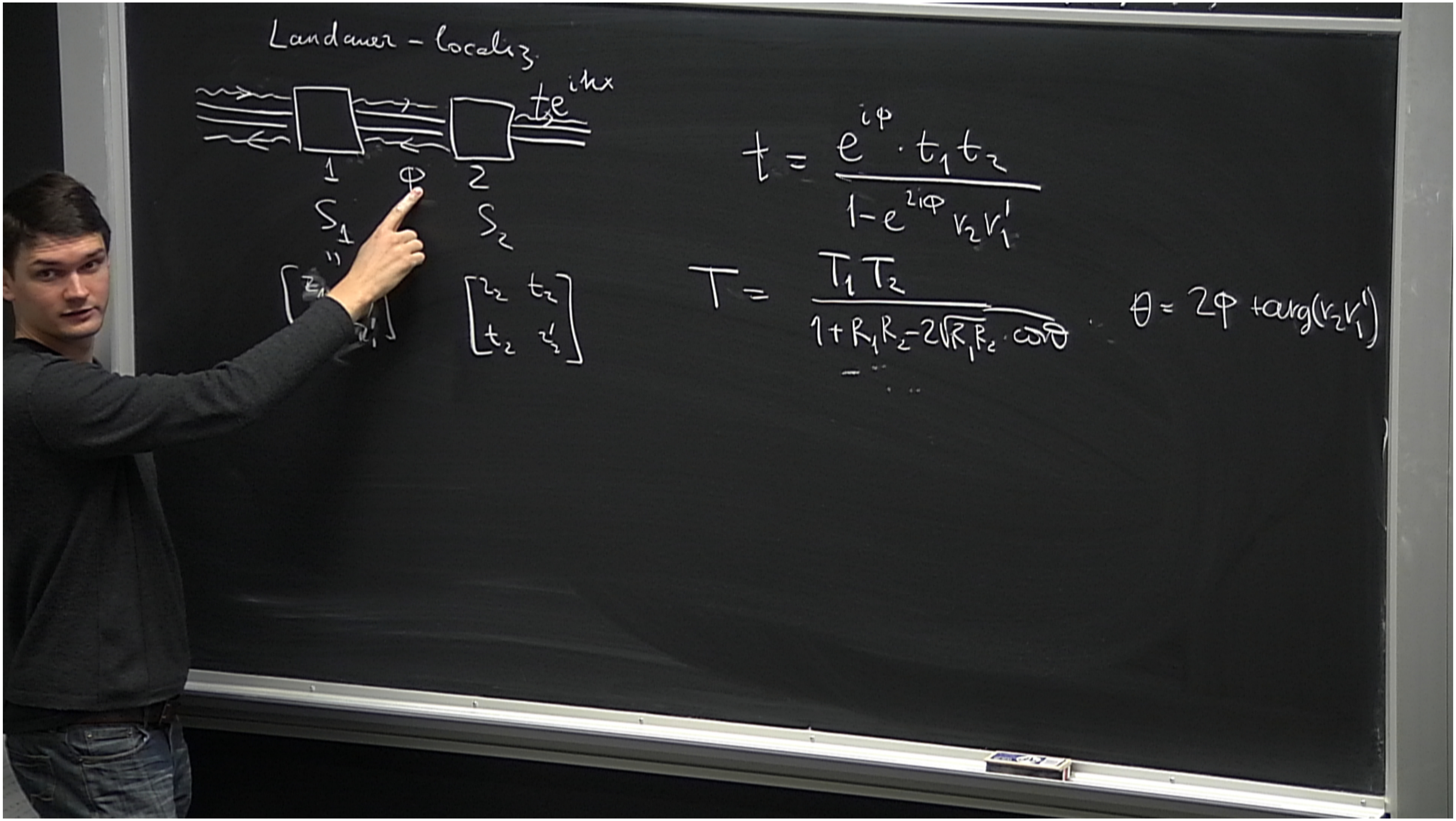


$S_1 \qquad\qquad S_2$

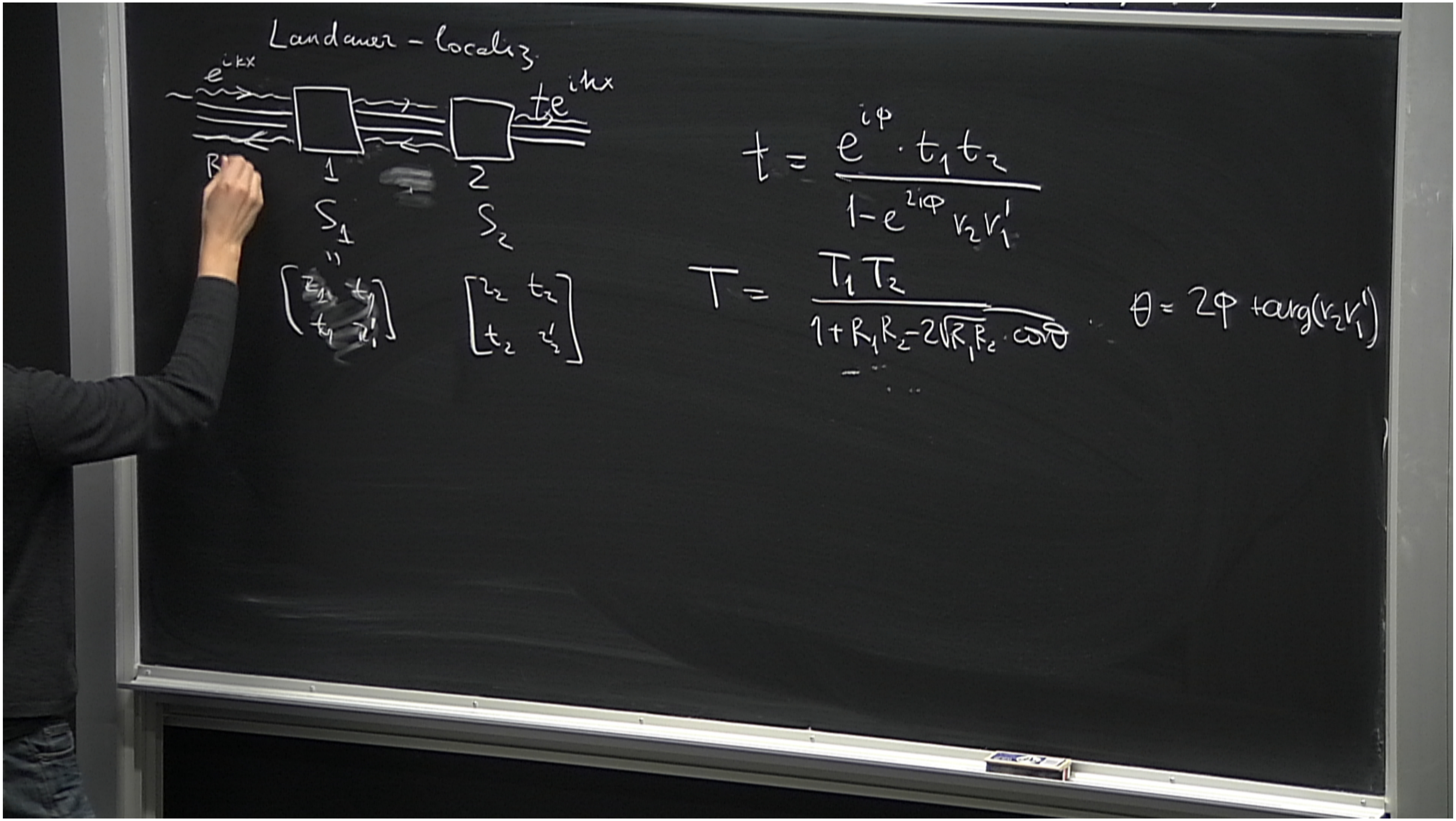
$$S_1 = \begin{bmatrix} r_1 & t_1 \\ t_1 & r'_1 \end{bmatrix} \qquad \begin{bmatrix} r_2 & t_2 \\ t_2 & r'_2 \end{bmatrix}$$

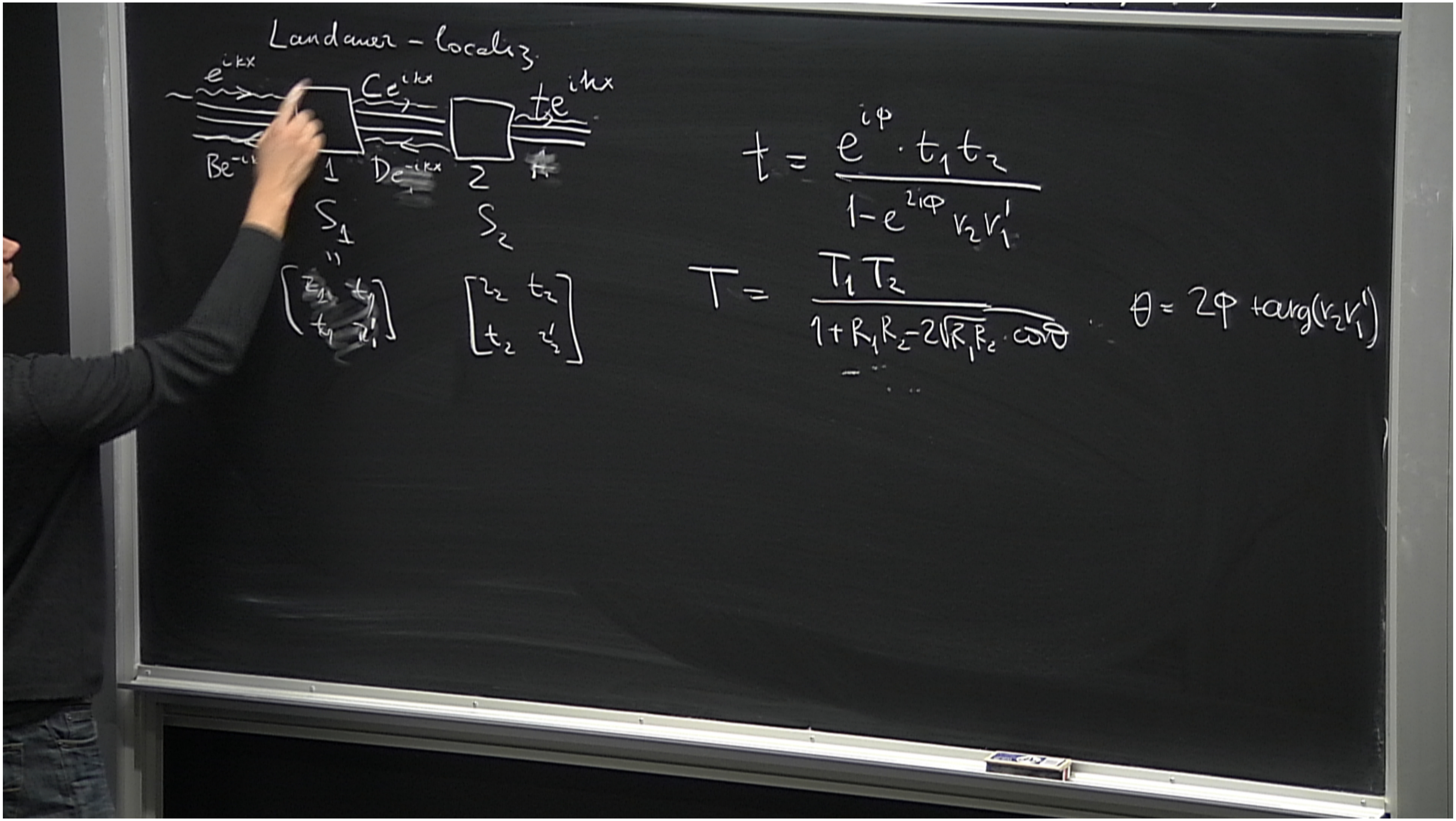
$$t = \frac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r'_1}$$

$$T = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cdot \cos\theta} \qquad \theta = 2\varphi + \arg(r_2 r'_1)$$

