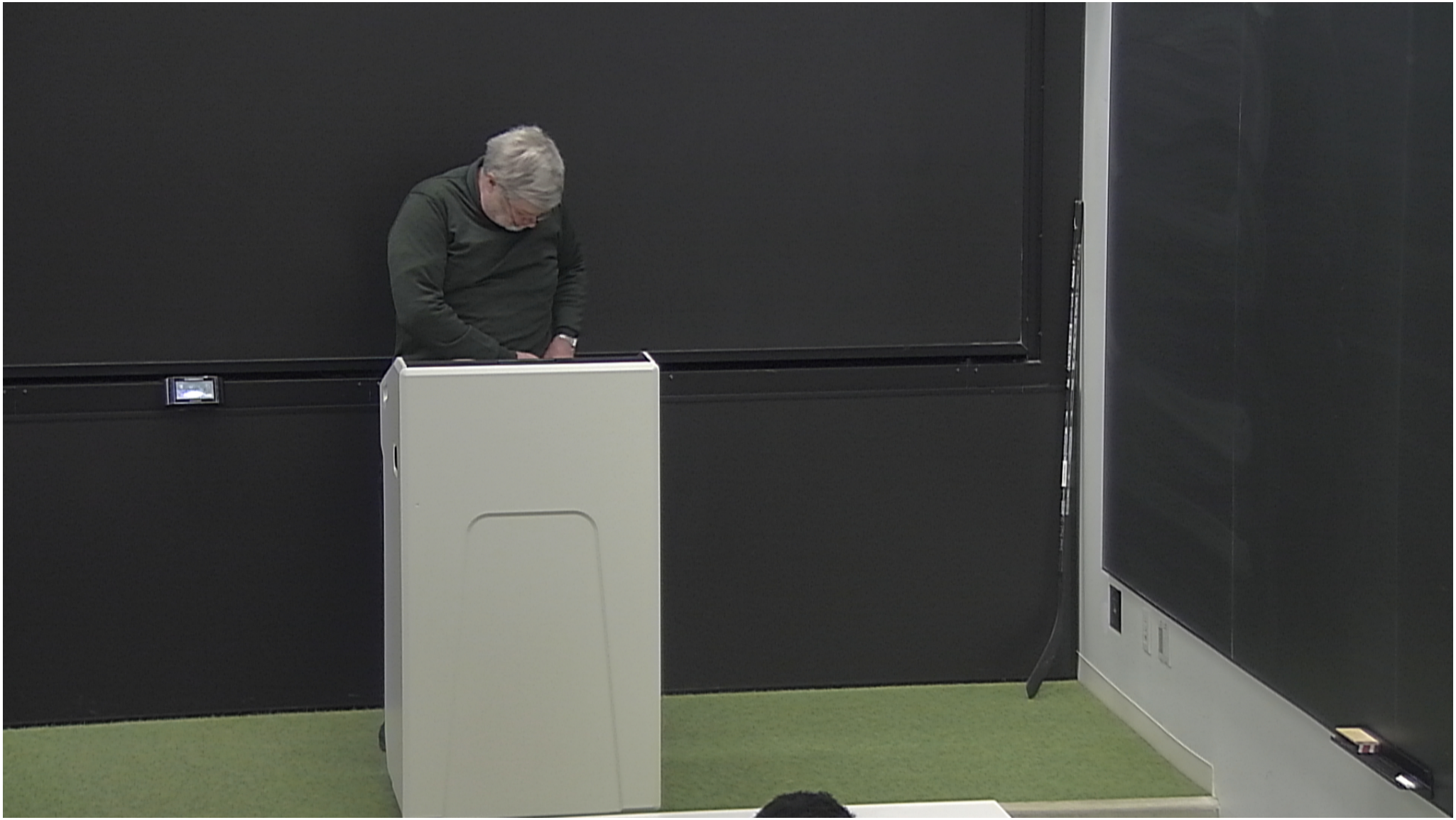
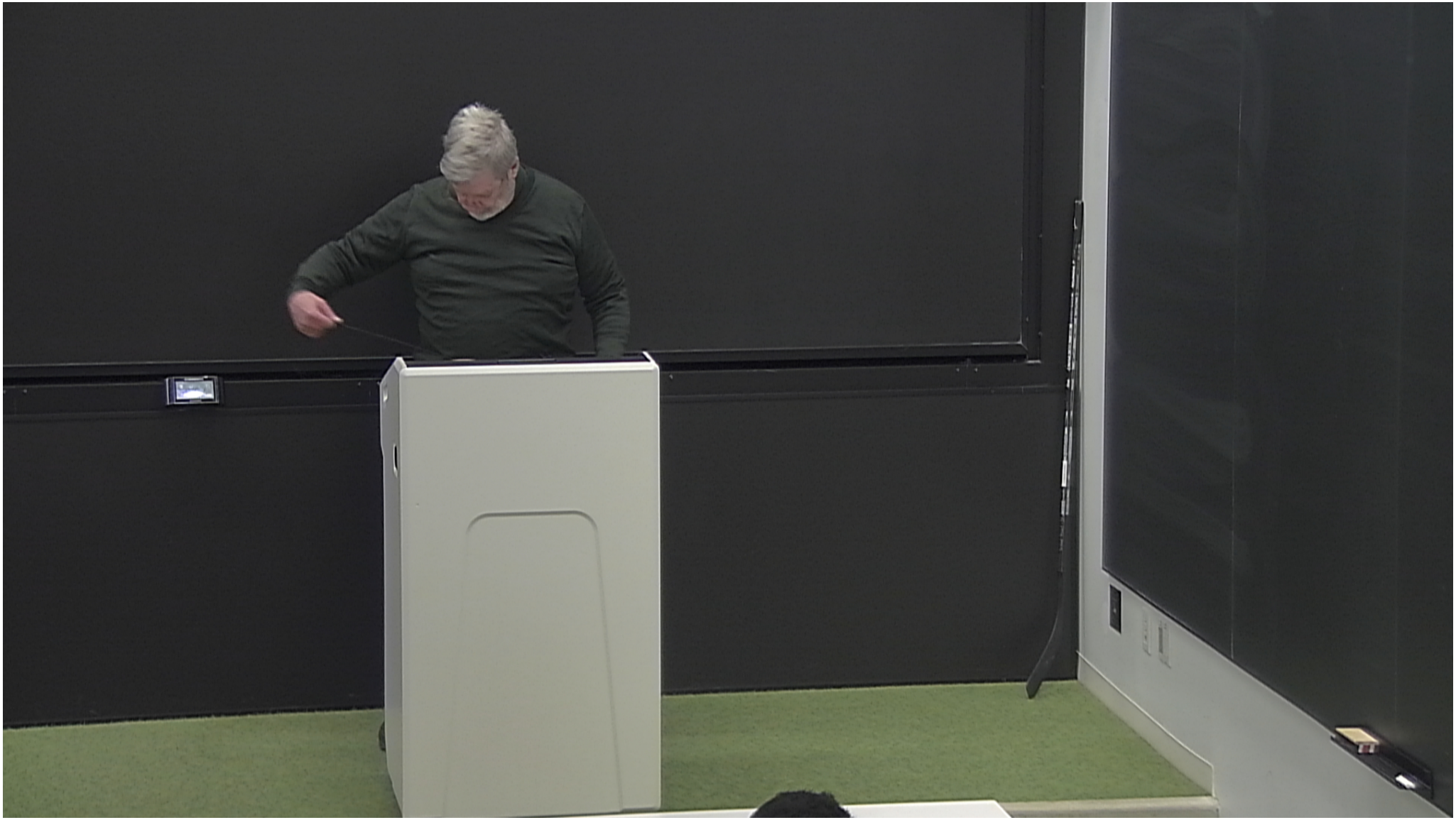
Title: 13/14 PSI - Standard Model Review - Lecture 6

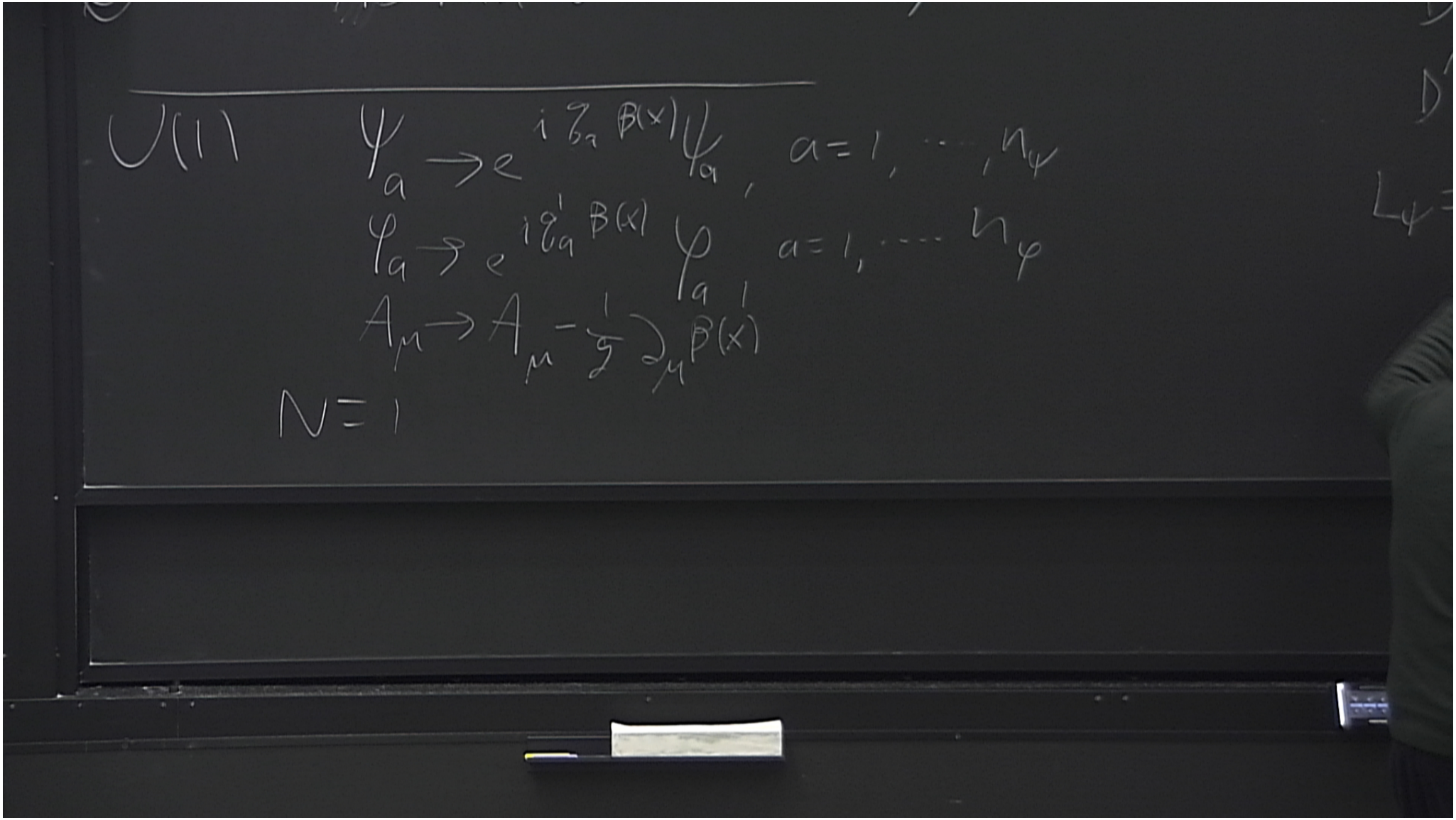
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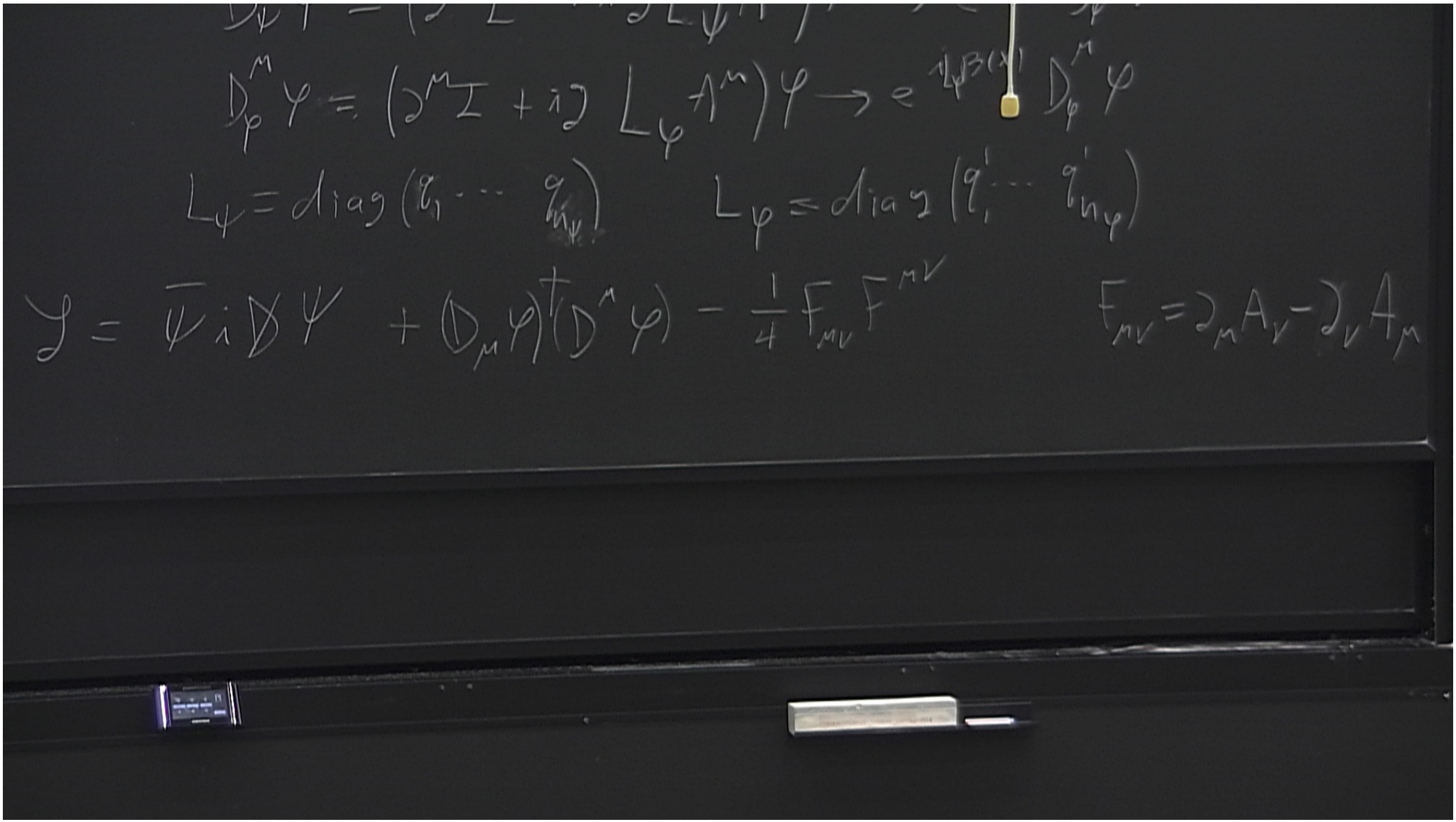
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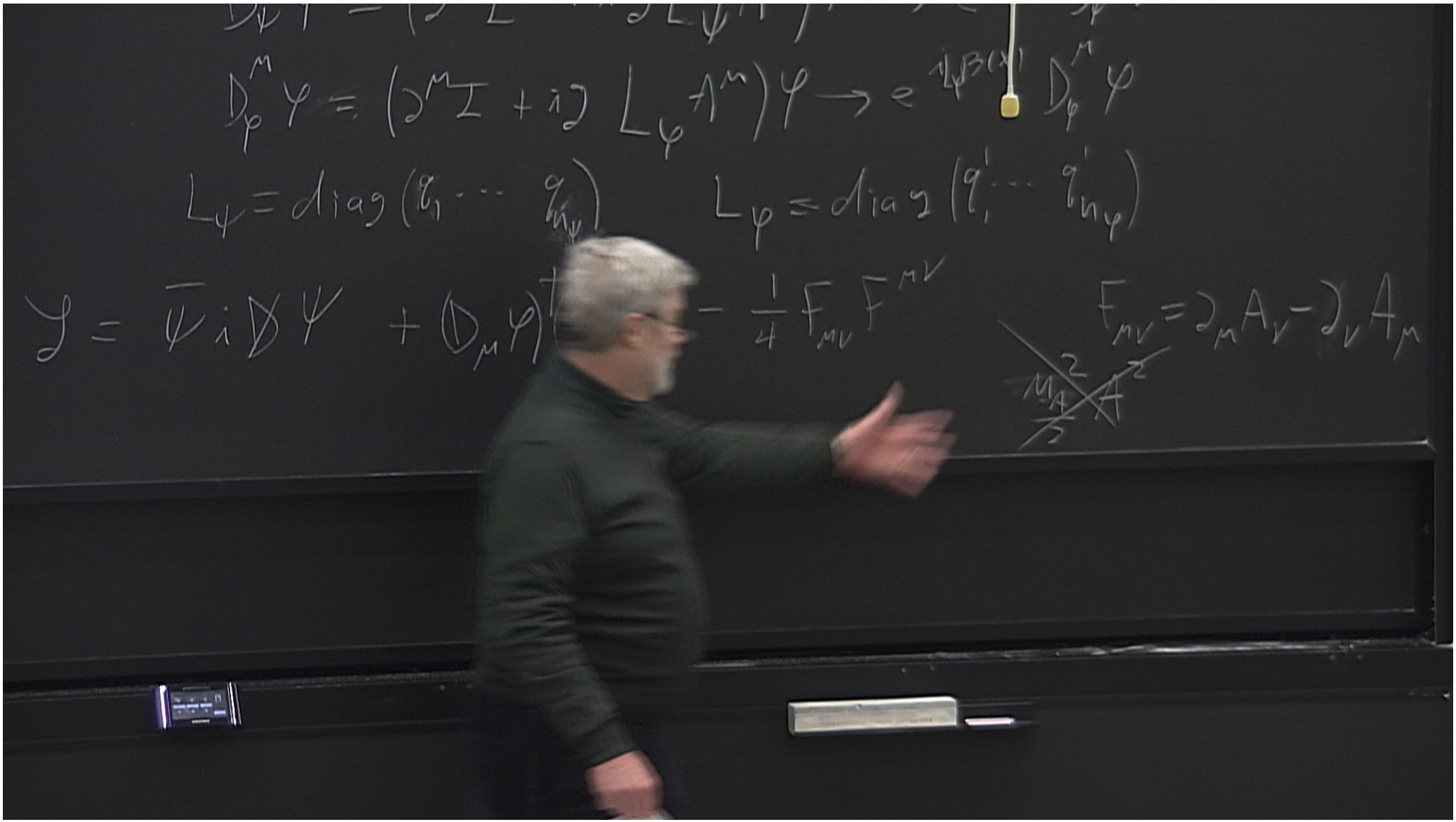
Abstract:

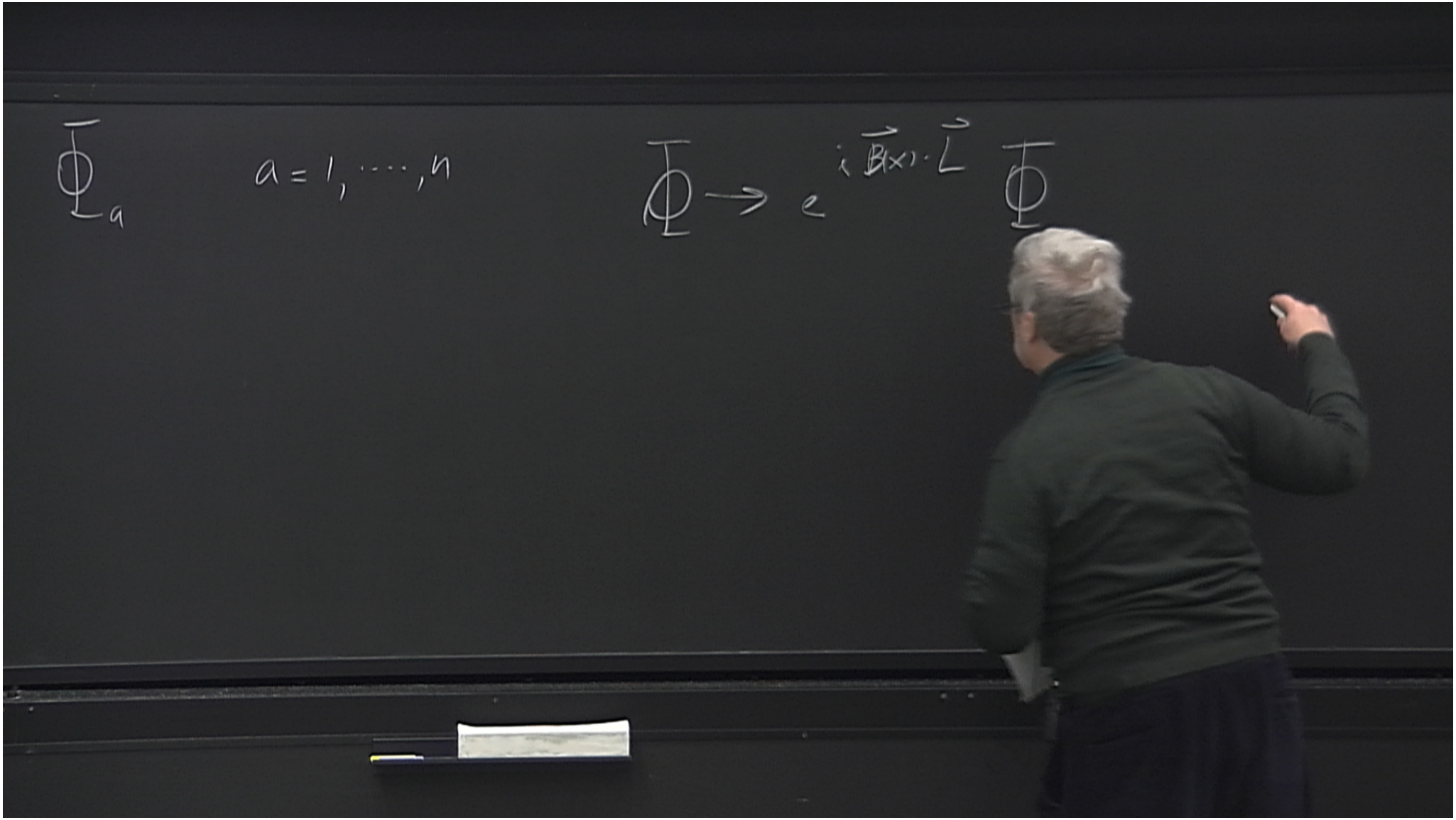


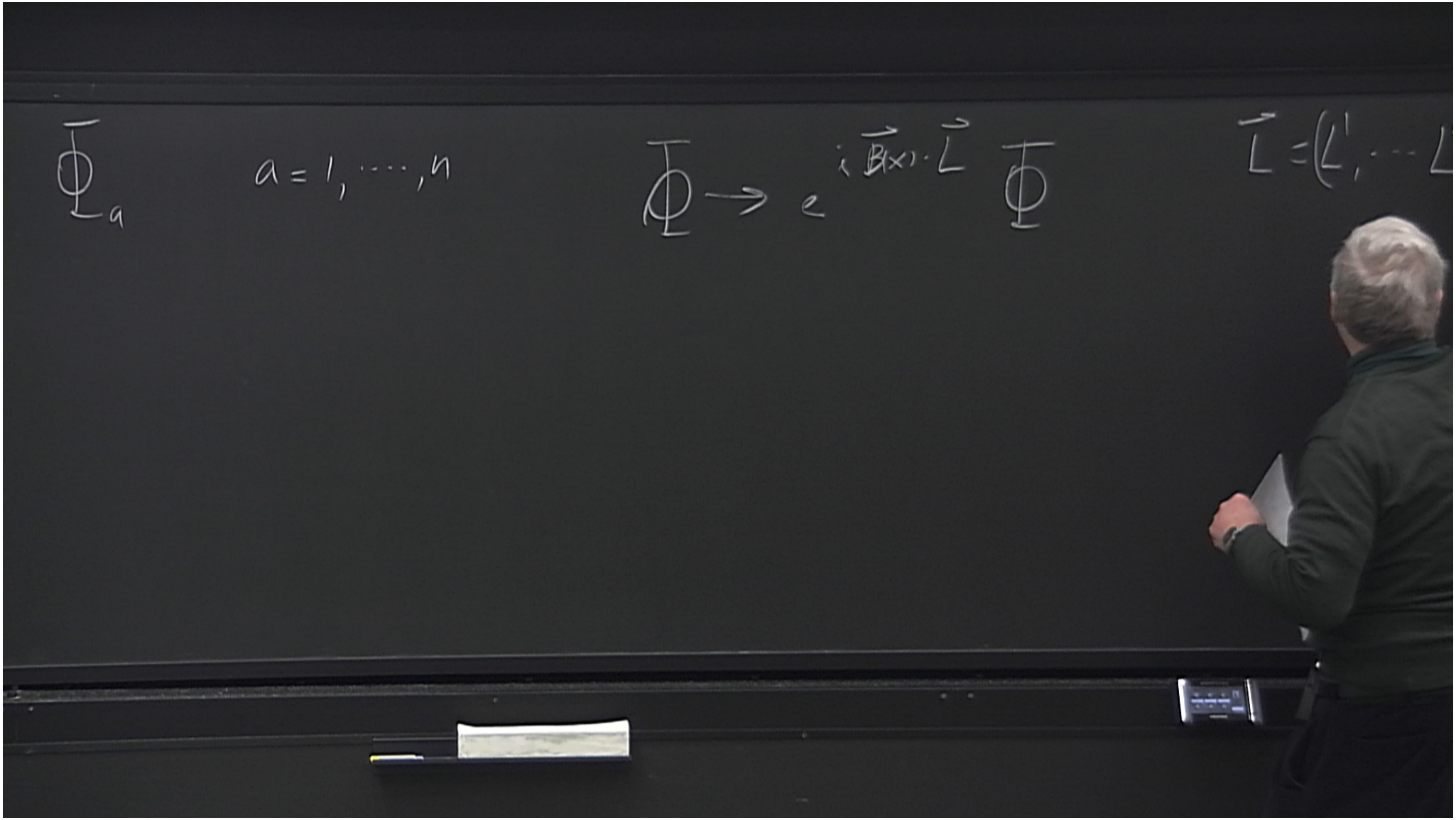



U(1)
$\psi_a \to e^{i q_a \beta(x)} \psi_a, \quad a = 1, \cdots, n_\psi$
$\varphi_a \to e^{i q'_a \beta(x)} \varphi_a \quad a = 1, \cdots n_\varphi$
$A_\mu \to A_\mu - \frac{1}{g} \partial_\mu \beta(x)$
N=1


$D_\phi^\mu \psi = (\partial^\mu I + i g L_\psi A^\mu)\psi \to e^{i\alpha B(x)} D_\phi^\mu \psi$
$L_\psi = \mathrm{diag}(q_1 \cdots q_{N_\psi})$
$L_\phi = \mathrm{diag}(q_1' \cdots q_{N_\phi}')$
$\mathcal{L} = \bar{\psi} i \not{D} \psi + (D_\mu \phi)^\dagger (D^\mu \phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