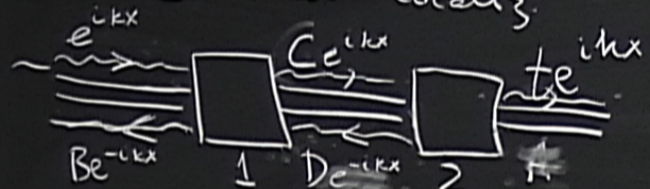


Landauer - localiz.
$t e^{ikx}$
1 φ 2
S_1 S_2
$\begin{bmatrix} r_2 & t_2' \\ t_2 & r_2' \end{bmatrix}$
$t = \frac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r_1'}$
$T = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cdot \cos\theta}$
$\theta = 2\varphi + \arg(r_2 r_1')$


Landauer - localiz.
e^{ikx}
te^{ikx}
1
2
S_1
S_2
t = e^{iφ} · t_1 t_2 / (1 - e^{2iφ} r_2 r_1')
T = T_1 T_2 / (1 + R_1 R_2 - 2√(R_1 R_2) · cos θ)
θ = 2φ + arg(r_2 r_1')


Landauer - localiz.
e^{ikx}
Ce^{ikx}
te^{ikx}
Be^{-ikx}
1
De^{-ikx}
2
S_1
S_2
$t = \frac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r_1'}$
$T = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cdot \cos\theta}$
$\theta = 2\varphi + \arg(r_2 r_1')$

Landauer - localiz.

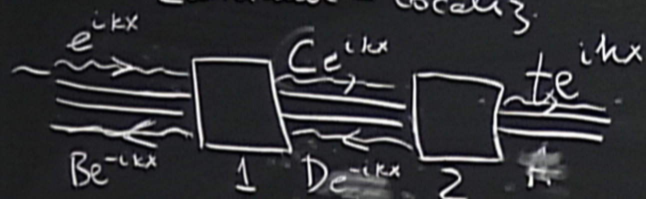


$$S_1 = \begin{bmatrix} r_1 & t_1' \\ t_1 & r_1' \end{bmatrix} \qquad S_2 \quad \begin{bmatrix} r_2 & t_2' \\ t_2 & r_2' \end{bmatrix}$$

$$t = \frac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r_1'}$$

$$T = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cdot \cos\theta} \qquad \theta = 2\varphi + \arg(r_2 r_1')$$

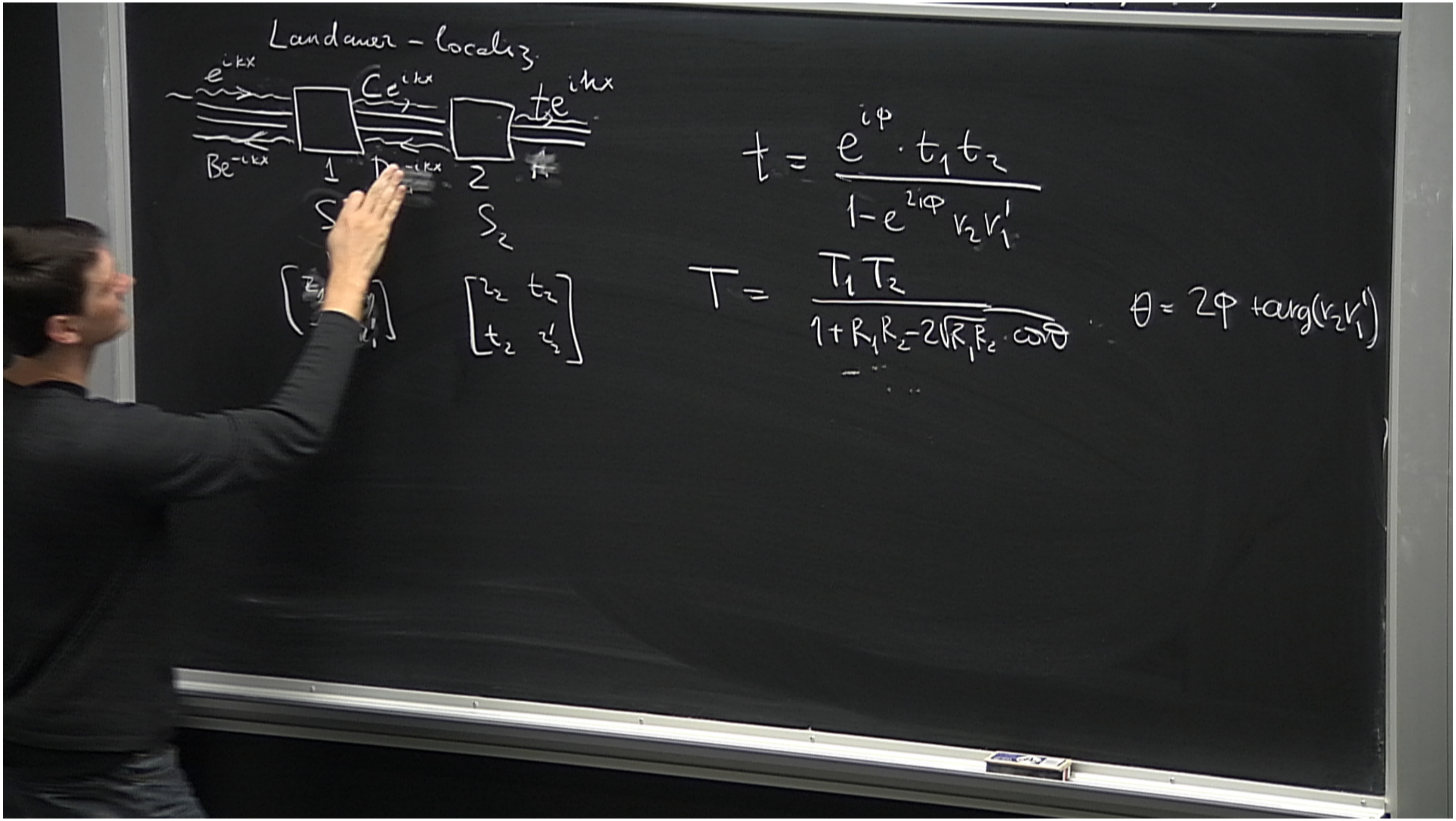
Landauer – localiz.