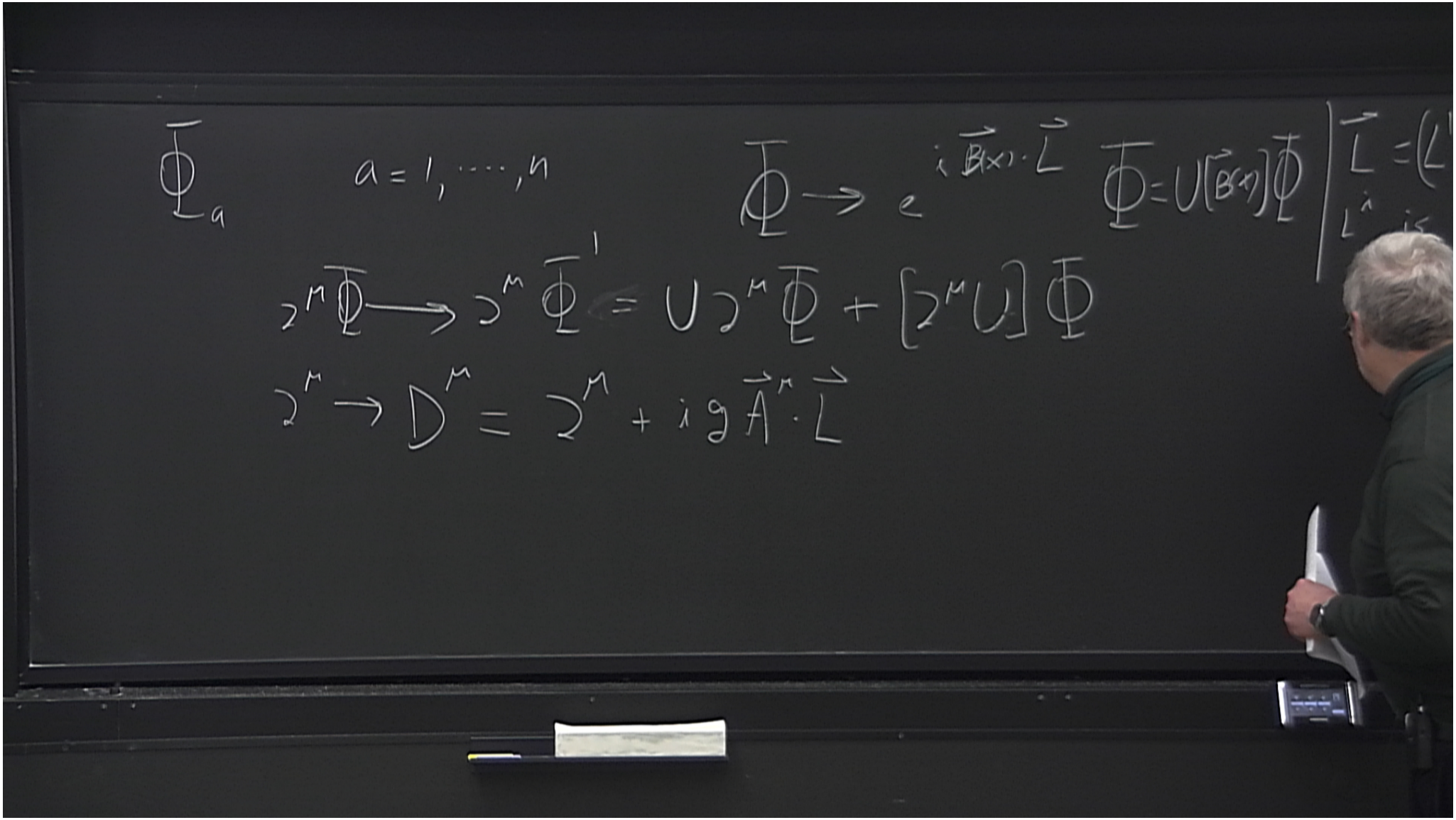

$D_\mu^M \psi = (\partial^M I + i g L_\psi A^M)\psi \to e^{i\alpha B(x)} D_\mu^M \psi$
$L_\psi = \mathrm{diag}(q_1 \cdots q_{n_\psi})$
$L_\varphi = \mathrm{diag}(q_1' \cdots q_{n_\varphi}')$
$\mathcal{L} = \bar{\psi} i \not{D} \psi + (D_\mu \varphi)^\dagger$
$- \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

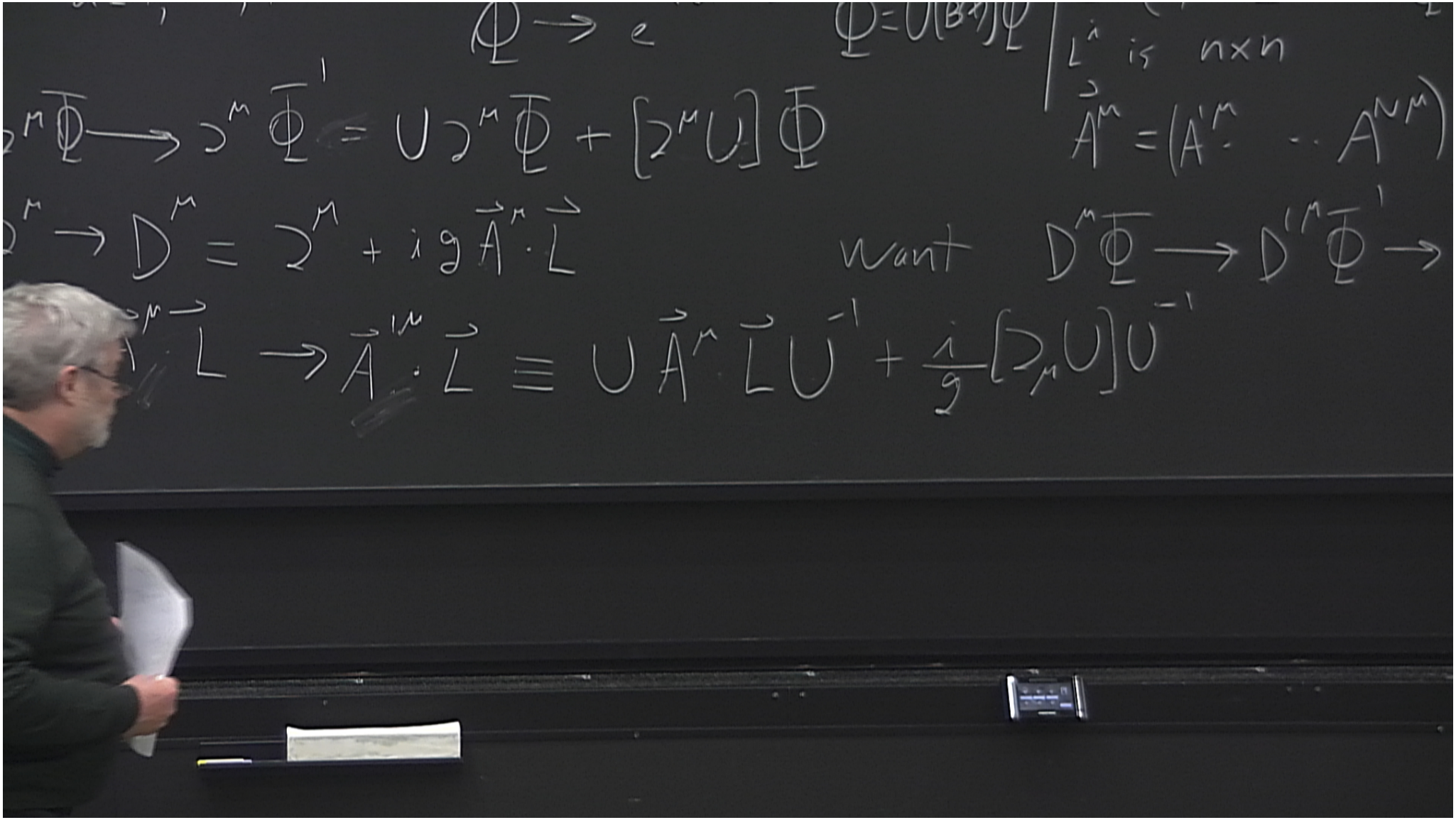

Φ_a
$a = 1, \cdots, n$
$\Phi \to e^{i \vec{B}(x) \cdot \vec{L}} \Phi$

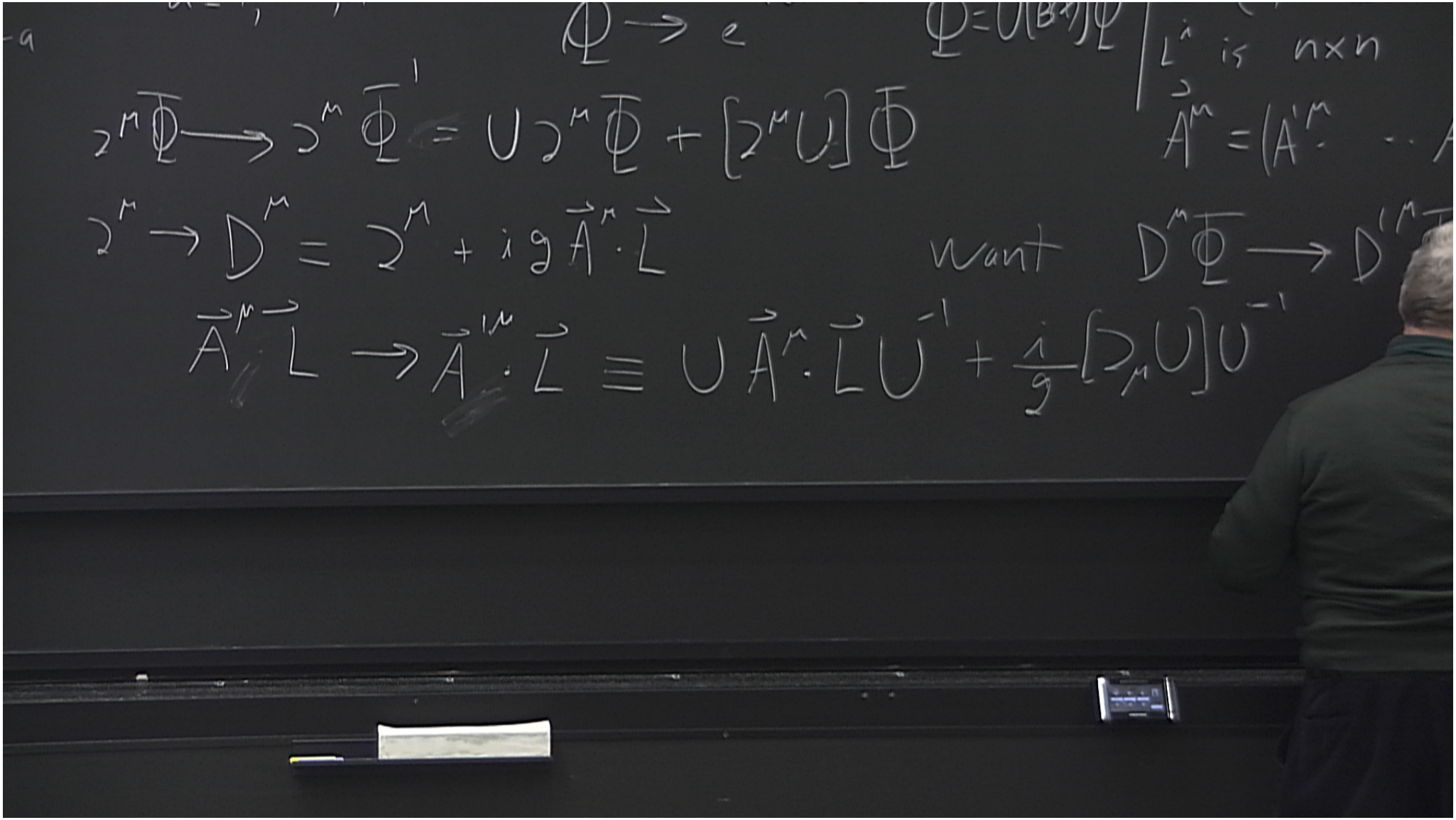

Φ_a
$a = 1, \cdots, n$
$\Phi \to e^{i \vec{B}(x) \cdot \vec{L}} \Phi$
$\vec{L} = (L^1, \cdots$

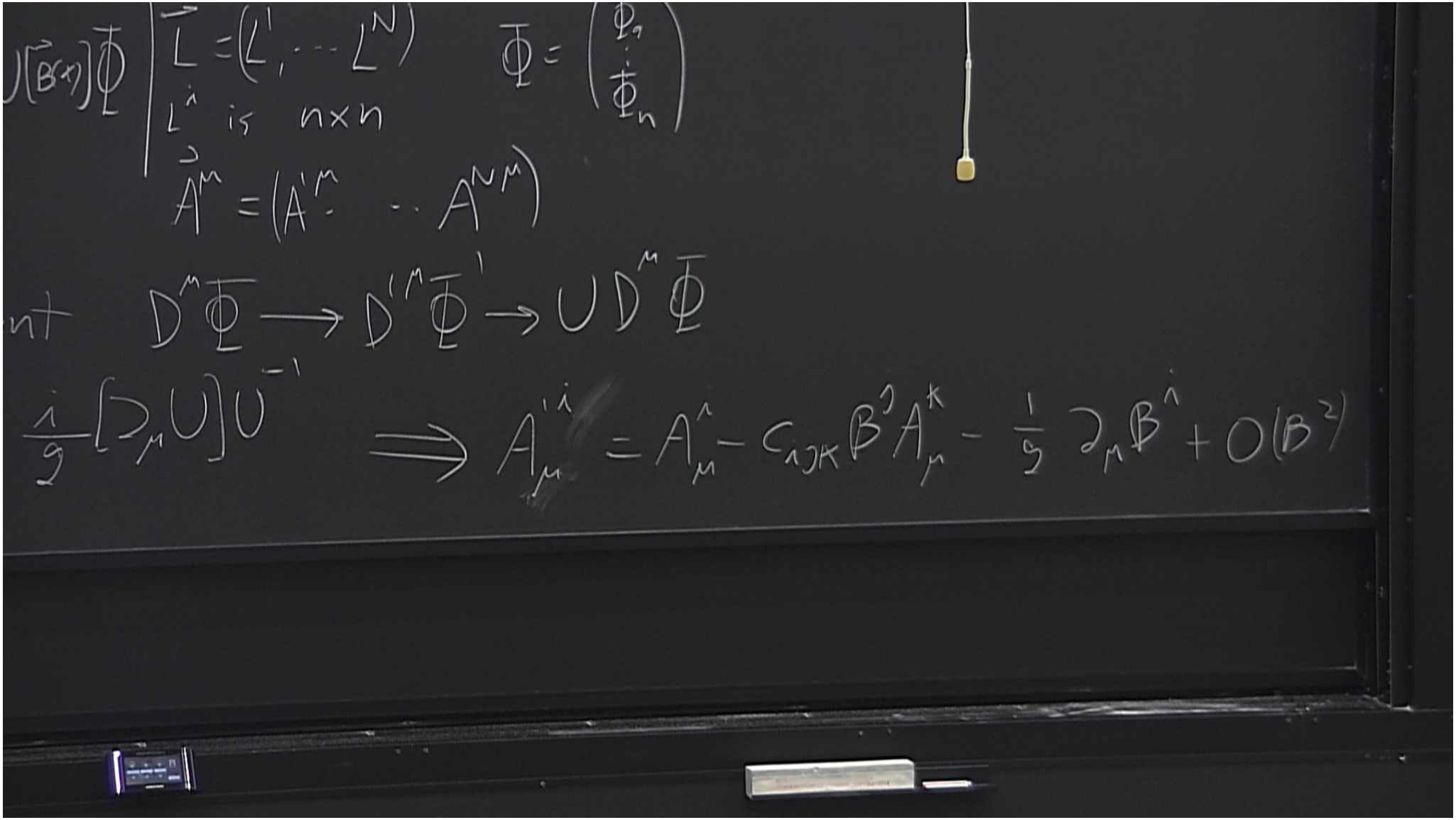
$\ldots, n$ $\quad \Phi \to e^{i\vec{B}(x)\cdot\vec{L}}\,\Phi = U(\vec{B}(x))\,\Phi \quad \Big| \quad \vec{L} = (L^1, \ldots L^N)$ $\quad L^a$ is $n \times n$ $\quad \Phi = \begin{pmatrix} \Phi_1 \\ \vdots \\ \Phi_n \end{pmatrix}$

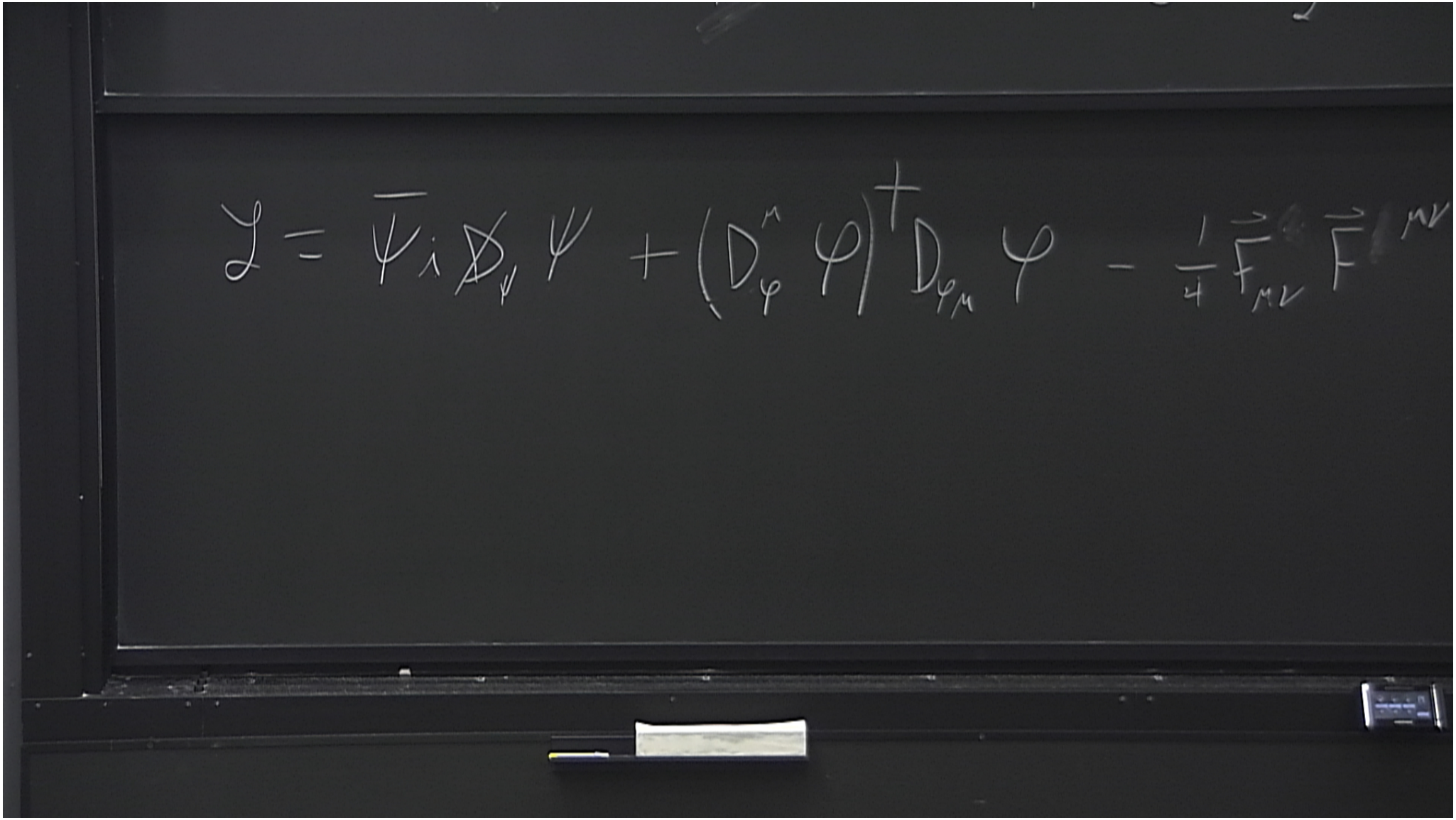
$\partial^\mu \Phi = U \partial^\mu \Phi + [\partial^\mu U]\,\Phi$

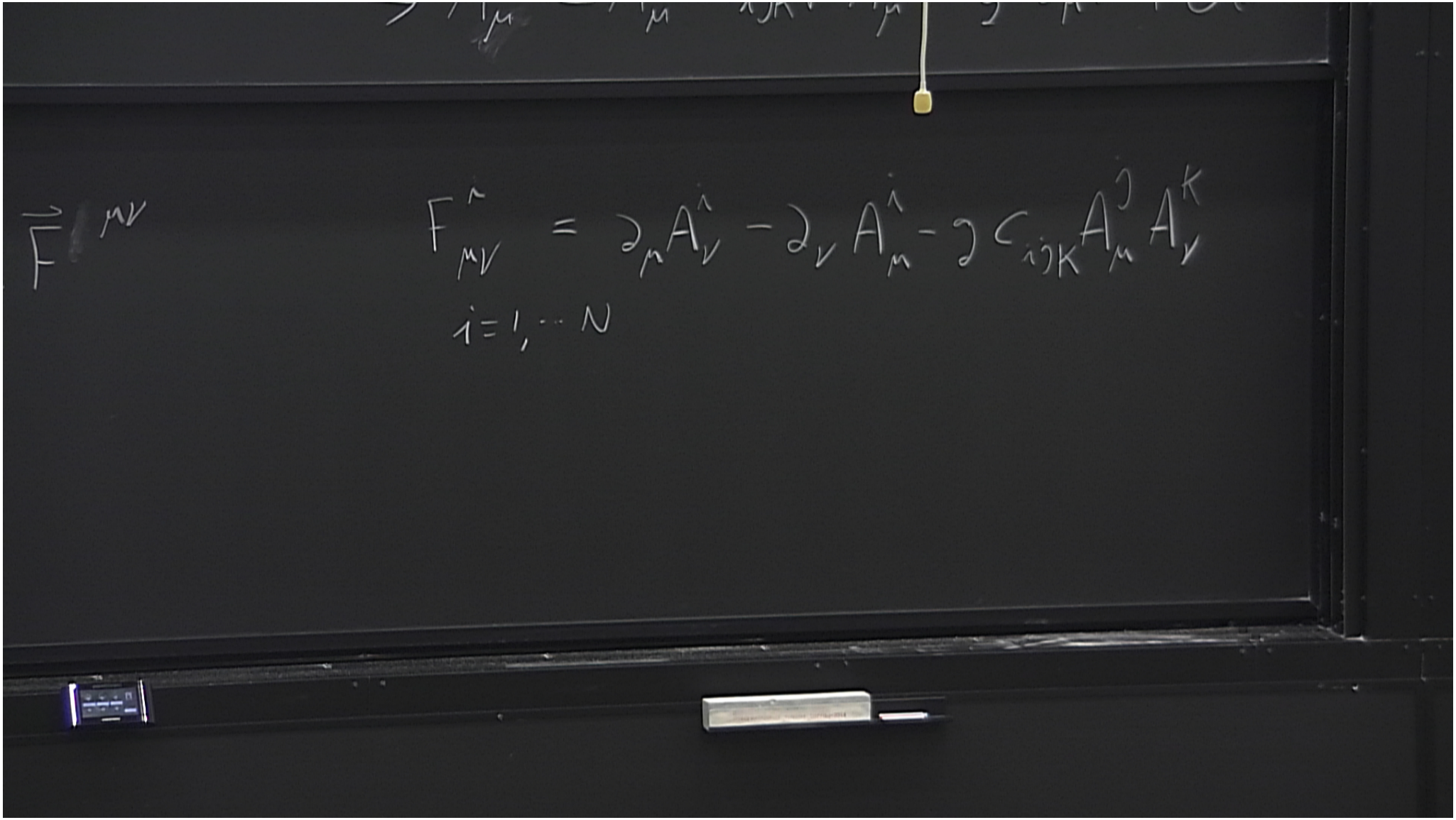

Φ_a $a = 1, \cdots, n$
$\Phi \to e^{i\vec{B}(x)\cdot\vec{L}}$ $\Phi = U(\vec{B}(x))\Phi$
$\partial^\mu \Phi \to \partial^\mu \Phi' = U\partial^\mu \Phi + [\partial^\mu U]\Phi$
$\partial^\mu \to D^\mu = \partial^\mu + ig\vec{A}^\mu \cdot \vec{L}$


$\Phi \to e$
$\Phi = U(B_\mu)\Phi$
L^i is $n \times n$
$\partial^\mu \Phi \to \partial^\mu \Phi' = U \partial^\mu \Phi + [\partial^\mu U]\Phi$
$\vec{A}^\mu = (A^{1\mu} \ldots A^{N\mu})$
$\partial^\mu \to D^\mu = \partial^\mu + ig \vec{A}^\mu \cdot \vec{L}$
want $D^\mu \Phi \to D'^\mu \Phi' \to$
$\vec{A}^\mu \cdot \vec{L} \to \vec{A}'^\mu \cdot \vec{L} \equiv U \vec{A}^\mu \vec{L} U^{-1} + \frac{i}{g}[D_\mu U] U^{-1}$