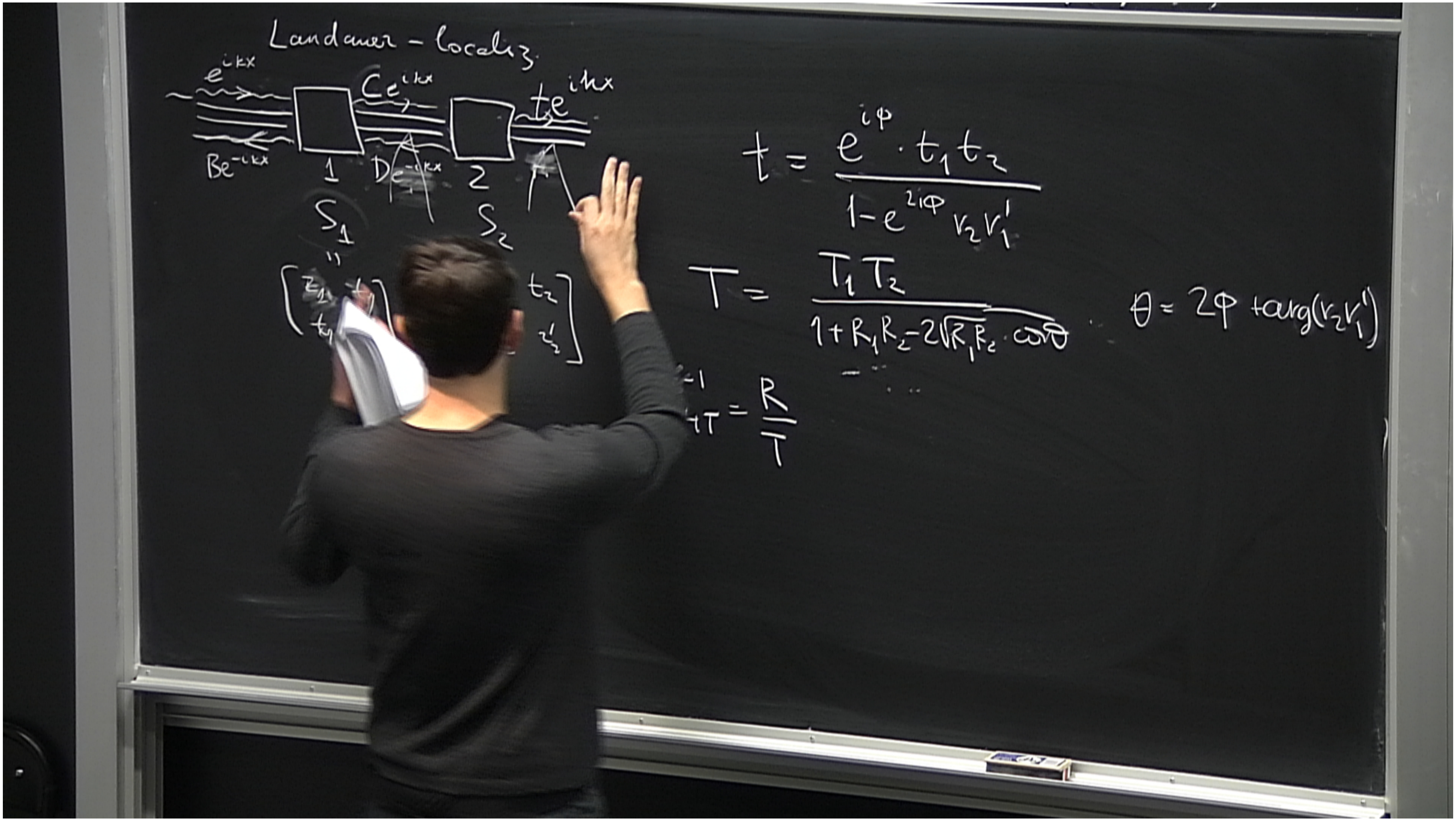


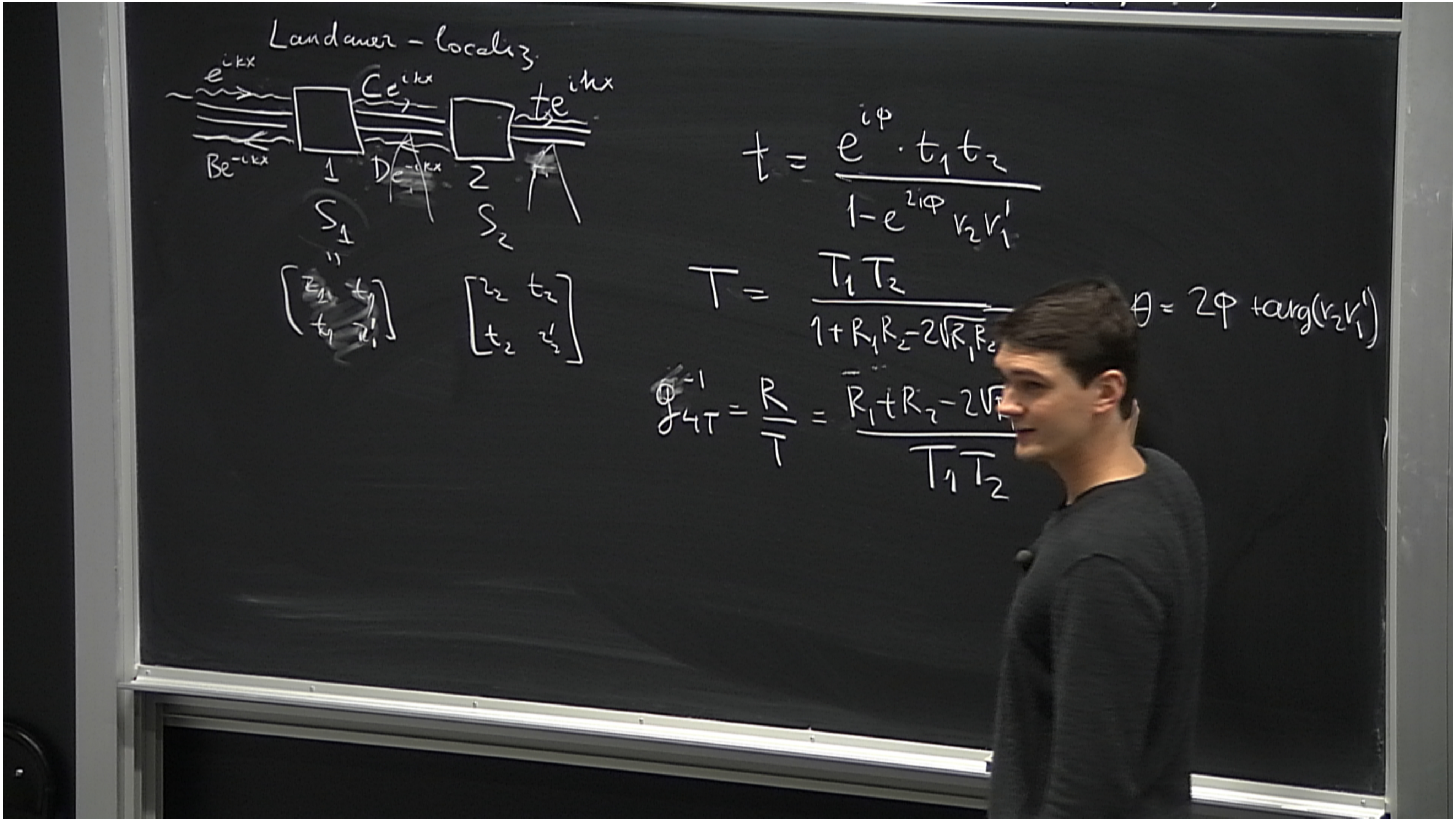
$$S_1 = \begin{bmatrix} r_1 & t_1' \\ t_1 & r_1' \end{bmatrix} \qquad S_2 \quad \begin{bmatrix} r_2 & t_2' \\ t_2 & r_2' \end{bmatrix}$$

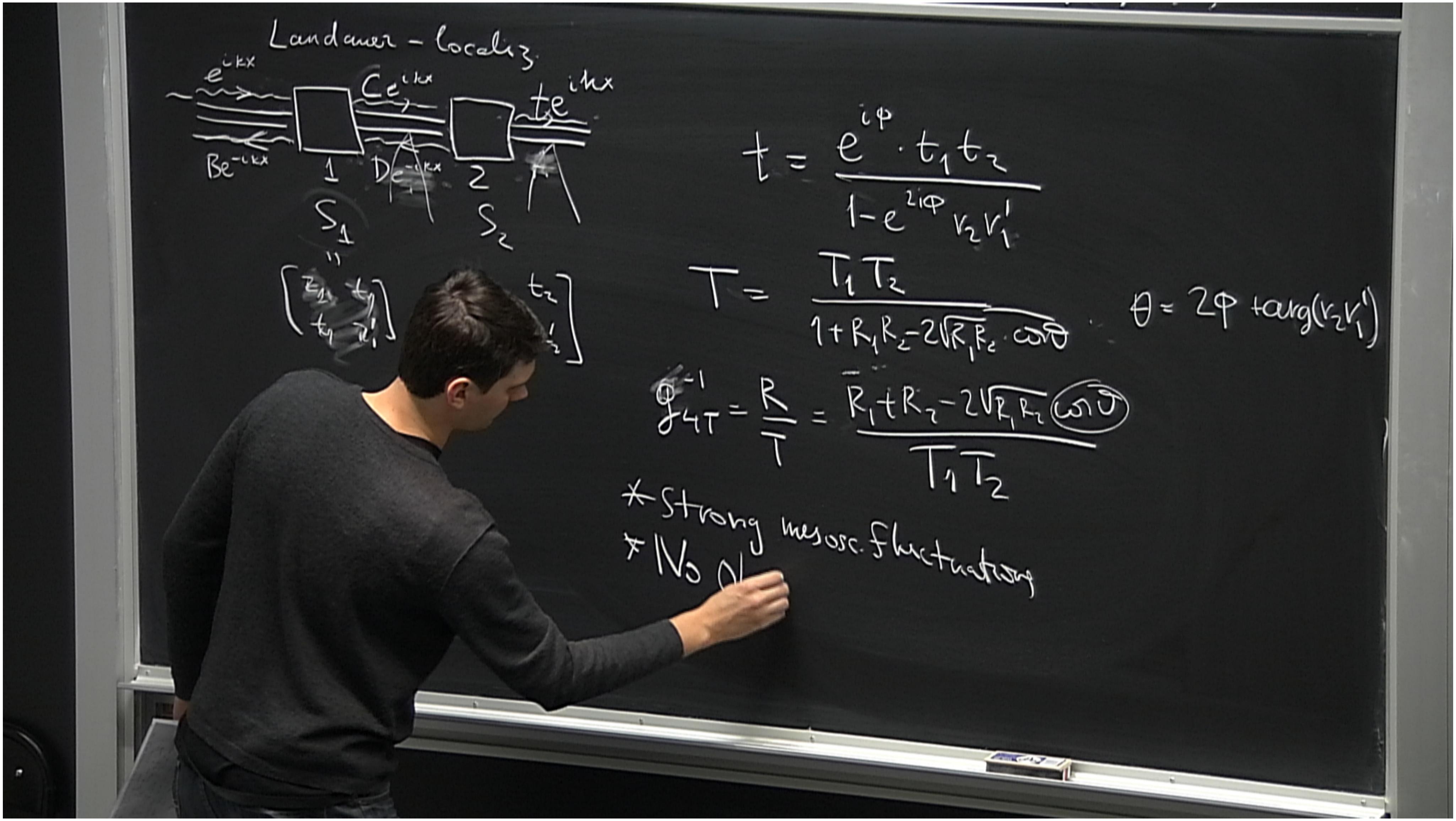
$$t = \frac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r_1'}$$

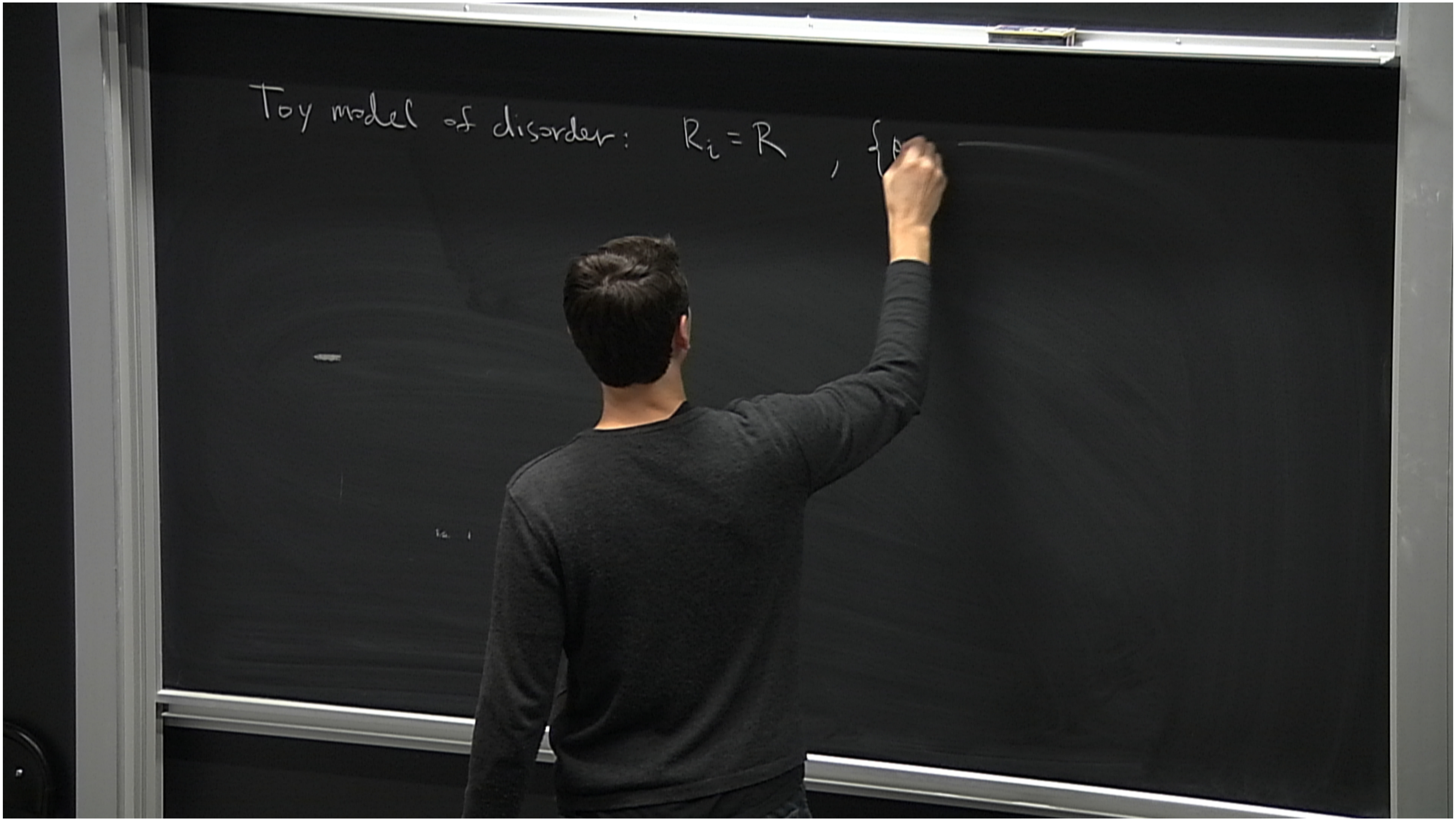
$$T = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cdot \cos\theta} \qquad \theta = 2\varphi + \arg(r_2 r_1')$$