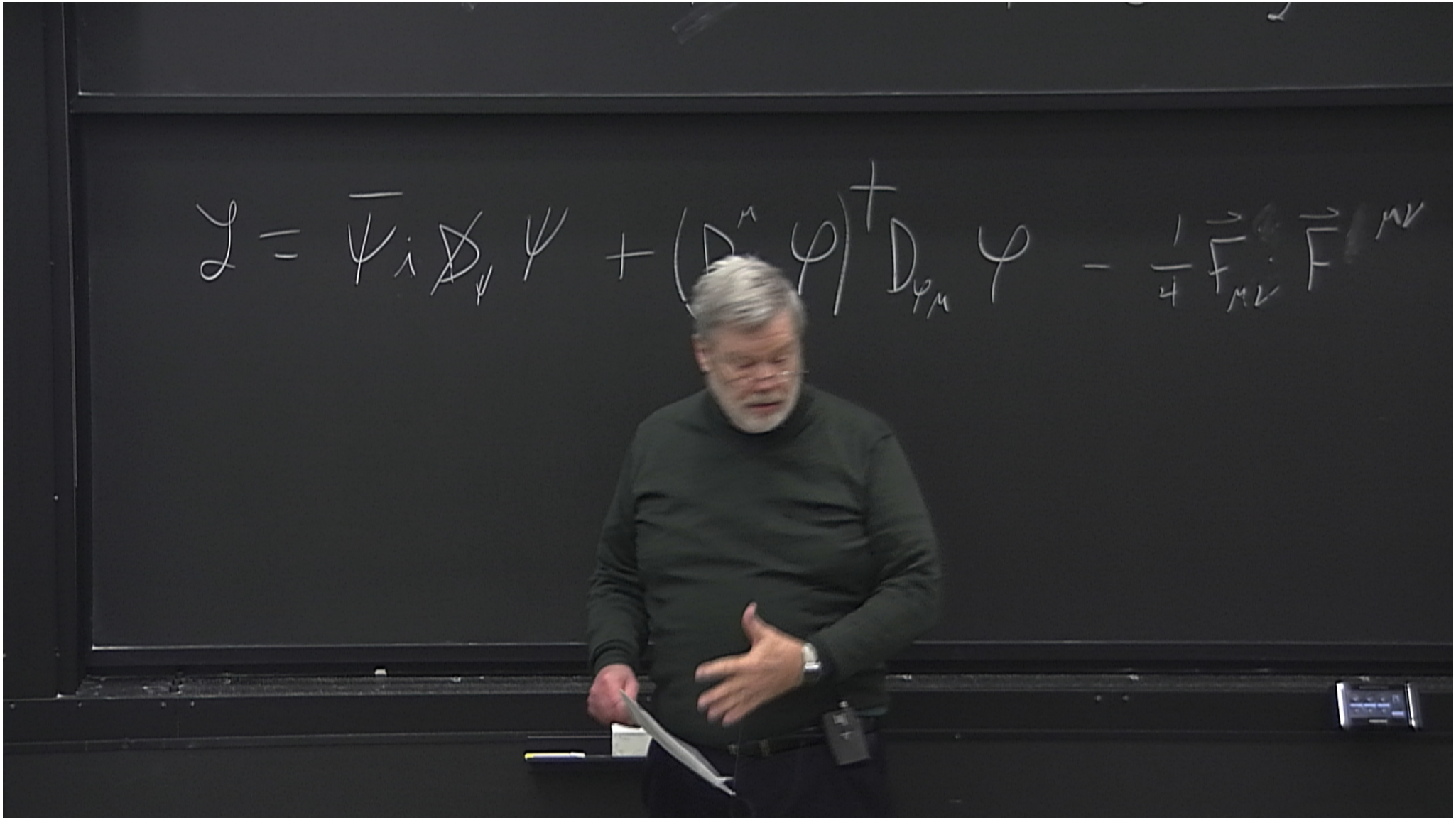

$\Phi \to e$
$\Phi = U(B)\Phi$
L^i is $n \times n$
$\partial^\mu \Phi \to \partial^\mu \Phi' = U \partial^\mu \Phi + [\partial^\mu U]\Phi$
$\vec{A}^\mu = (A'^\mu \ldots$
$\partial^\mu \to D^\mu = \partial^\mu + ig\vec{A}^\mu \cdot \vec{L}$
want $D^\mu \Phi \to D'^\mu$
$\vec{A}^\mu \cdot \vec{L} \to \vec{A}'^\mu \cdot \vec{L} \equiv U \vec{A}^\mu \cdot \vec{L} U^{-1} + \frac{i}{g}[\partial_\mu U]U^{-1}$

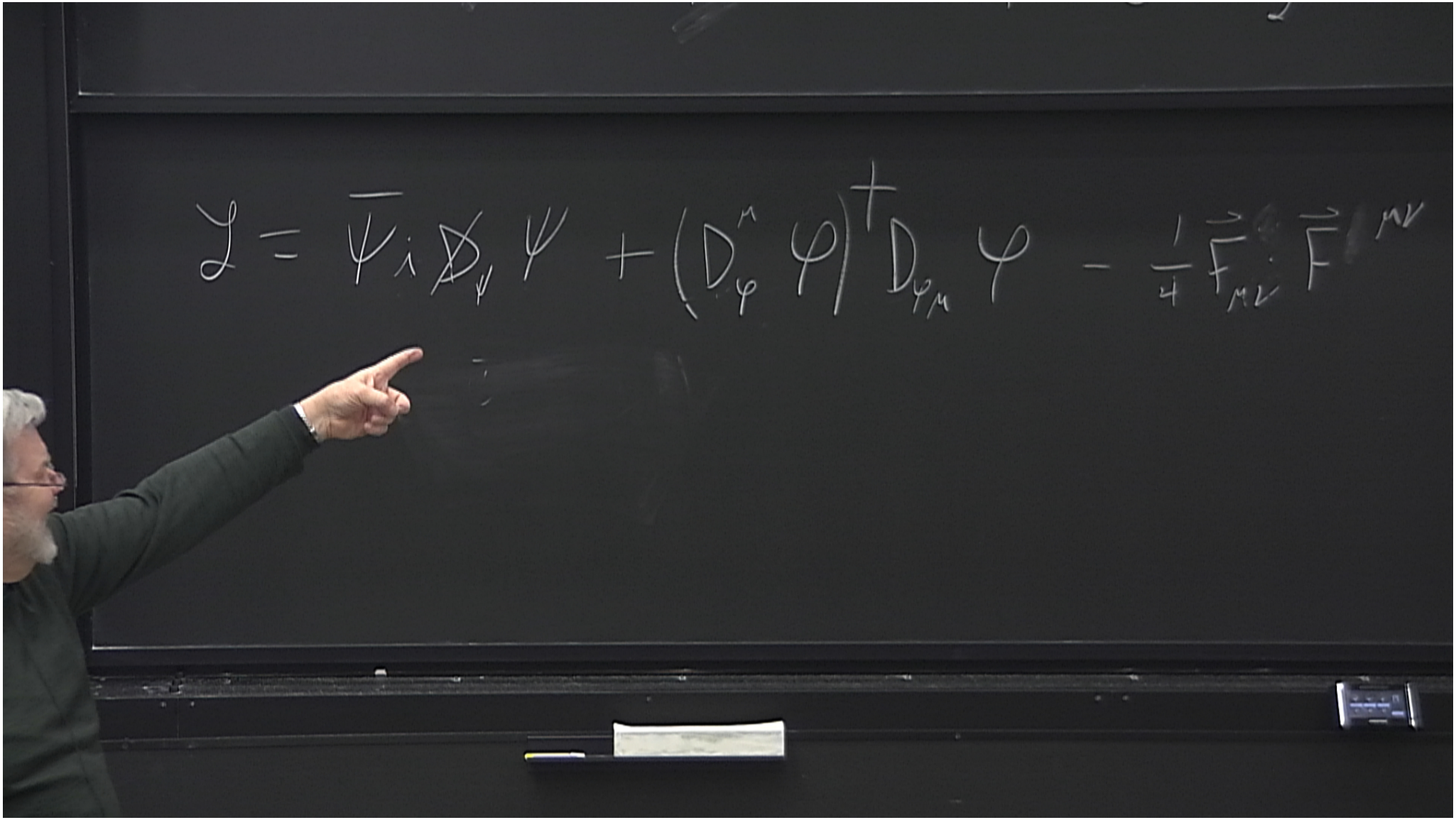

$U(B(x))\Phi$
$\vec{L} = (L^1, \cdots L^N)$
L^i is $n \times n$
$\Phi = \begin{pmatrix} \Phi_1 \\ \vdots \\ \Phi_n \end{pmatrix}$
$\vec{A}^\mu = (A^{1\mu} \cdots A^{N\mu})$
$D^\mu \Phi \longrightarrow D'^\mu \Phi' \rightarrow U D^\mu \Phi$
$\frac{i}{g}[\partial_\mu U]U^{-1} \Longrightarrow A'^i_\mu = A^i_\mu - C_{ijk} B^j A^k_\mu - \frac{1}{g}\partial_\mu B^i + O(B^2)$

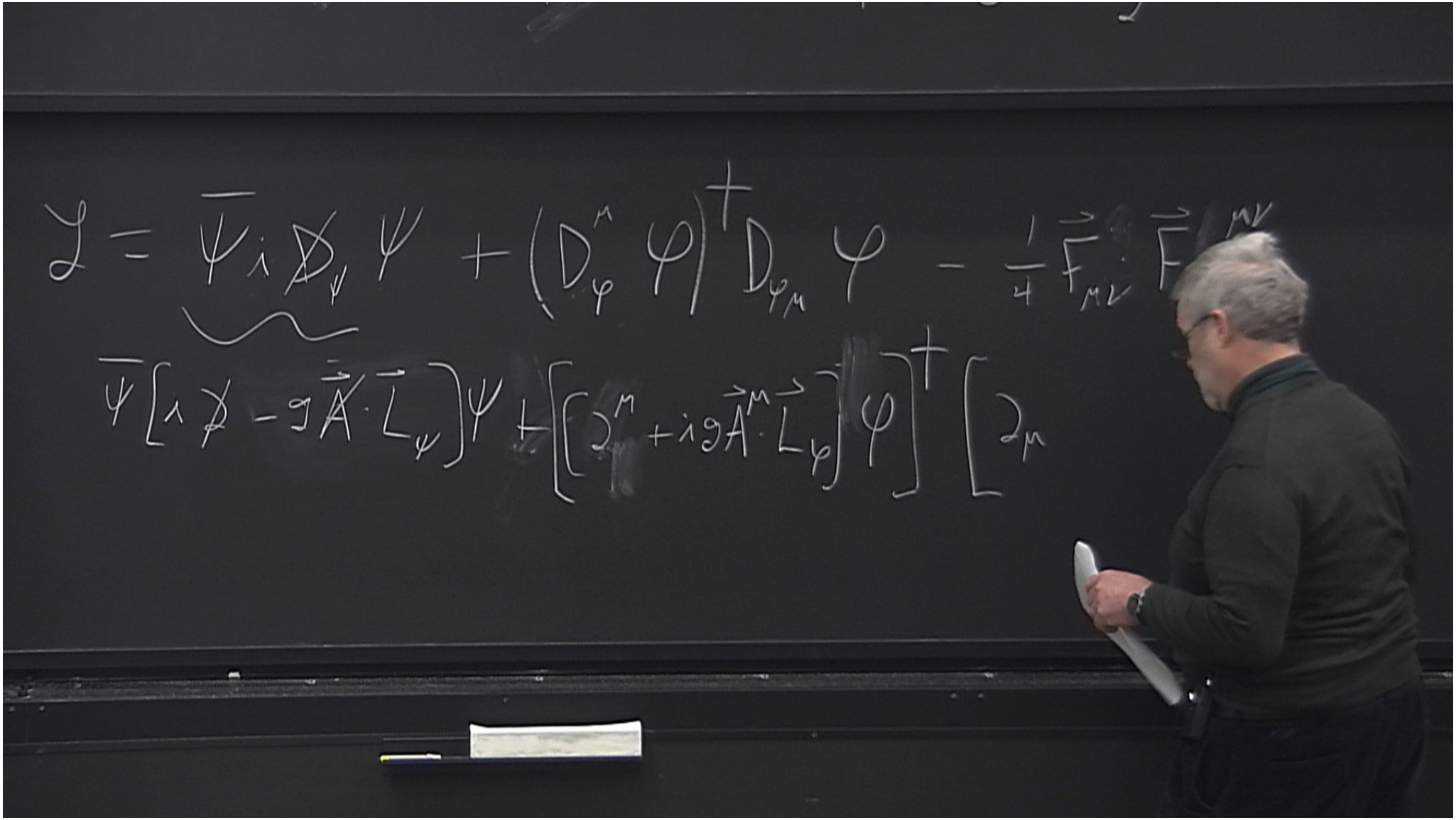

$\mathcal{L} = \bar{\psi} i \not{D} \psi + (D_\varphi^\mu \varphi)^\dagger D_{\varphi\mu} \varphi - \frac{1}{4} \vec{F}_{\mu\nu} \vec{F}^{\mu\nu}$


$\vec{F}^{\mu\nu}$
$F^{\hat{}}_{\mu\nu} = \partial_\mu A^{\hat{}}_\nu - \partial_\nu A^{\hat{}}_\mu - g\, c_{ijk} A^j_\mu A^k_\nu$
$i = 1, \cdots N$

$$\mathcal{L} = \bar{\psi} i \not{D} \psi + (D^{\mu}_{\phi} \phi)^{\dagger} D_{\phi\mu} \phi - \frac{1}{4} \vec{F}_{\mu\nu} \cdot \vec{F}^{\mu\nu}$$


$\mathcal{L} = \bar{\psi} i \not{D} \psi + (D^{\mu}\varphi)^{\dagger} D_{\mu} \varphi - \frac{1}{4} \vec{F}_{\mu\nu} \vec{F}^{\mu\nu}$