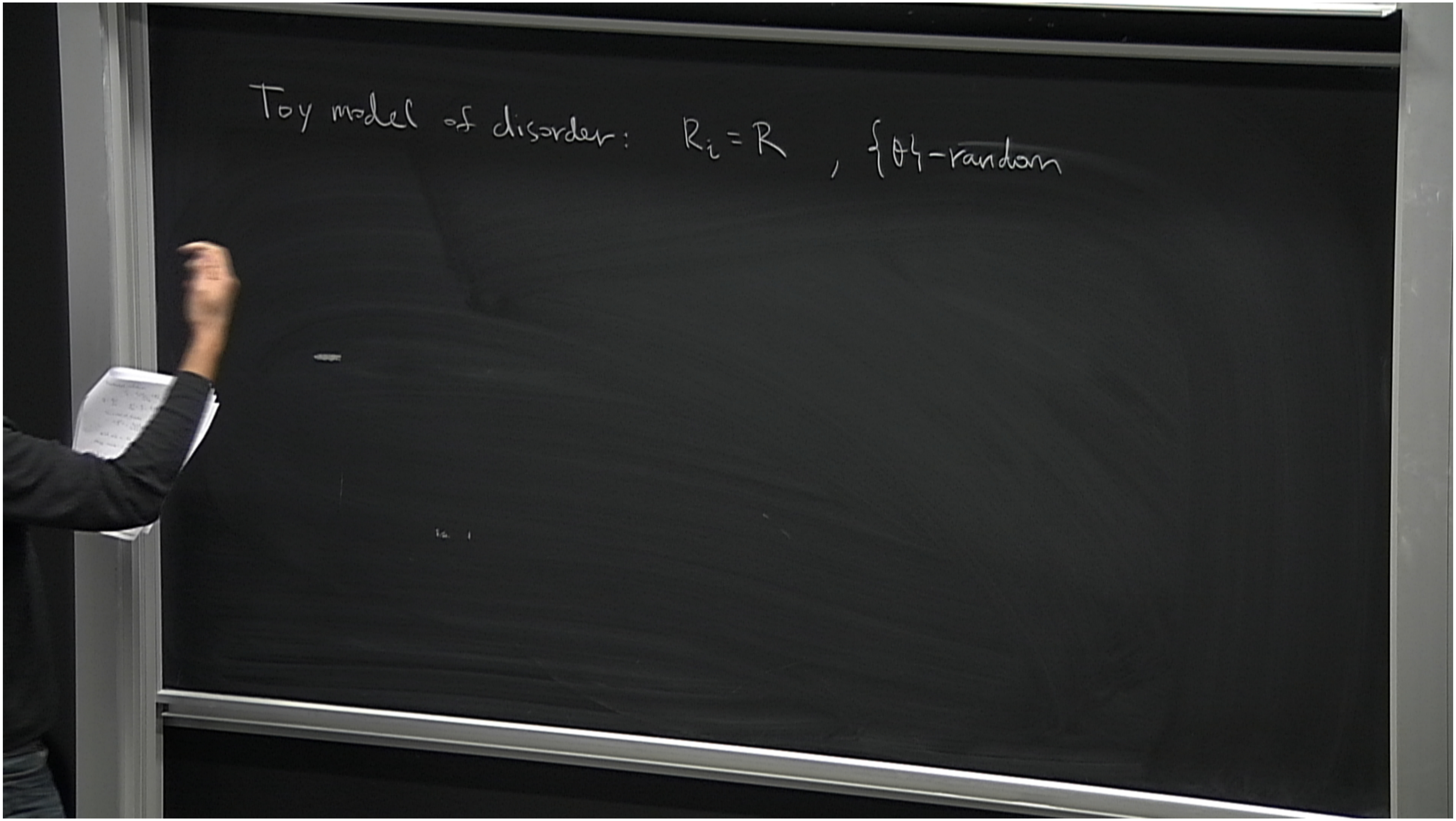

Landauer – localiz.
e^{ikx}
Ce^{ikx}
te^{ikx}
Be^{-ikx}
1
2
S_2
$\begin{bmatrix} r_2 & t_2 \\ t_2 & r_2' \end{bmatrix}$
$t = \dfrac{e^{i\varphi}\cdot t_1 t_2}{1-e^{2i\varphi}\, r_2 r_1'}$
$T = \dfrac{T_1 T_2}{1+R_1R_2-2\sqrt{R_1R_2}\cdot\cos\theta}$
$\theta = 2\varphi + \arg(r_2 r_1')$


Landauer - localiz.
$t = \frac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r_1'}$
$T = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cdot \cos\theta}$
$\theta = 2\varphi + \arg(r_2 r_1')$

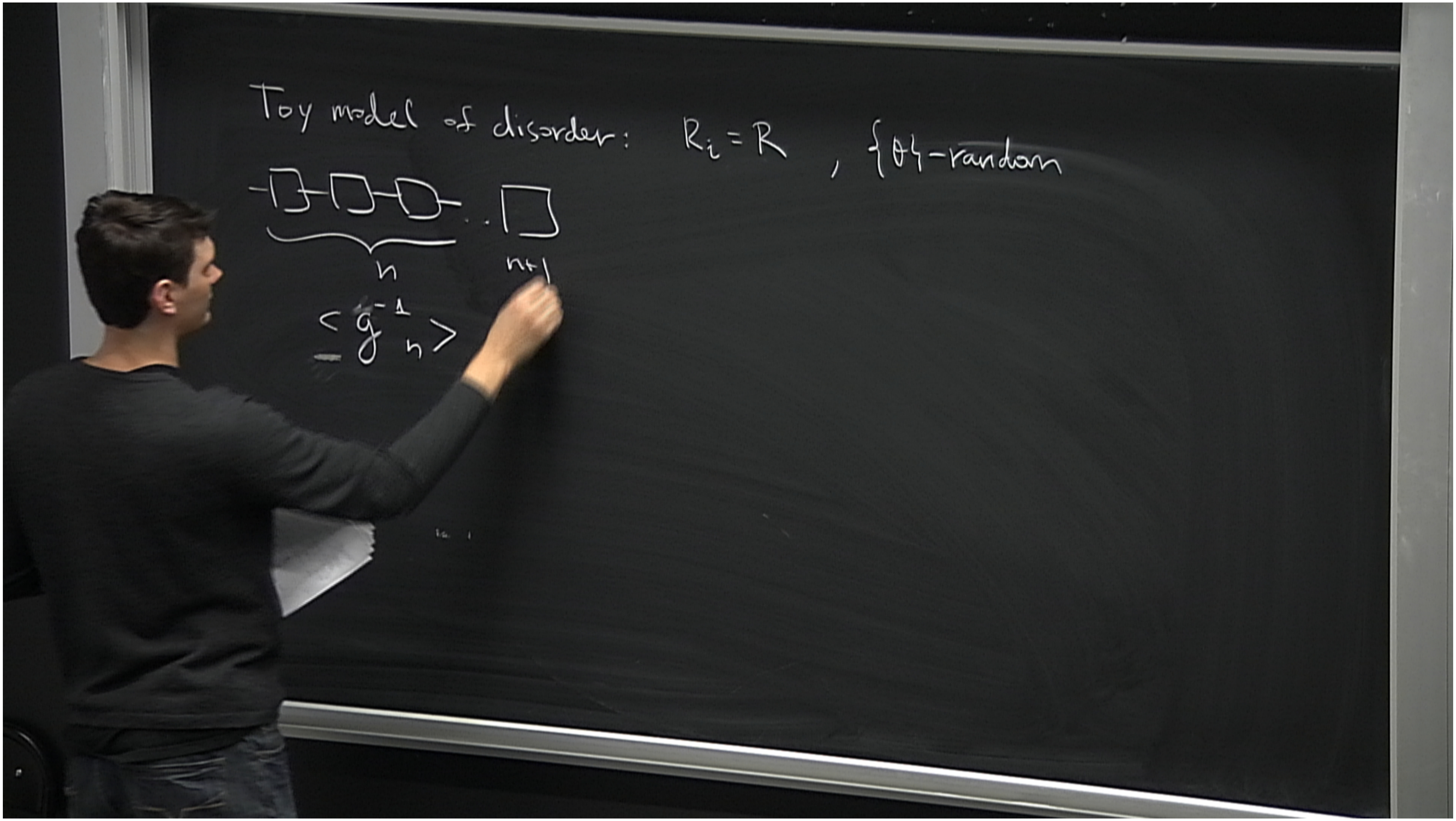

Landauer – localiz.
e^{ikx}
Be^{-ikx}
Ce^{ikx}
De^{-ikx}
te^{ikx}
1
2
S_1
S_2
$\begin{bmatrix} r_1 & t_1 \\ t_1 & r_1' \end{bmatrix}$
$\begin{bmatrix} r_2 & t_2 \\ t_2 & r_2' \end{bmatrix}$
$t = \dfrac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r_1'}$
$\theta = 2\varphi + \arg(r_2 r_1')$

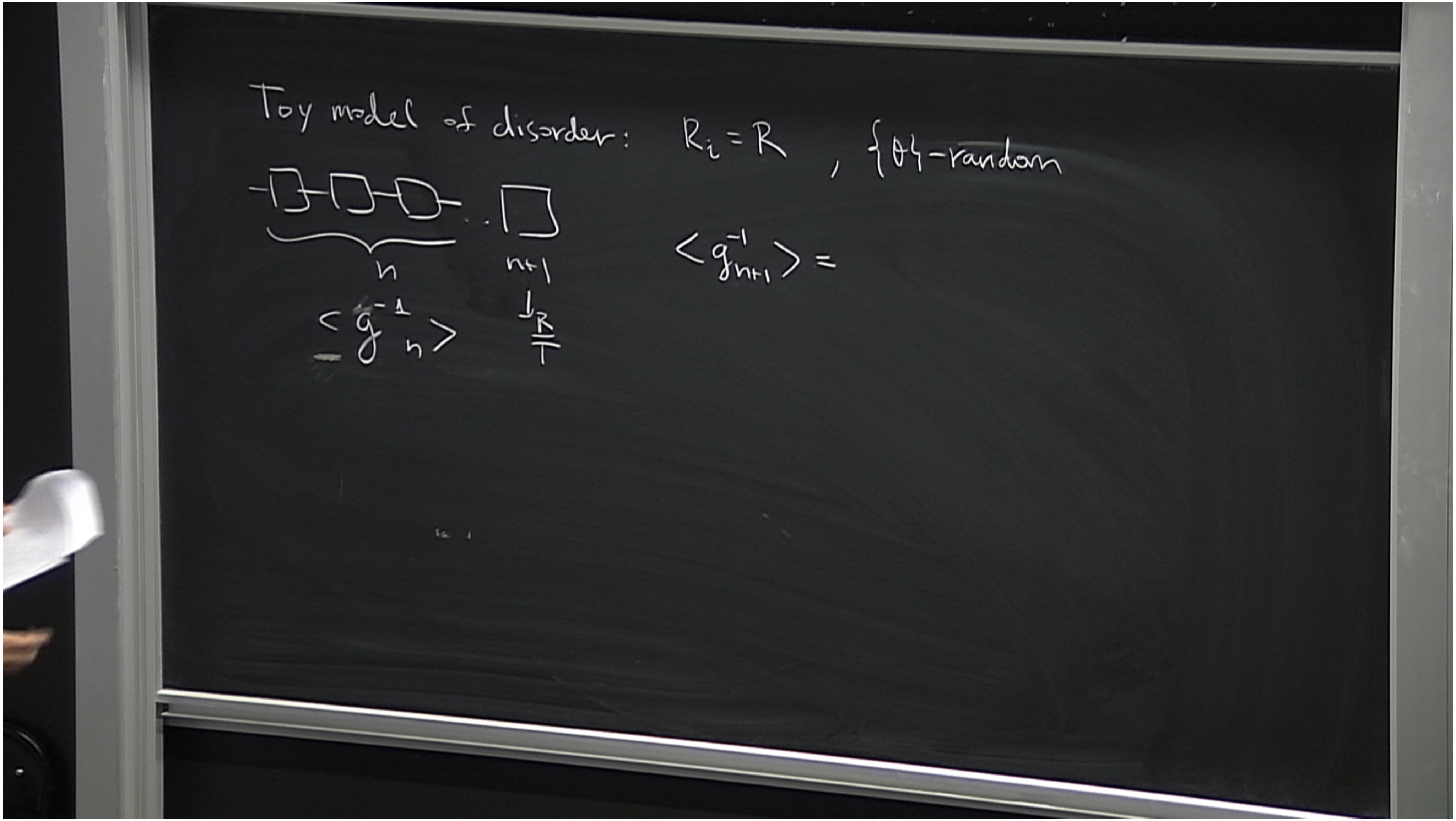

Landauer - localiz.
e^{ikx}
Ce^{ikx}
te^{ikx}
Be^{-ikx}
1
De^{-ikx}
2
S_1
S_2
$t = \frac{e^{i\varphi} \cdot t_1 t_2}{1 - e^{2i\varphi} r_2 r_1'}$
$T = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cdot \cos\theta}$
$\theta = 2\varphi + \arg(r_2 r_1')$
$g_{4T}^{-1} = \frac{R}{T} = \frac{R_1 + R_2 - 2\sqrt{R_1 R_2} \cos\theta}{T_1 T_2}$
* Strong mesosc. fluctuations

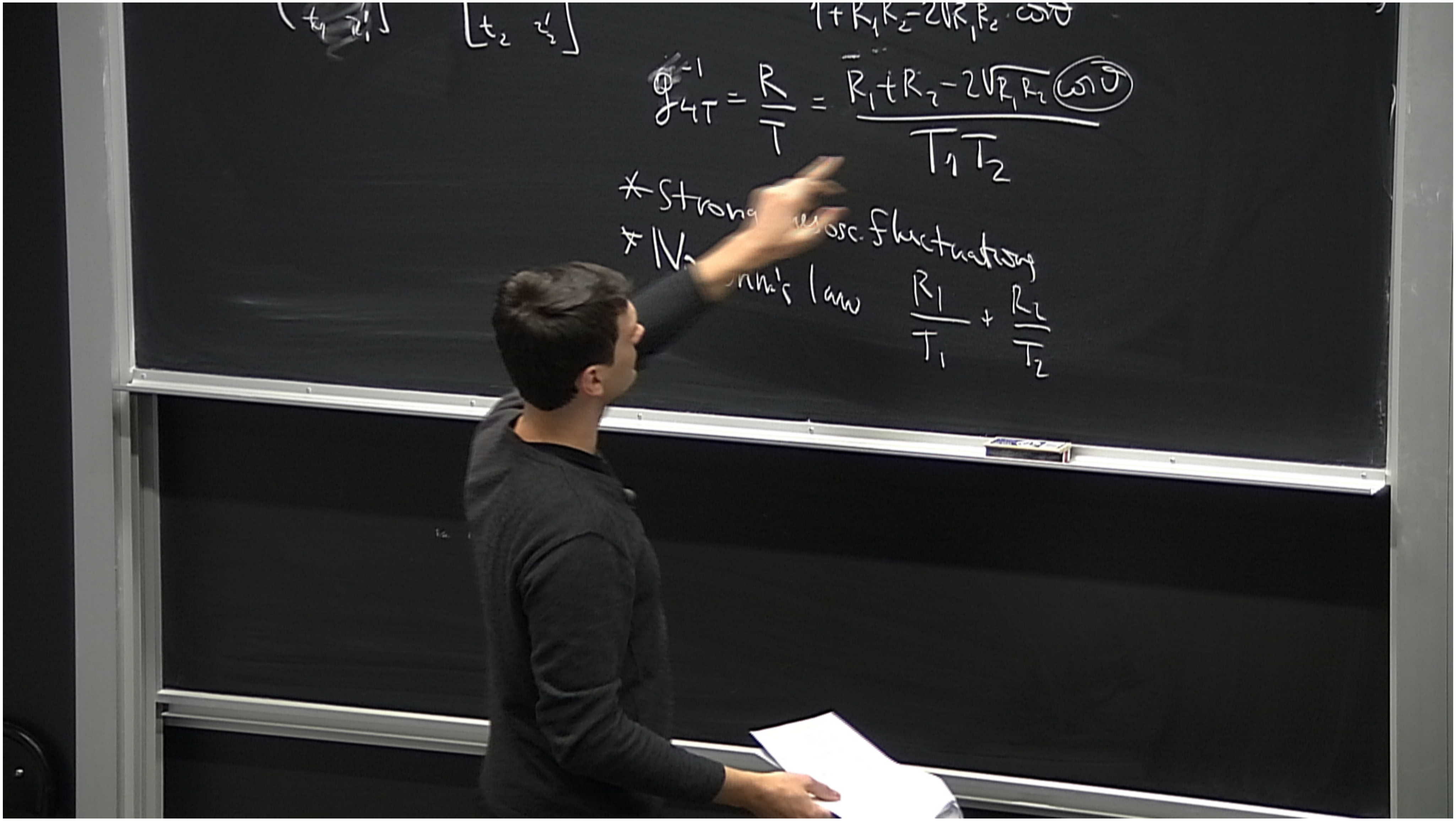

Toy model of disorder: $R_i = R$, {

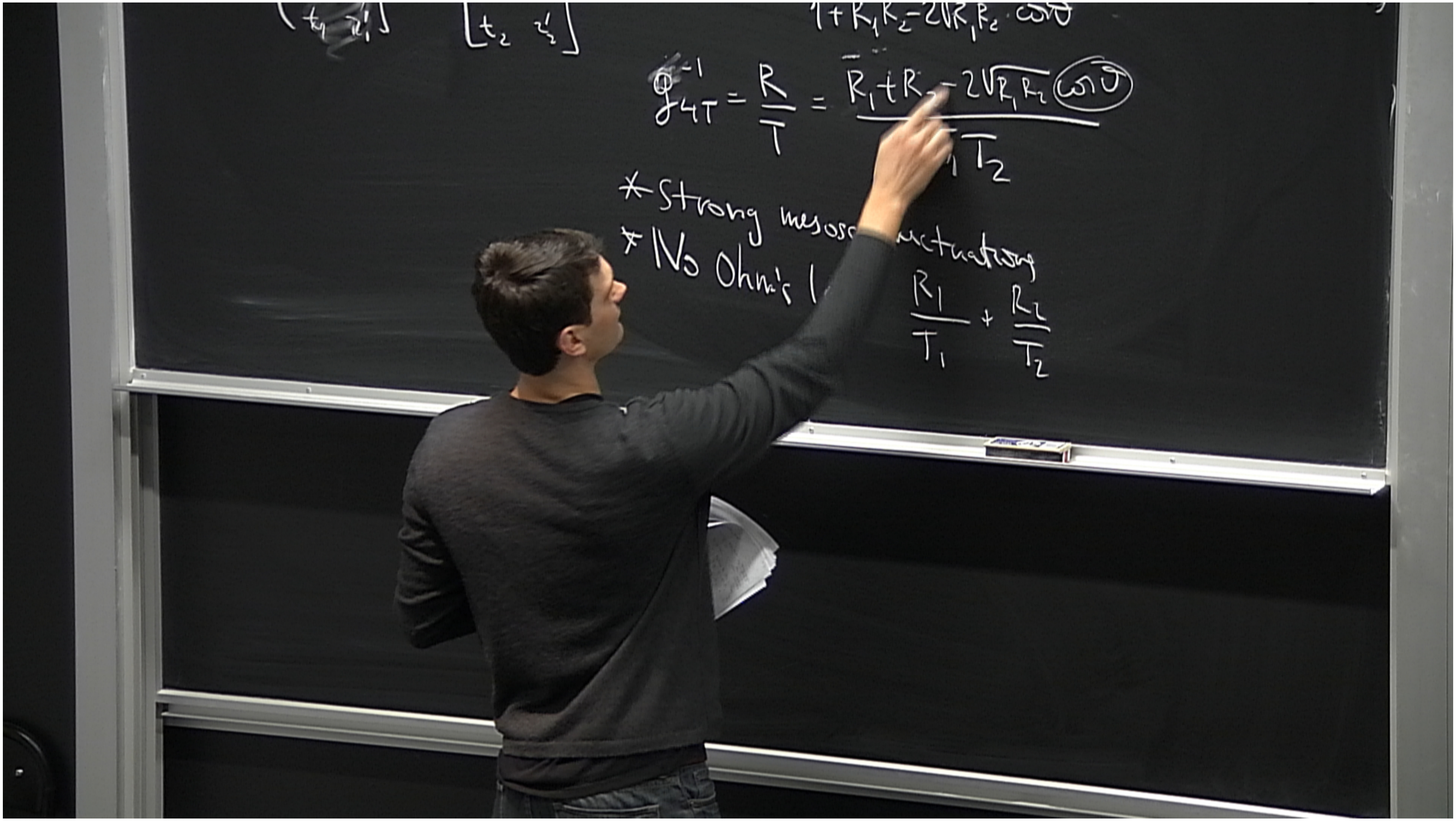


Toy model of disorder: $R_i = R$, $\{\theta\}$-random

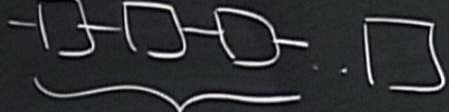

Toy model of disorder: $R_i = R$, $\{\theta\}$-random
n
n+1
$\langle g^{-1}_n \rangle$


Toy model of disorder: $R_i = R$, $\{\theta\}$-random
n
n+1
$\langle g_n^{-1} \rangle$
$\langle g_{n+1}^{-1} \rangle =$