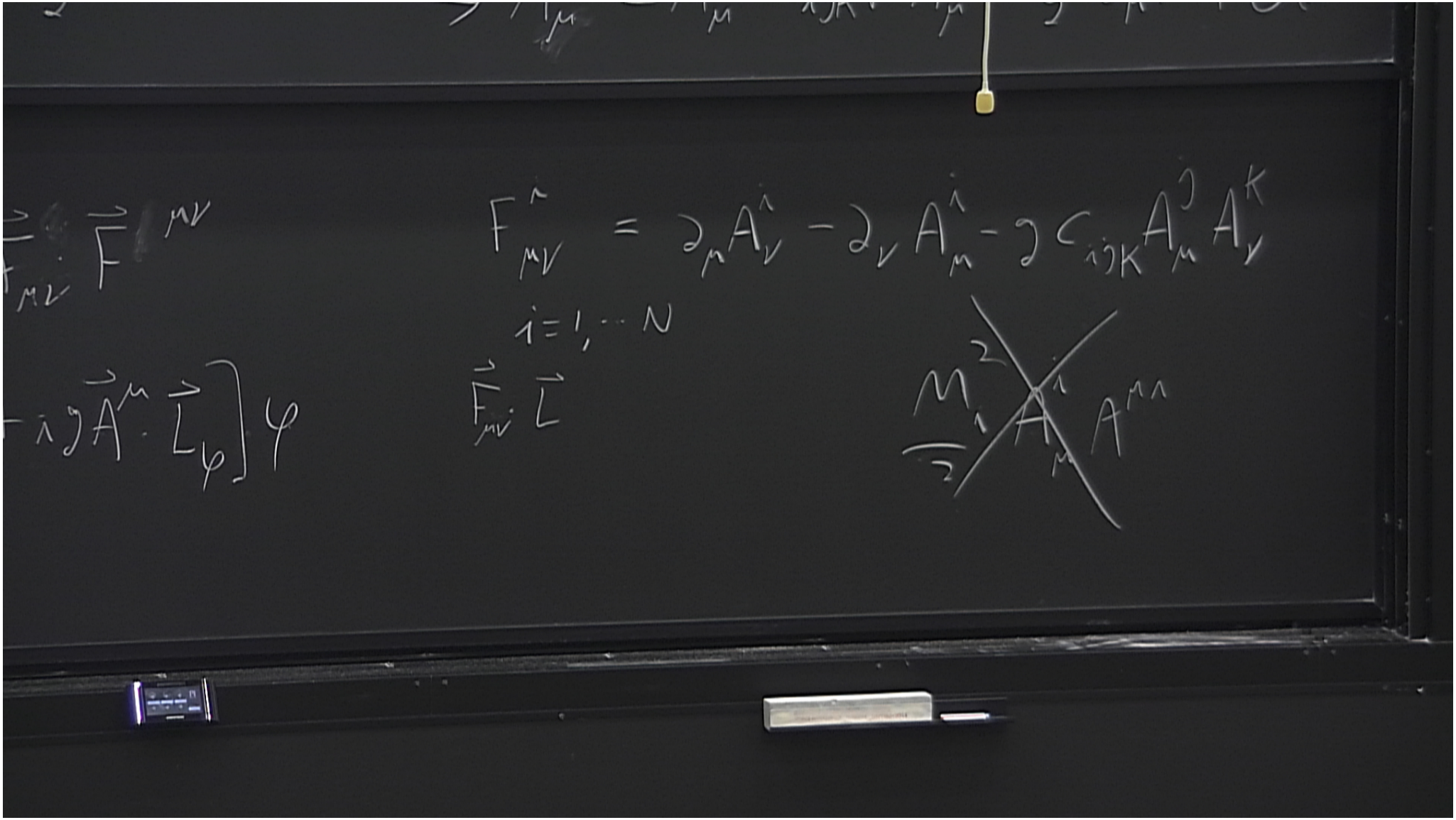

$\mathcal{L} = \bar{\psi} i \not{D} \psi + (D^{\mu}_{\phi} \phi)^{\dagger} D_{\phi\mu} \phi - \frac{1}{4} \vec{F}_{\mu\nu} \cdot \vec{F}^{\mu\nu}$

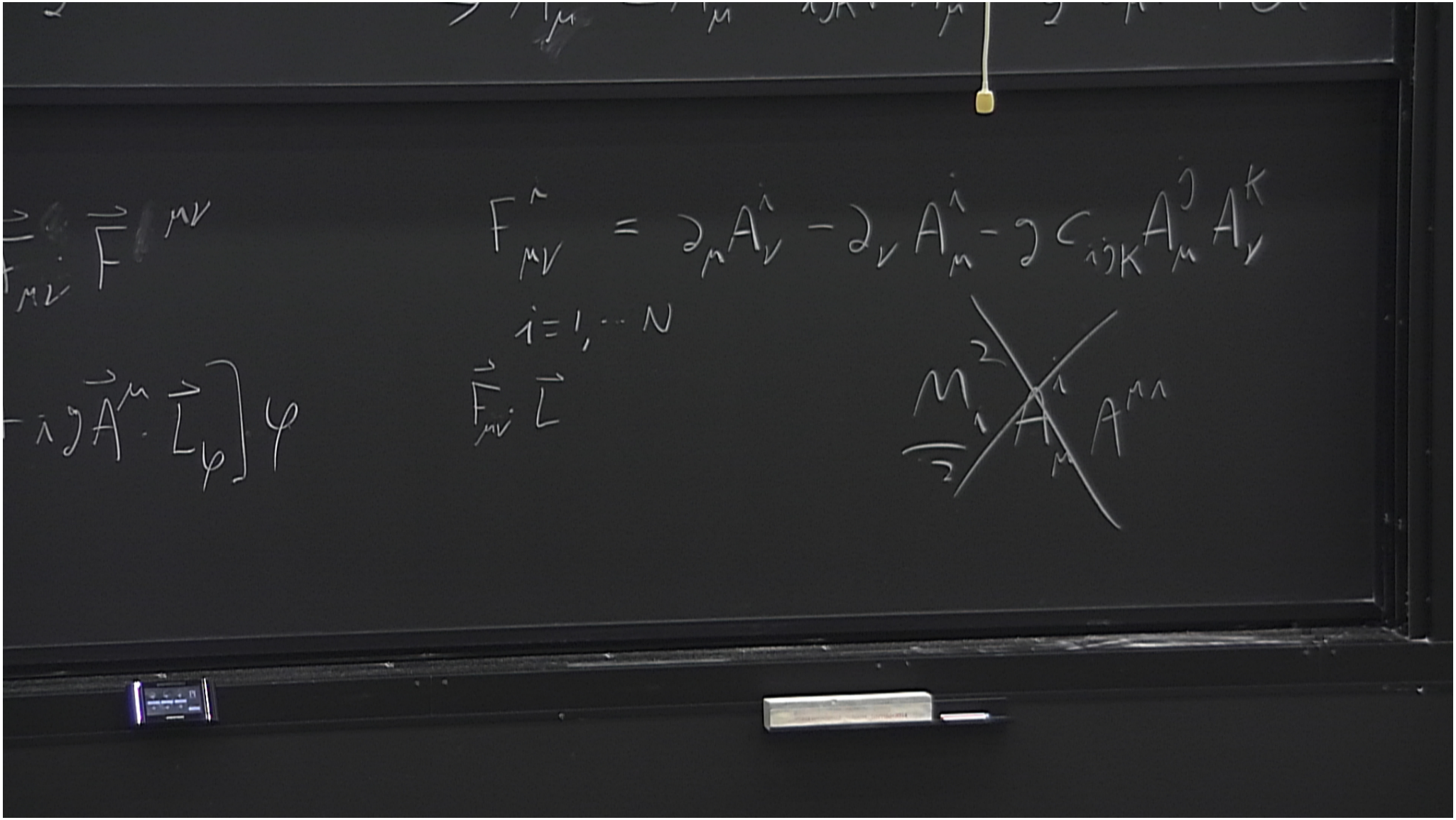

$\mathcal{L} = \bar{\psi} i \not{D} \psi + (D^\mu \varphi)^\dagger D_\mu \varphi - \frac{1}{4} \vec{F}_{\mu\nu} \cdot \vec{F}^{\mu\nu}$
$\bar{\psi} [i \not{\partial} - g \not{\vec{A}} \cdot \vec{L}_\psi] \psi + [(\partial^\mu + i g \vec{A}^\mu \cdot \vec{L}_\varphi) \varphi]^\dagger [\partial_\mu$

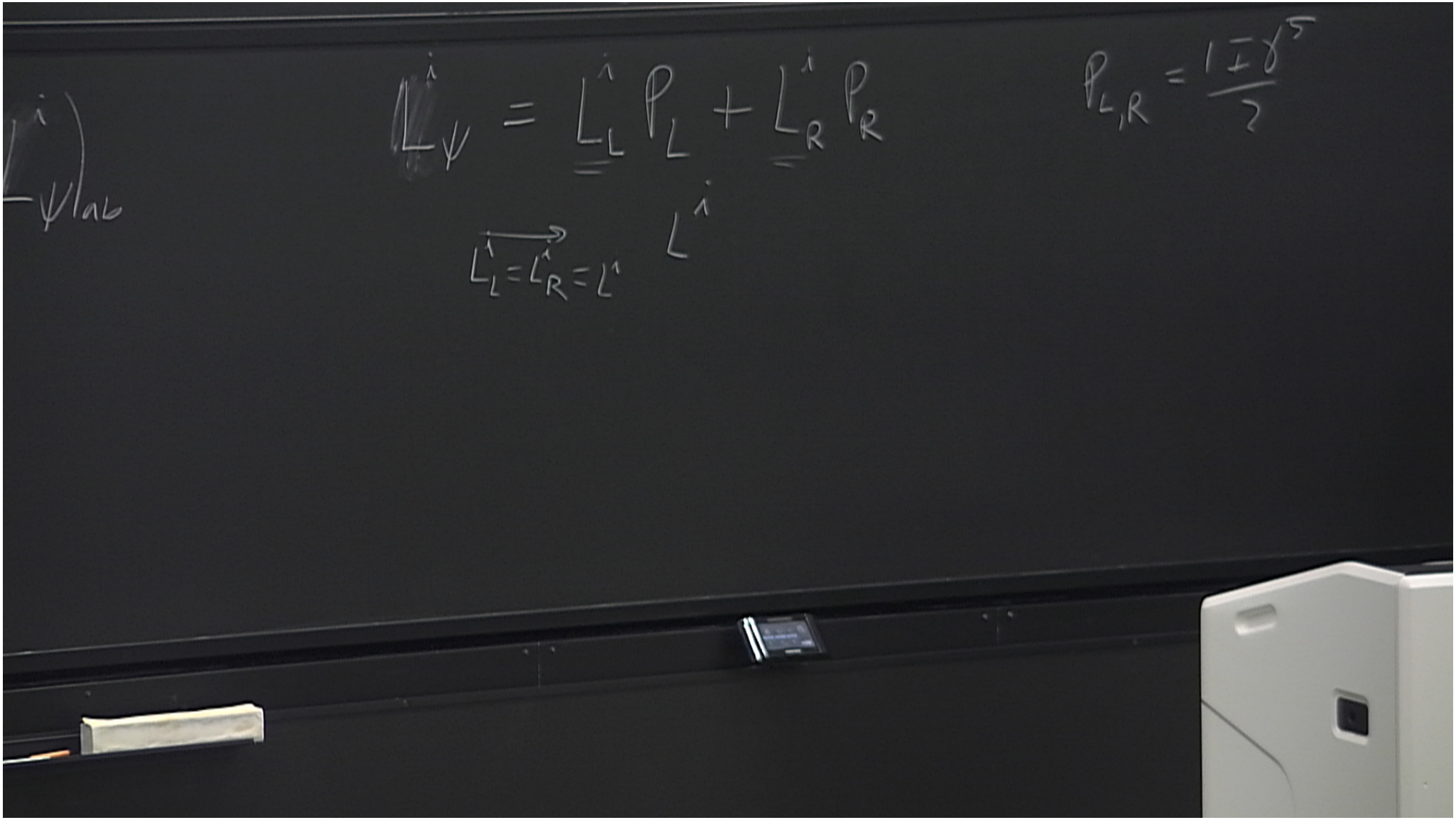
$$\mathcal{L} = \bar{\psi} i \not{D} \psi + (D^{\mu}\varphi)^{\dagger} D_{\mu}\varphi - \frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu}$$

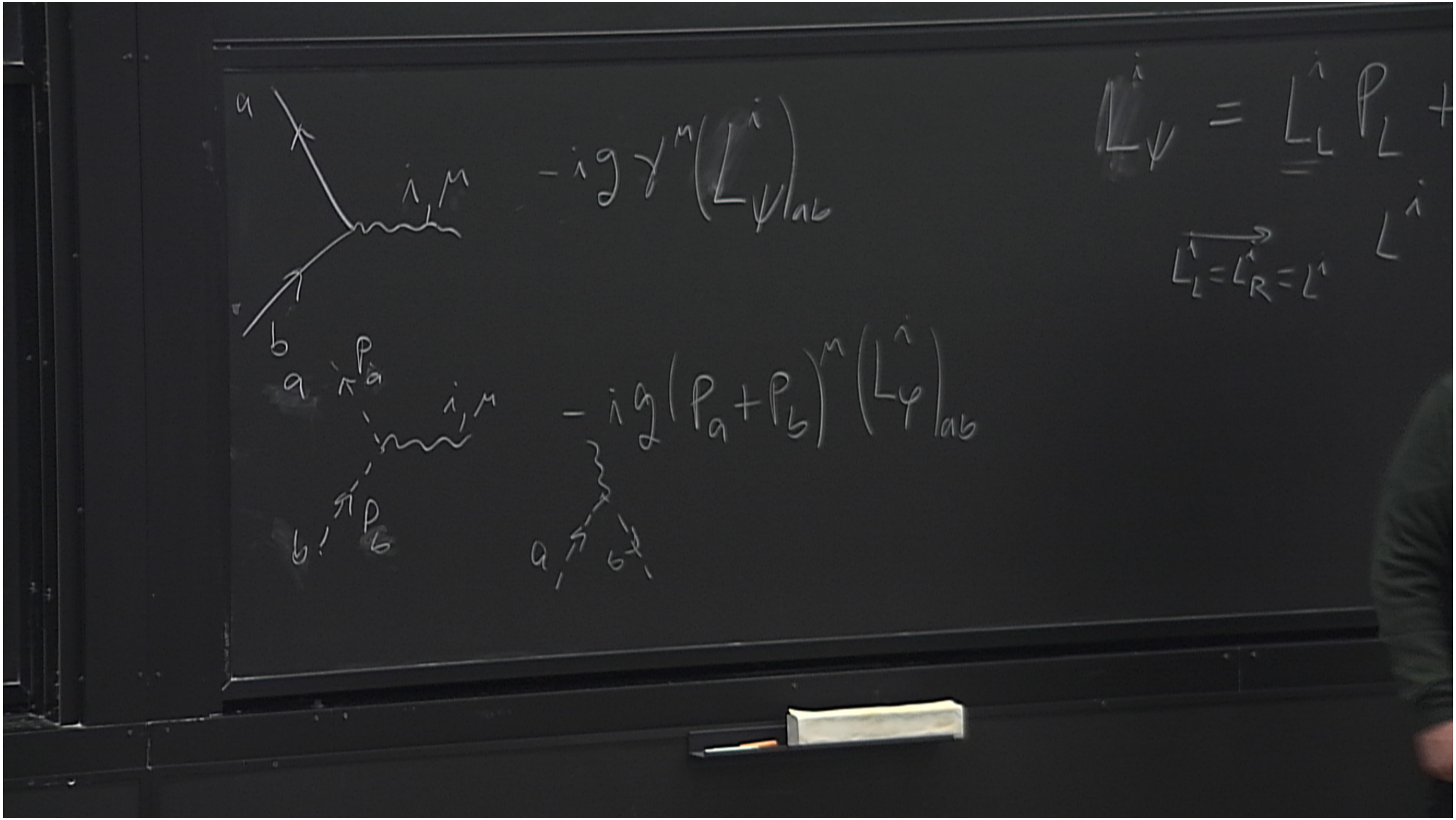
$$\bar{\psi}\left[i\not{\partial} - g\not{\vec{A}}\cdot\vec{L}_{\psi}\right]\psi + \left[\partial^{\mu} + ig\vec{A}^{\mu}\cdot\vec{L}_{\varphi}\right]\varphi^{\dagger}\left[\partial_{\mu} + ig\vec{A}^{\mu}\cdot\vec{L}_{\varphi}\right]\varphi$$