* Strong
* No Ohm's

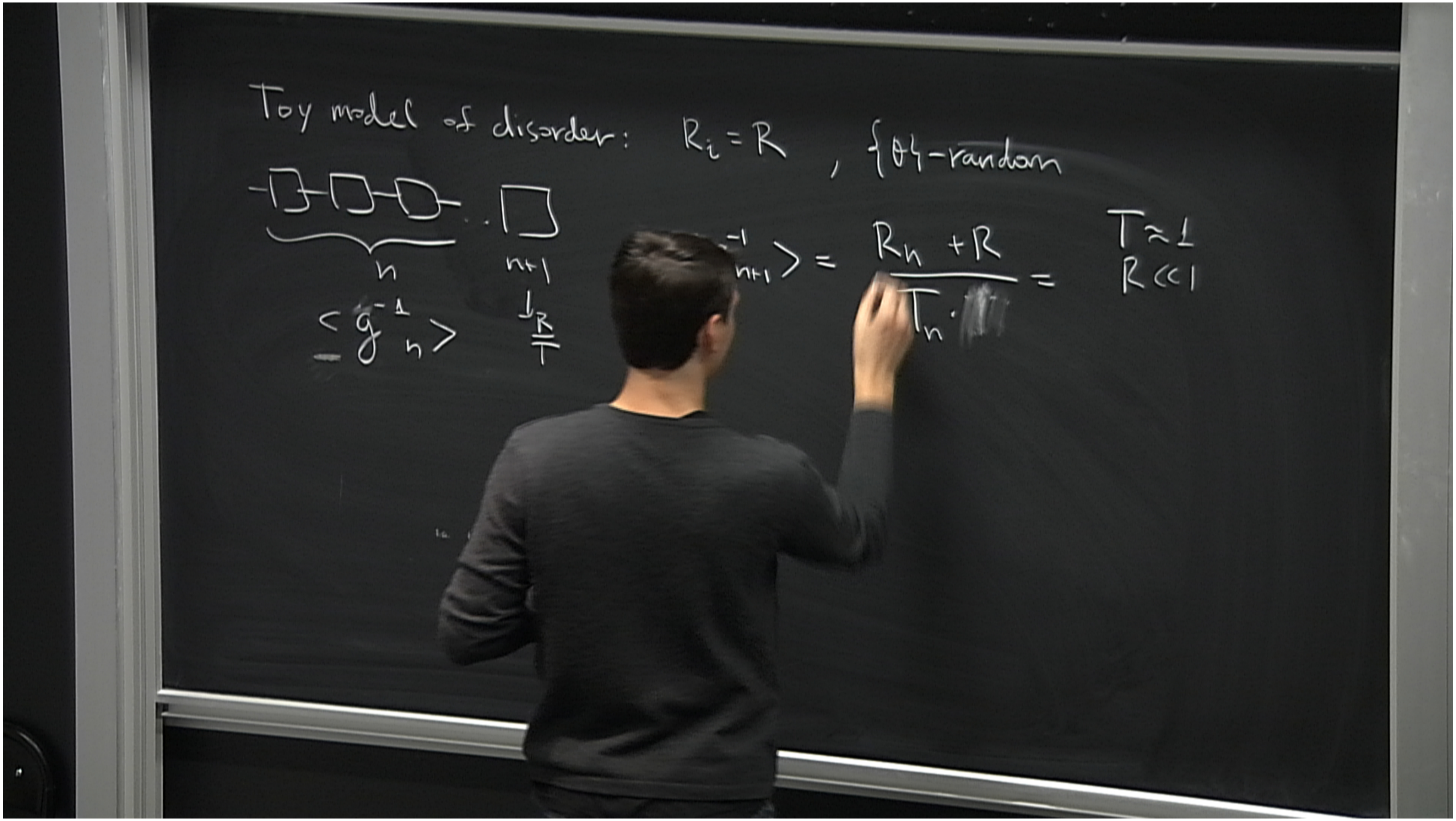
Toy model of disorder: $R_i = R$, $\{\theta\}$-random

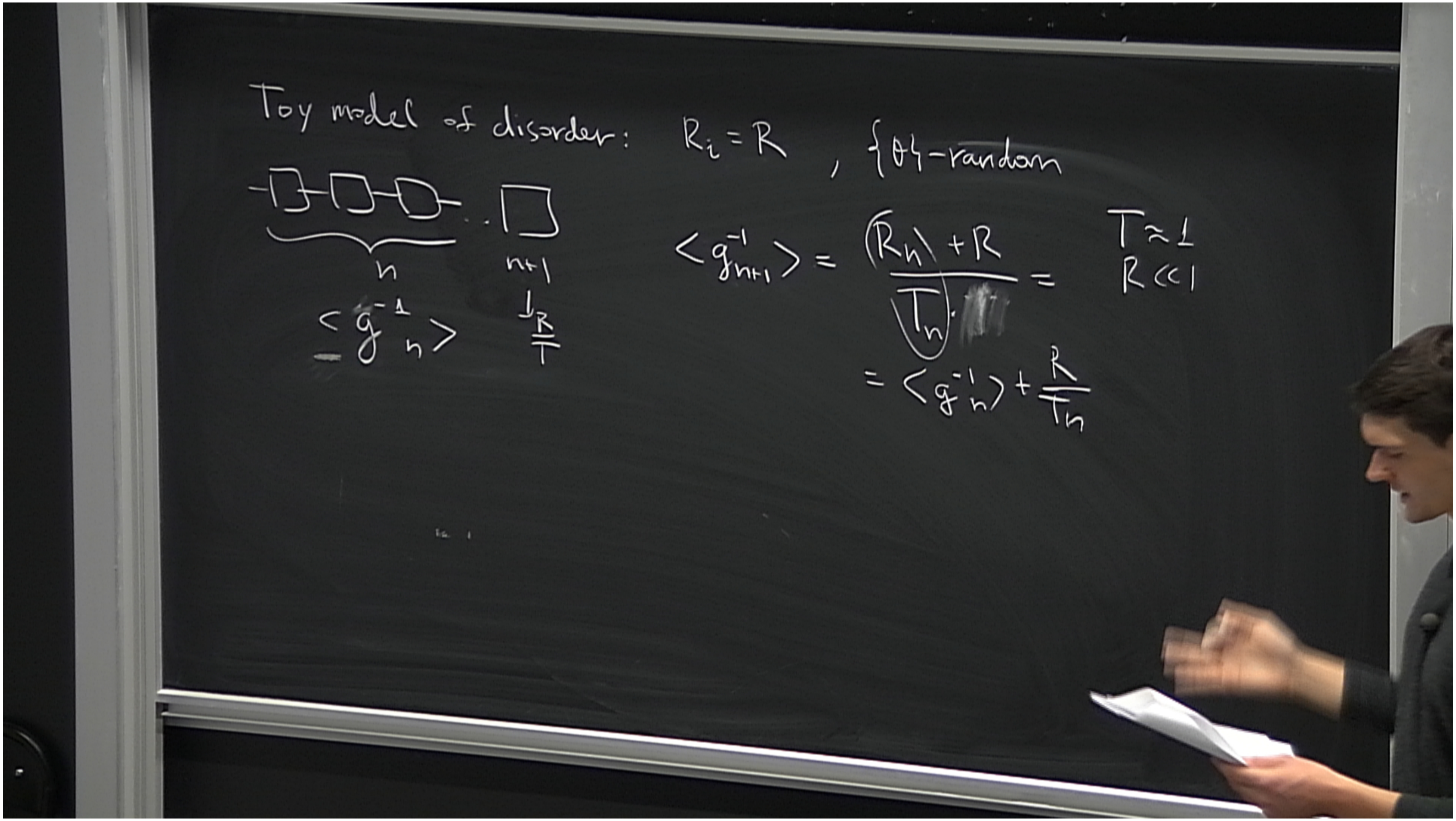


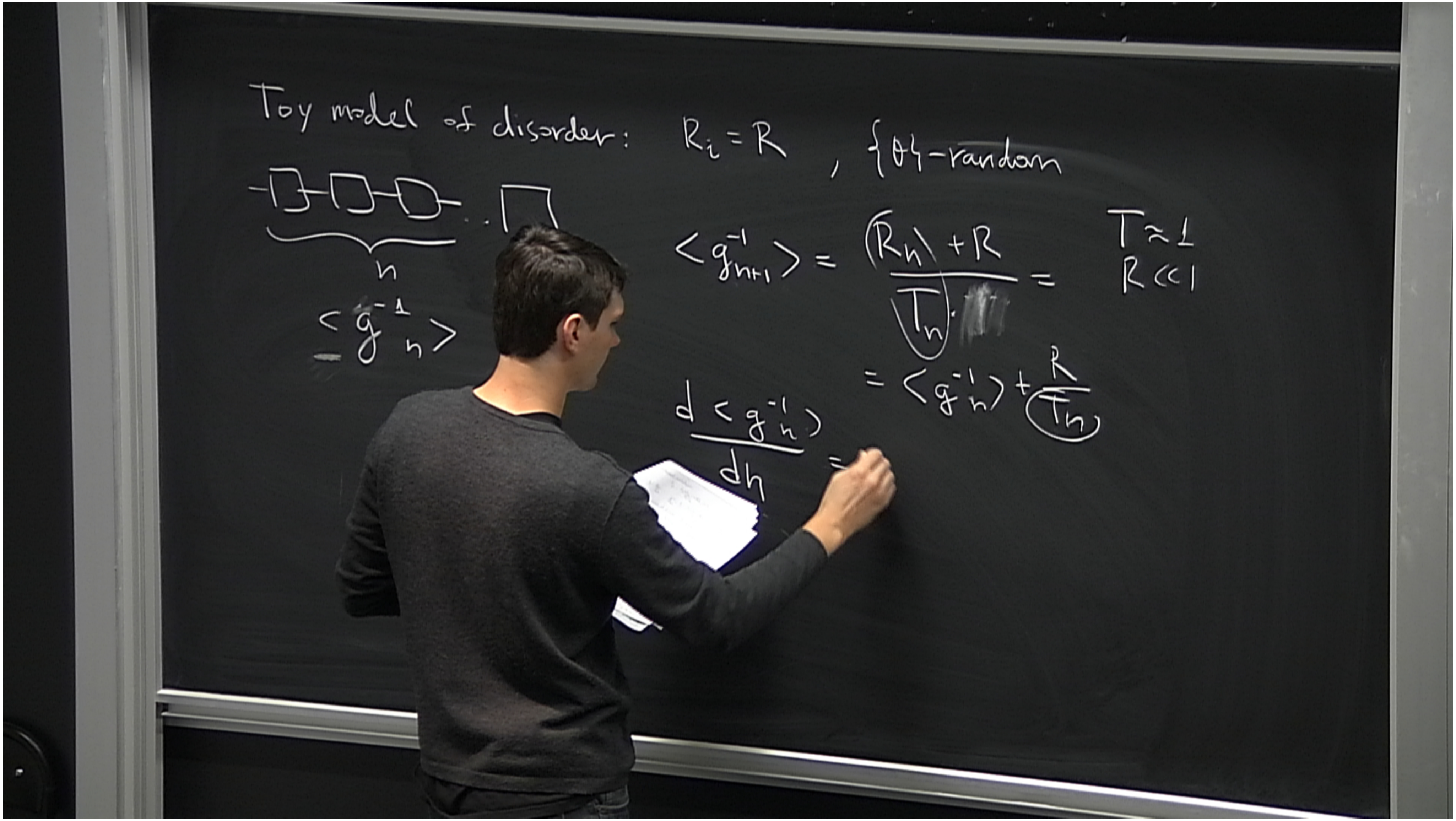
n $\qquad$ $n+1$

$\langle g^{-1}_{n} \rangle$ $\qquad$ $\frac{R}{T}$

$$\langle g^{-1}_{n+1} \rangle = \frac{R_n + R}{T_n \cdot T}$$


Toy model of disorder: R_i = R , {θ}-random
n
n+1
<g^-1 n>
T≈1
R<<1
R_n + R
T_n


Toy model of disorder: $R_i = R$, $\{\theta\}$-random
n
$n+1$
$\langle g^{-1}_n \rangle$
1
$\frac{R}{T}$
$\langle g^{-1}_{n+1} \rangle = \frac{R_n + R}{T_n} =$
$= \langle g^{-1}_n \rangle + \frac{R}{T_n}$
$T \approx 1$
$R \ll 1$


Toy model of disorder: Ri = R , {θ}-random
n
<g-1n>
<g-1n+1> = (Rn + R) / Tn =
T ≈ 1
R << 1
= <g-1n> + R / Tn
d<g-1n> / dn =