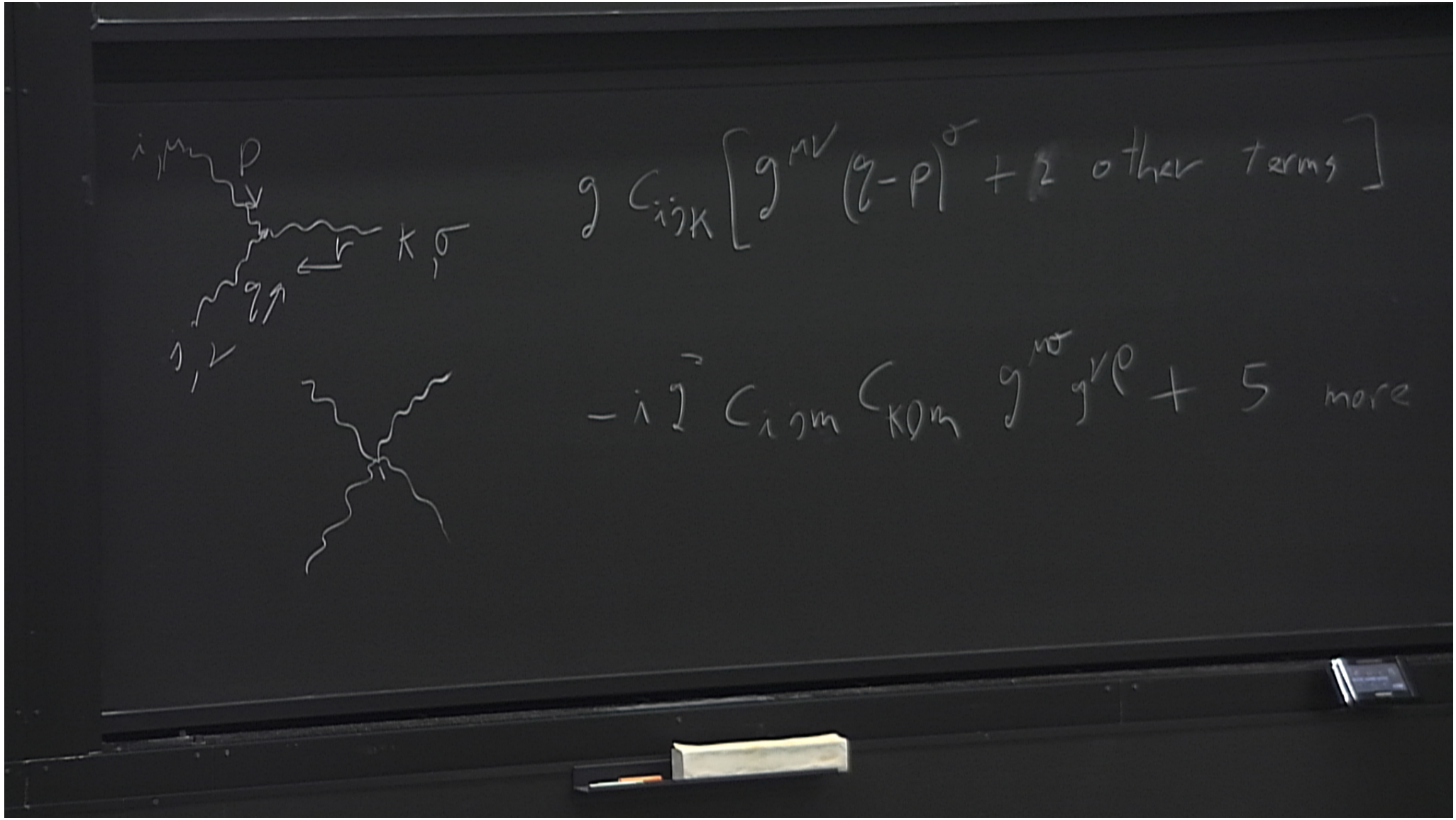
seagull

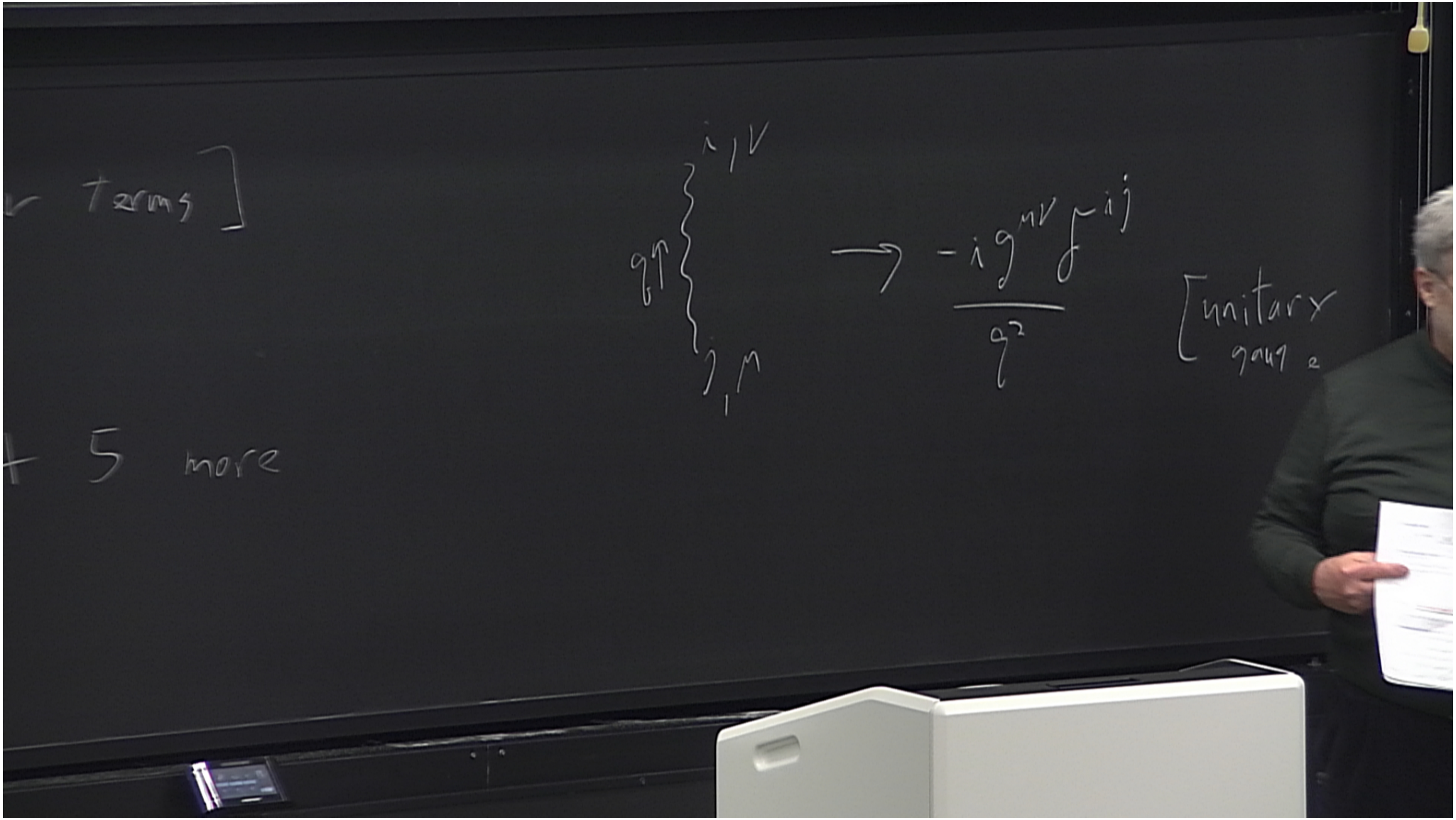

$F^{\mu\nu}$
$\hat{F}^{\mu\nu} = \partial^\mu \hat{A}^\nu - \partial^\nu \hat{A}^\mu - g C_{ijk} A^j_\mu A^k_\nu$
$i = 1, \cdots N$
$\vec{F}_{\mu\nu} \cdot \vec{L}$
$\vec{A}^\mu \cdot \vec{L}_\phi \Big] \varphi$
M^2
A^μ


$\hat{F}_{\mu\nu} = \partial_\mu \hat{A}_\nu - \partial_\nu \hat{A}_\mu - g C_{ijk} A^j_\mu A^k_\nu$
$i = 1, \cdots N$
$\vec{F}_{\mu\nu} \cdot \vec{L}$
M_1^2
A^1_μ
$A^{\mu\nu}$


$L^i_\psi = L^i_L P_L + L^i_R P_R$
$P_{L,R} = \frac{1 \mp \gamma^5}{2}$
$L^i_L = L^i_R = L^i$
L^i


a
b
$-ig\gamma^\mu \left(L_V^i\right)_{ab}$
$L_V^i = L_L^i P_L +$
$L_L^i = L_R^i = L^i$
L^i
a p_a
b p_b
$-ig(p_a+p_b)^\mu \left(L_\varphi^i\right)_{ab}$
a
b


i, μ
p
k, σ
q
j, ν
$g\, C_{ij3k}\left[g^{\mu\nu}(q-p)^{\sigma} + 2 \text{ other terms}\right]$
$-i\tilde{2}\, C_{i3m} C_{kDm}\, g^{\mu\sigma} g^{\nu\rho} + 5$ more

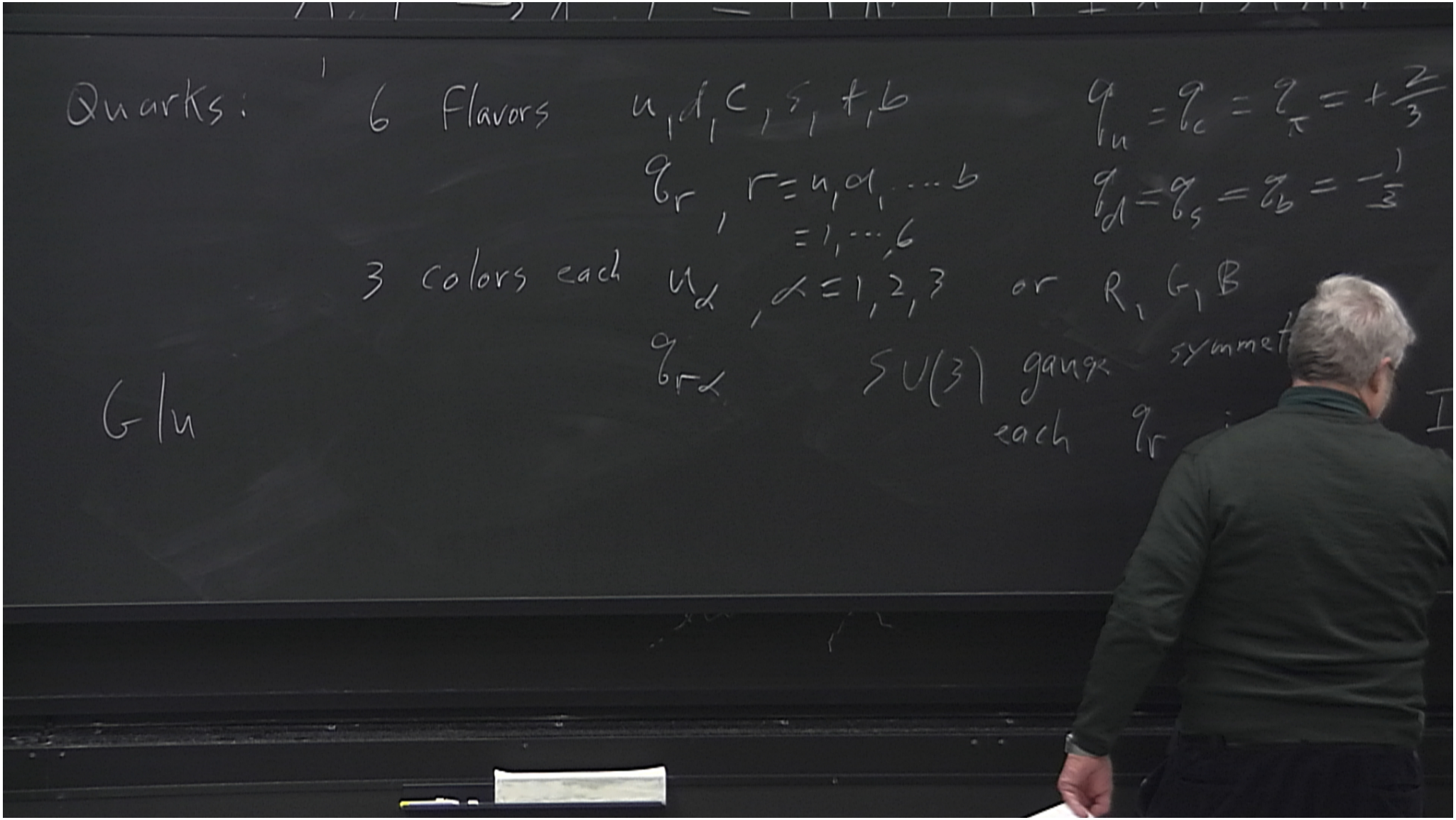

terms]
+ 5 more
i, μ
j, ν
q
$\rightarrow \frac{-ig^{\mu\nu}\delta^{ij}}{q^2}$
[unitary
gauge