Toy model of disorder: $R_i = R$, $\{\theta\}$-random

n $\quad$ $n+1$

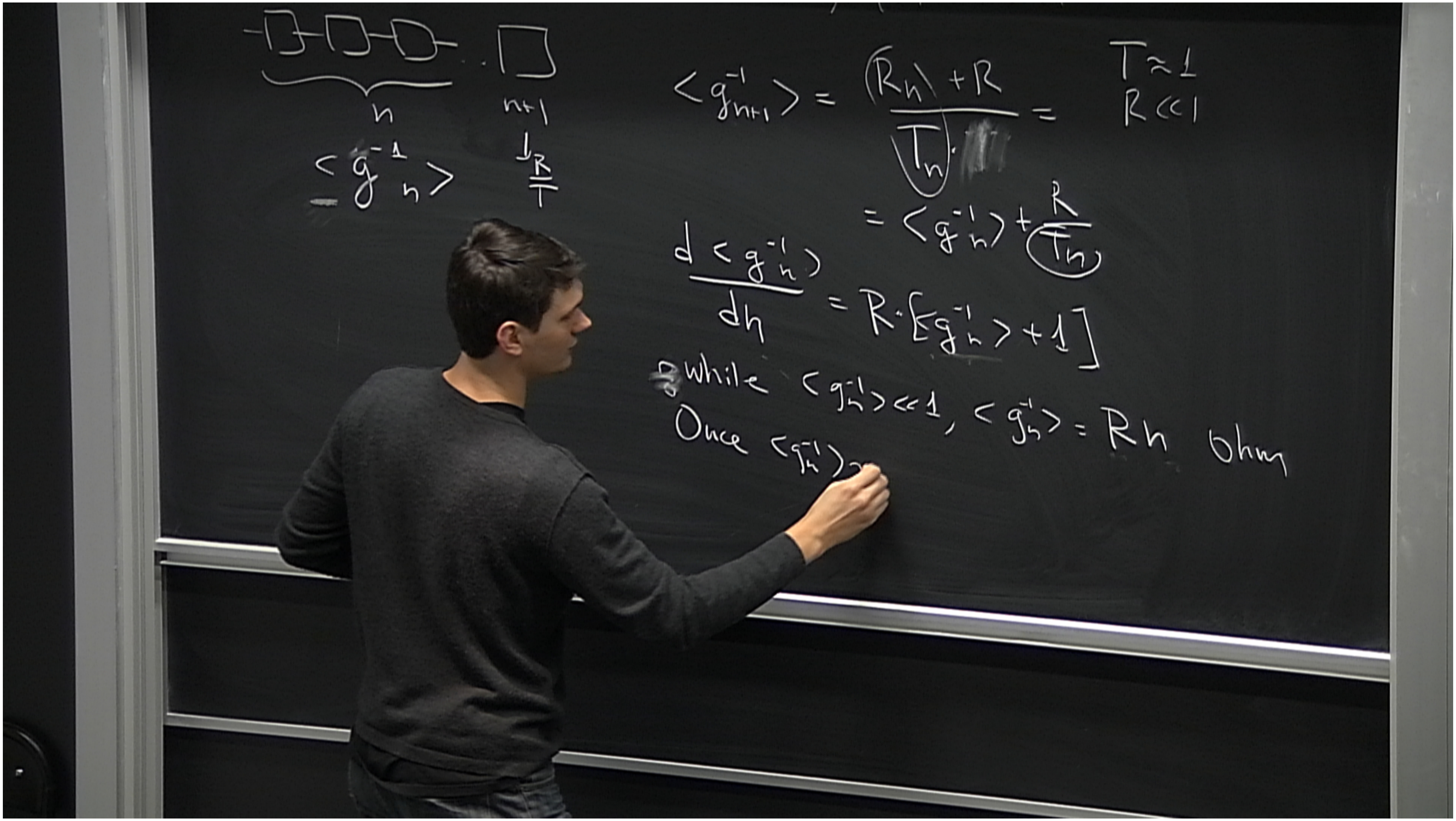
$\langle g^{-1}_{n} \rangle$ $\quad$ $1\ \frac{R}{T}$

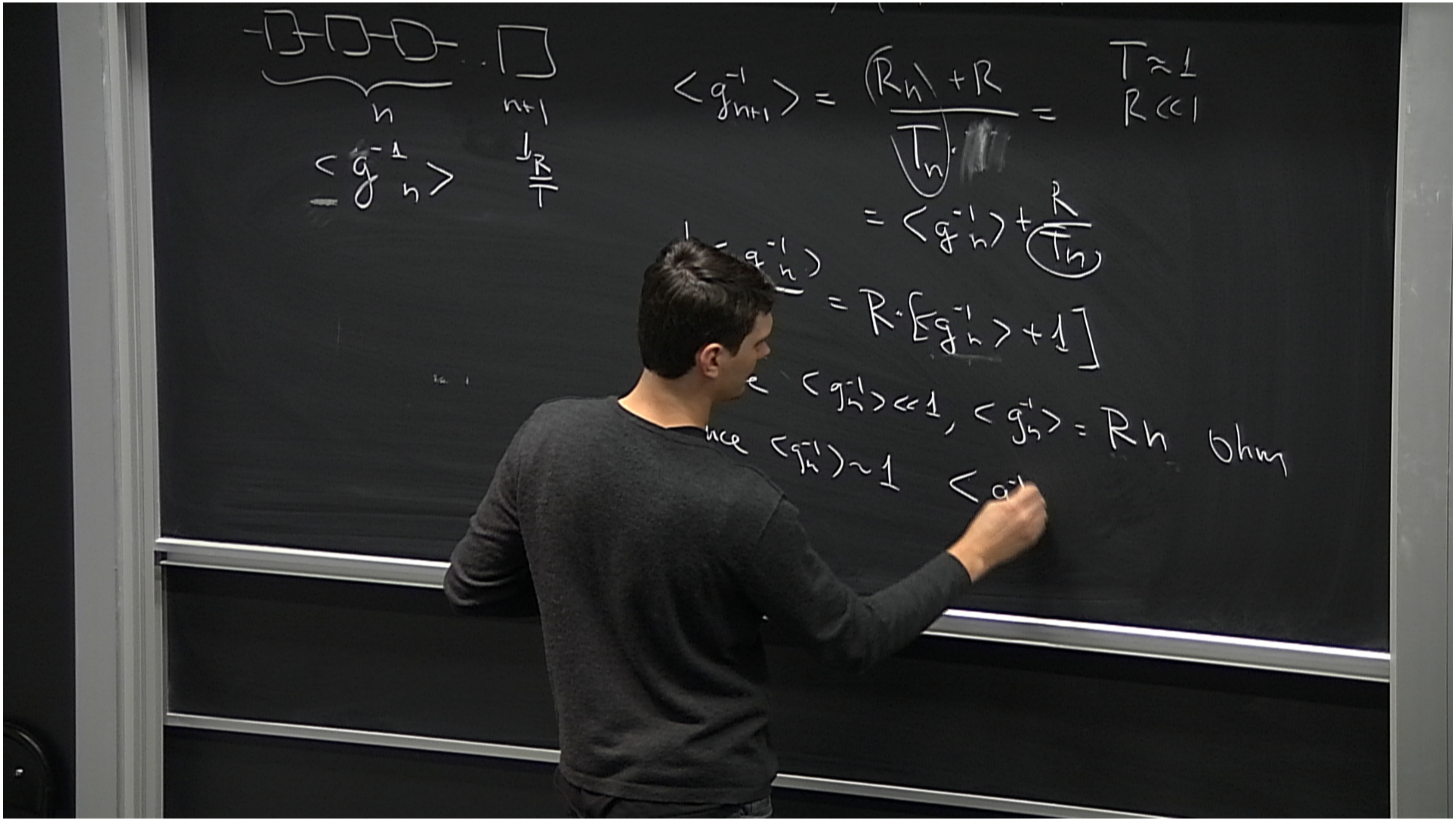
$$\langle g^{-1}_{n+1} \rangle = \frac{R_n + R}{T_n} = \langle g^{-1}_{n} \rangle + \frac{R}{T_n}$$

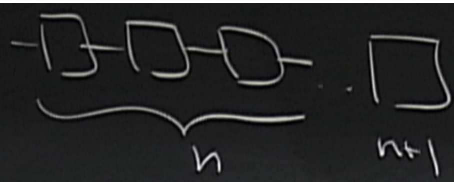
$T \approx 1$

$R \ll 1$

$$\frac{d \langle g^{-1}_{n} \rangle}{dn} = R \cdot [\langle g^{-1}_{n} \rangle + 1]$$


n
n+1
$\langle g^{-1}_{n} \rangle$
$\langle g^{-1}_{n+1} \rangle = \frac{R_n + R}{T_n} =$
$T \approx 1$
$R \ll 1$
$= \langle g^{-1}_{n} \rangle + \frac{R}{T_n}$
$\frac{d \langle g^{-1}_{n} \rangle}{dn} = R \cdot [\langle g^{-1}_{n} \rangle + 1]$
while $\langle g^{-1}_{n} \rangle \ll 1$, $\langle g^{-1}_{n} \rangle = Rn$ Ohm
Once $\langle g^{-1}_{n} \rangle$


T ≈ 1
R << 1
= R·[<g_n^-1> + 1]
Ohm



$\langle g^{-1}_{n} \rangle$ $\quad \frac{R}{T}$

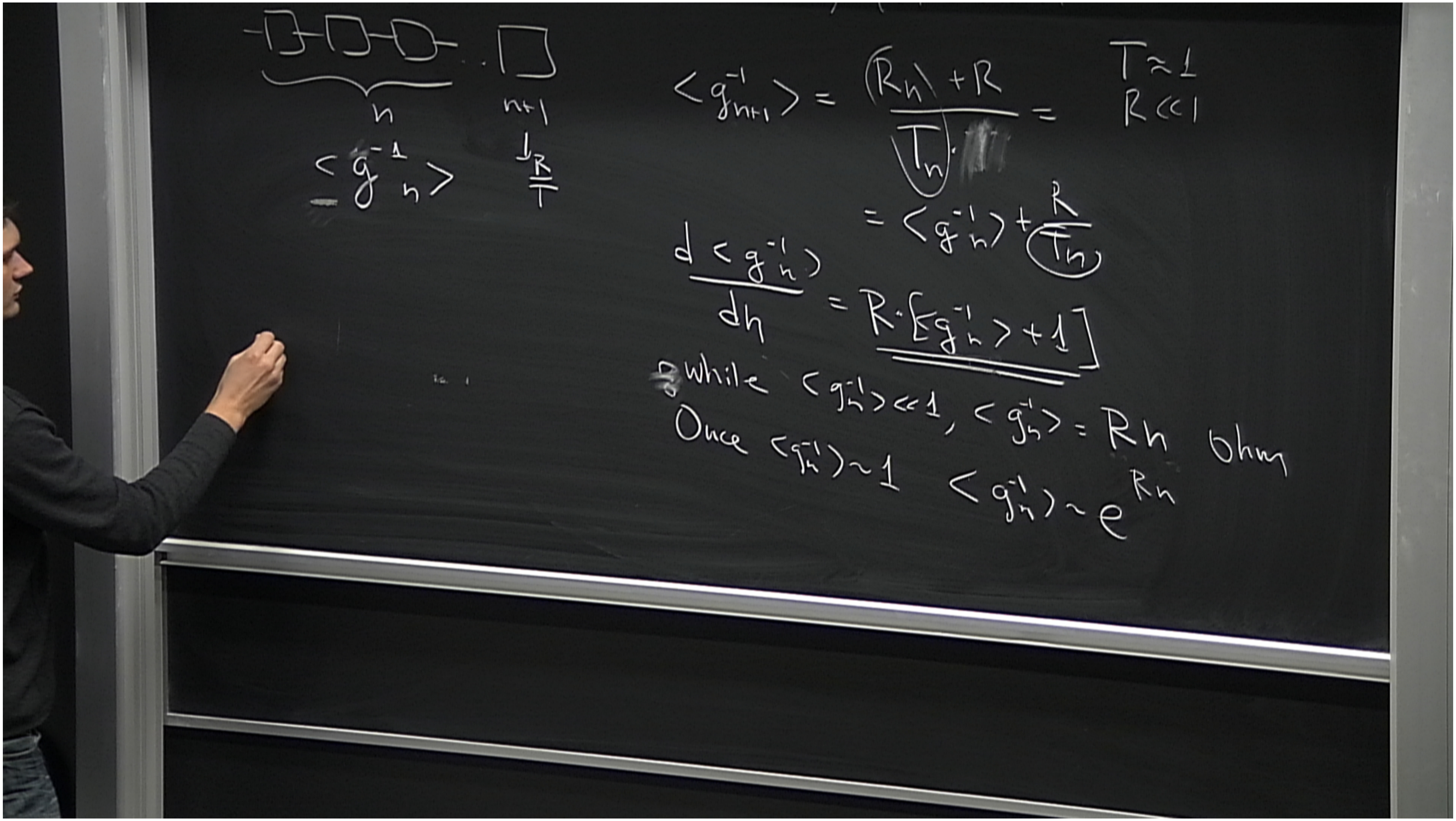
$$\langle g^{-1}_{n+1} \rangle = \frac{R_n + R}{T_n} = \qquad T \approx 1, \quad R \ll 1$$

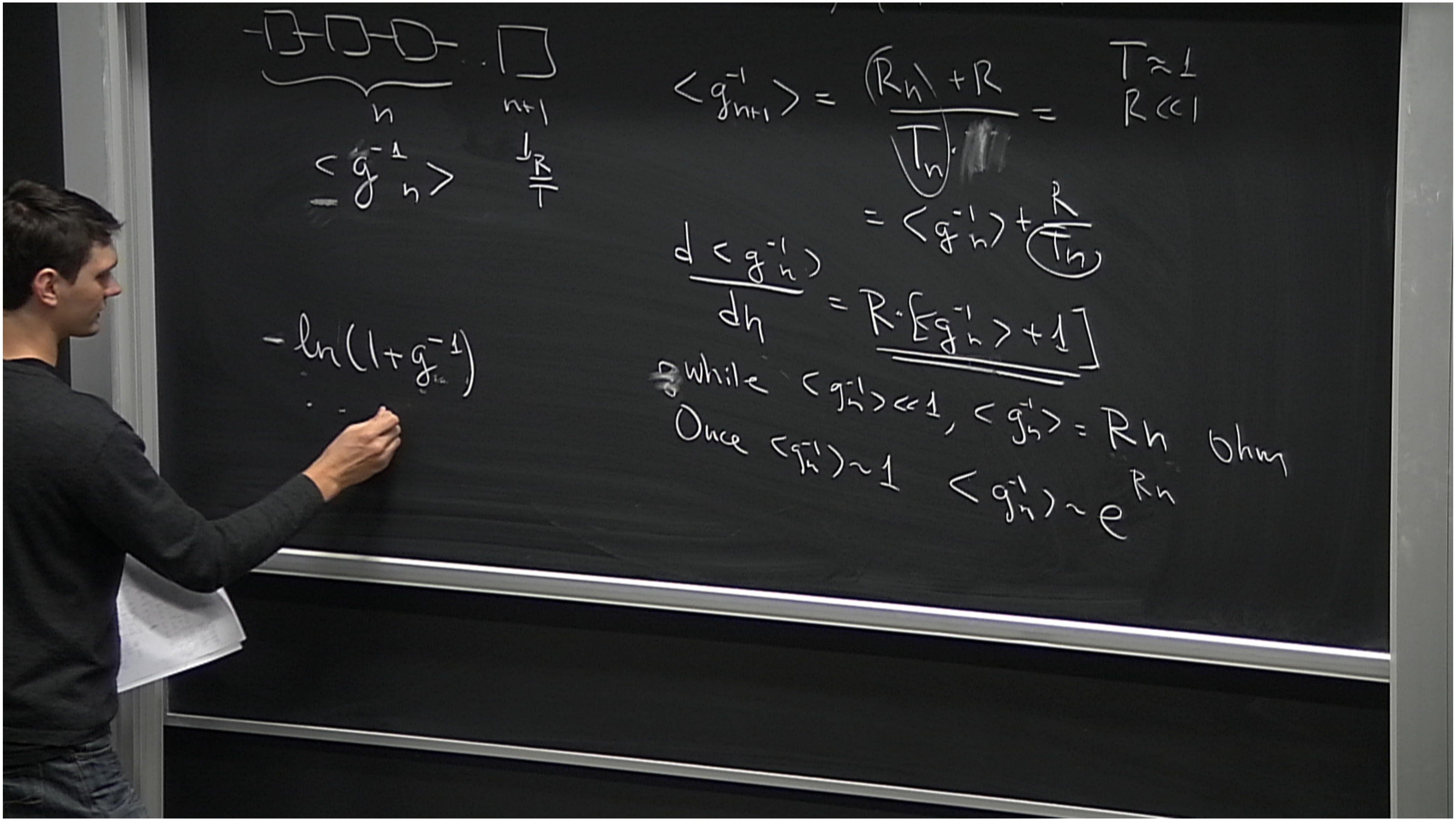
$$= \langle g^{-1}_{n} \rangle + \frac{R}{T_n}$$

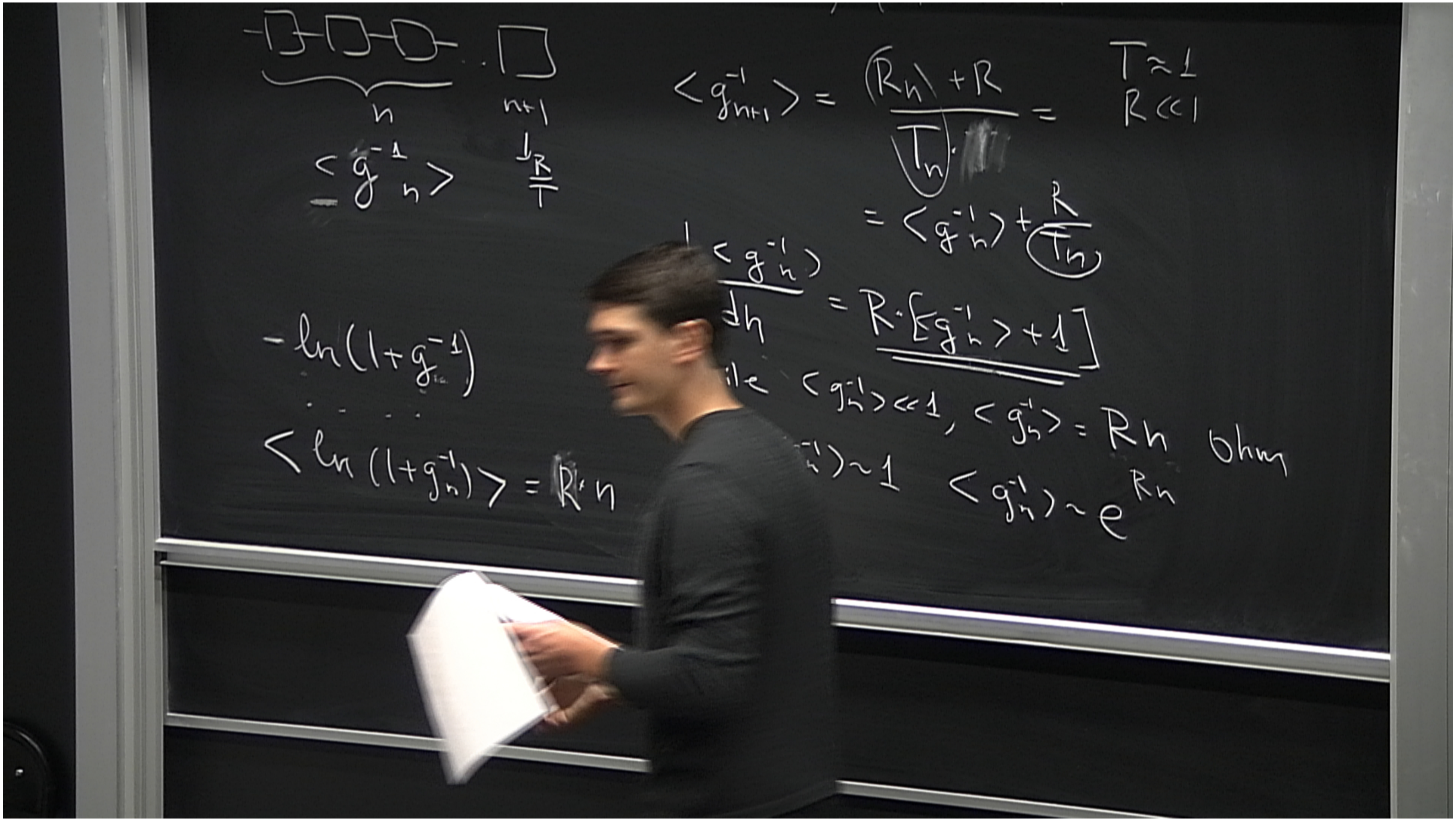
$$\frac{d\langle g^{-1}_{n} \rangle}{dn} = \underline{\underline{R \cdot [\langle g^{-1}_{n} \rangle + 1]}}$$

while $\langle g^{-1}_{n} \rangle \ll 1$, $\langle g^{-1}_{n} \rangle = Rn$ Ohm

Once $\langle g^{-1}_{n} \rangle \sim 1$ $\quad \langle g^{-1}_{n} \rangle \sim e^{Rn}$


n
n+1
$\langle g^{-1}_n \rangle$
$\frac{R}{T}$
$\langle g^{-1}_{n+1} \rangle = \frac{\langle g^{-1}_n \rangle + R}{T_n} =$
$T \approx 1$
$R \ll 1$
$= \langle g^{-1}_n \rangle + \frac{R}{T_n}$
$\frac{d \langle g^{-1}_n \rangle}{dn} = R \cdot [\langle g^{-1}_n \rangle + 1]$
while $\langle g^{-1}_n \rangle \ll 1$, $\langle g^{-1}_n \rangle = Rn$ Ohm
Once $\langle g^{-1}_n \rangle \sim 1$ $\langle g^{-1}_n \rangle \sim e^{Rn}$


n
n+1
$\langle g^{-1}_n \rangle$
$\frac{1}{R} / T$
$\langle g^{-1}_{n+1} \rangle = \frac{R_n + R}{T_n} =$
$T \approx 1$
$R \ll 1$
$= \langle g^{-1}_n \rangle + \frac{R}{T_n}$
$\frac{d \langle g^{-1}_n \rangle}{dn} = R \cdot [\langle g^{-1}_n \rangle + 1]$
$-\ln(1+g^{-1})$
while $\langle g^{-1}_n \rangle \ll 1$, $\langle g^{-1}_n \rangle = Rn$ Ohm
Once $\langle g^{-1}_n \rangle \sim 1$ $\langle g^{-1}_n \rangle \sim e^{Rn}$


n
n+1
⟨g_n^{-1}⟩
1_R/T
⟨g_{n+1}^{-1}⟩ = (R_n + R)/T_n =
T ≈ 1
R << 1
= ⟨g_n^{-1}⟩ + R/T_n
= R·[⟨g_n^{-1}⟩ + 1]
-ln(1+g^{-1})
⟨ln(1+g_n^{-1})⟩ = R·n
⟨g_n^{-1}⟩ << 1, ⟨g_n^{-1}⟩ = Rn Ohm
)~1 ⟨g_n^{-1}⟩ ~ e^{Rn}