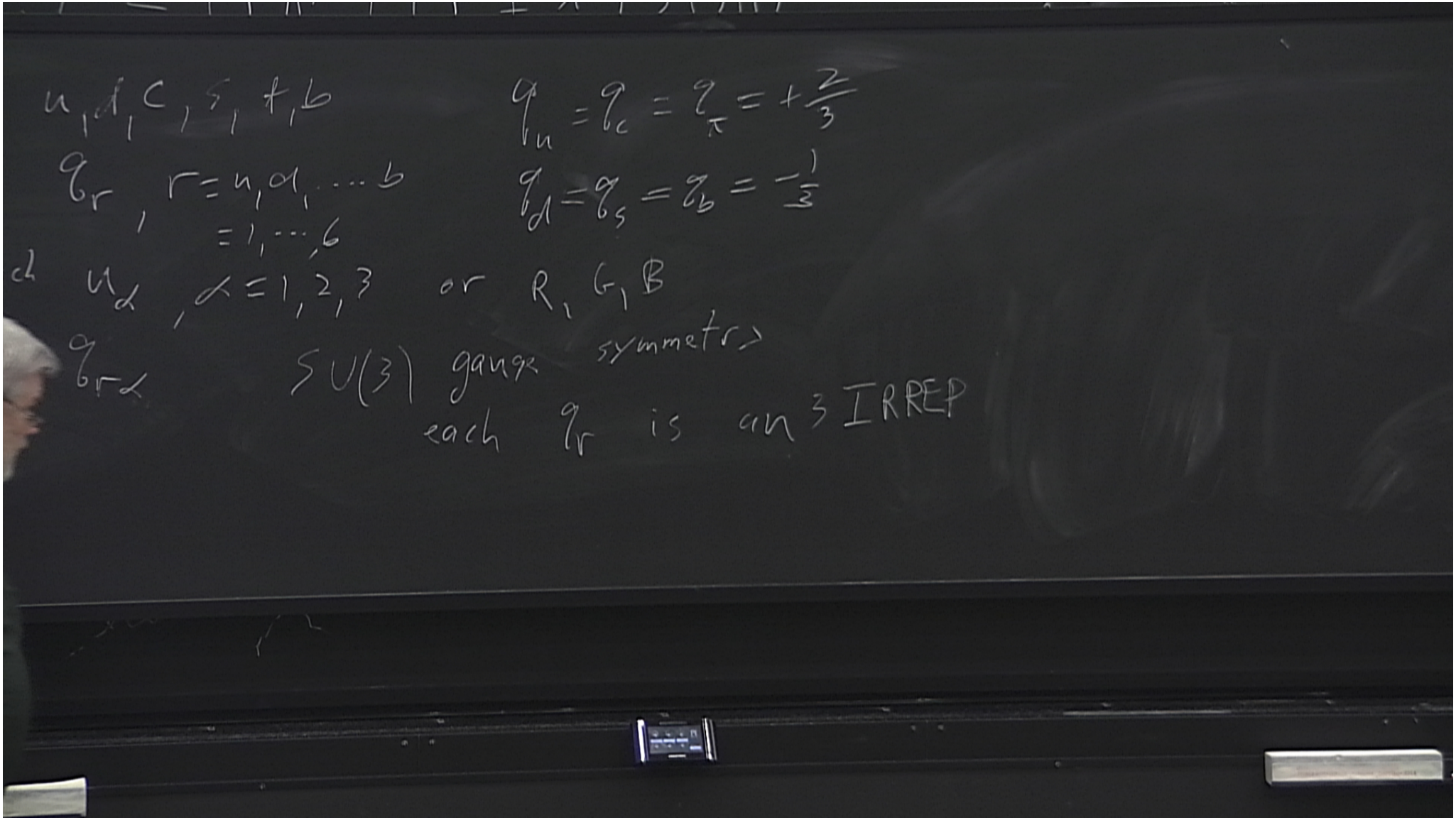
Quarks: 6 flavors u, d, c, s, t, b $\quad q_u = q_c = q_t = +\frac{2}{3}$

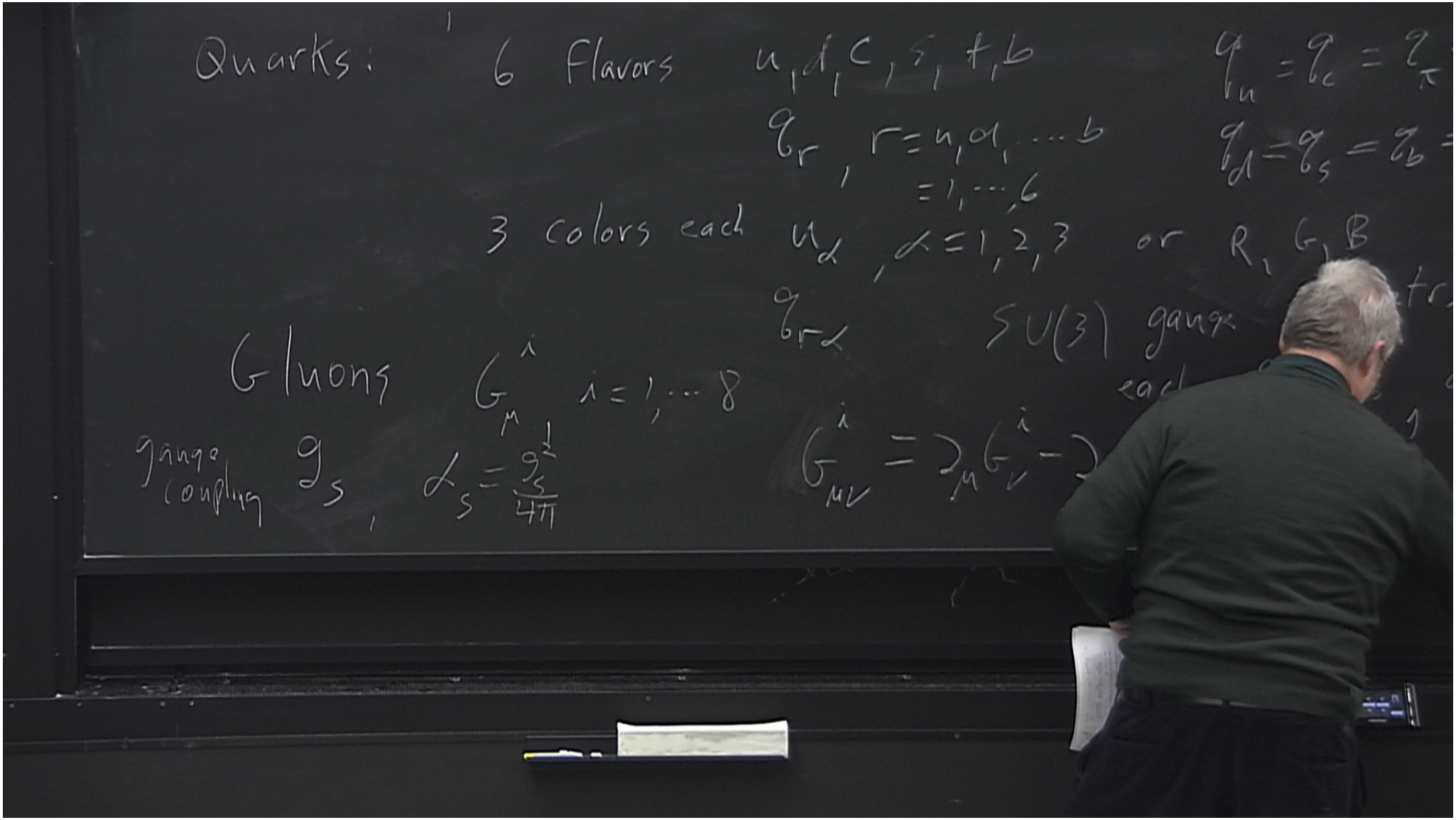
q_r, $r = u, d, \ldots b$ $\quad q_d = q_s = q_b = -\frac{1}{3}$

$= 1, \ldots, 6$

3 colors each u_α, $\alpha = 1, 2, 3$ or R, G, B


Quarks:
6 flavors u, d, c, s, t, b
q_r, $r = u, d, \ldots b$
$= 1, \ldots, 6$
$q_u = q_c = q_t = +\frac{2}{3}$
$q_d = q_s = q_b = -\frac{1}{3}$
3 colors each u_α, $\alpha = 1, 2, 3$ or R, G, B
$q_{r\alpha}$
$SU(3)$ gauge symmet
each q_r
G/u
I


u, d, c, s, t, b
q_r, $r = u, d, \ldots b$
$= 1, \ldots, 6$
$q_u = q_c = q_t = +\frac{2}{3}$
$q_d = q_s = q_b = -\frac{1}{3}$
u_α, $\alpha = 1, 2, 3$ or R, G, B
$q_{r\alpha}$
SU(3) gauge symmetry
each q_r is an 3 IRREP


Quarks: 6 Flavors u, d, c, s, t, b
q_r, $r = u, d, \ldots b$
$= 1, \ldots, 6$
3 colors each u_α, $\alpha = 1, 2, 3$ or R, G, B
$q_{r\alpha}$
SU(3) gauge
Gluons G^λ_μ $\lambda = 1, \ldots 8$
gauge coupling g_s, $\alpha_s = \frac{g_s^2}{4\pi}$
$G^\lambda_{\mu\nu} = \partial_\mu G^\lambda_\nu -$

6 flavors u, d, c, s, t, b $\quad q_u = q_c = q_t = +\frac{2}{3}$

q_r, $r = u, d, \ldots b$ $\quad q_d = q_s = q_b = -\frac{1}{3}$

$= 1, \ldots, 6$

3 colors each u_α, $\alpha = 1, 2, 3$ or R, G, B

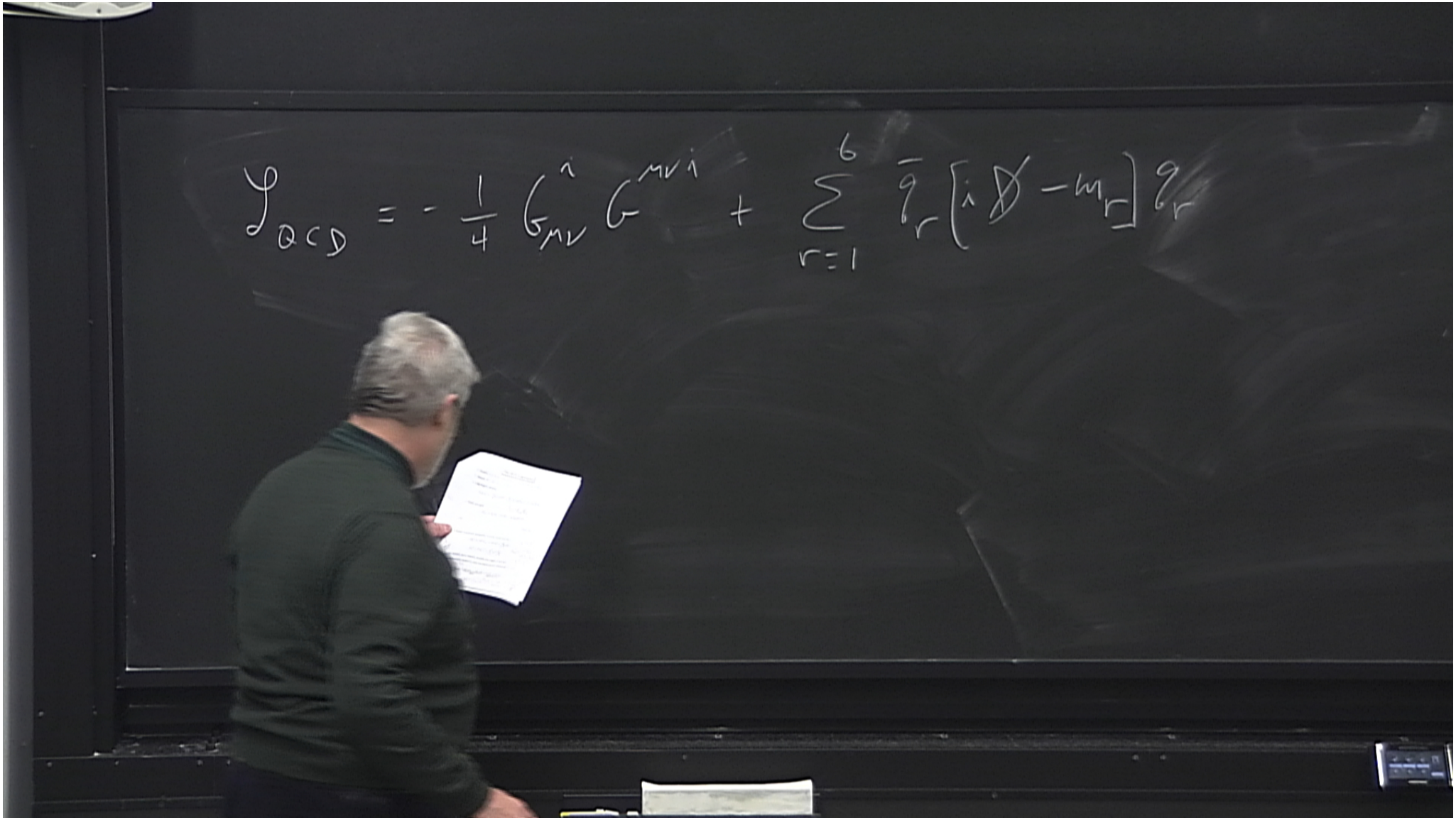
$q_{r\alpha}$ $\quad SU(3)$ gauge symmetry

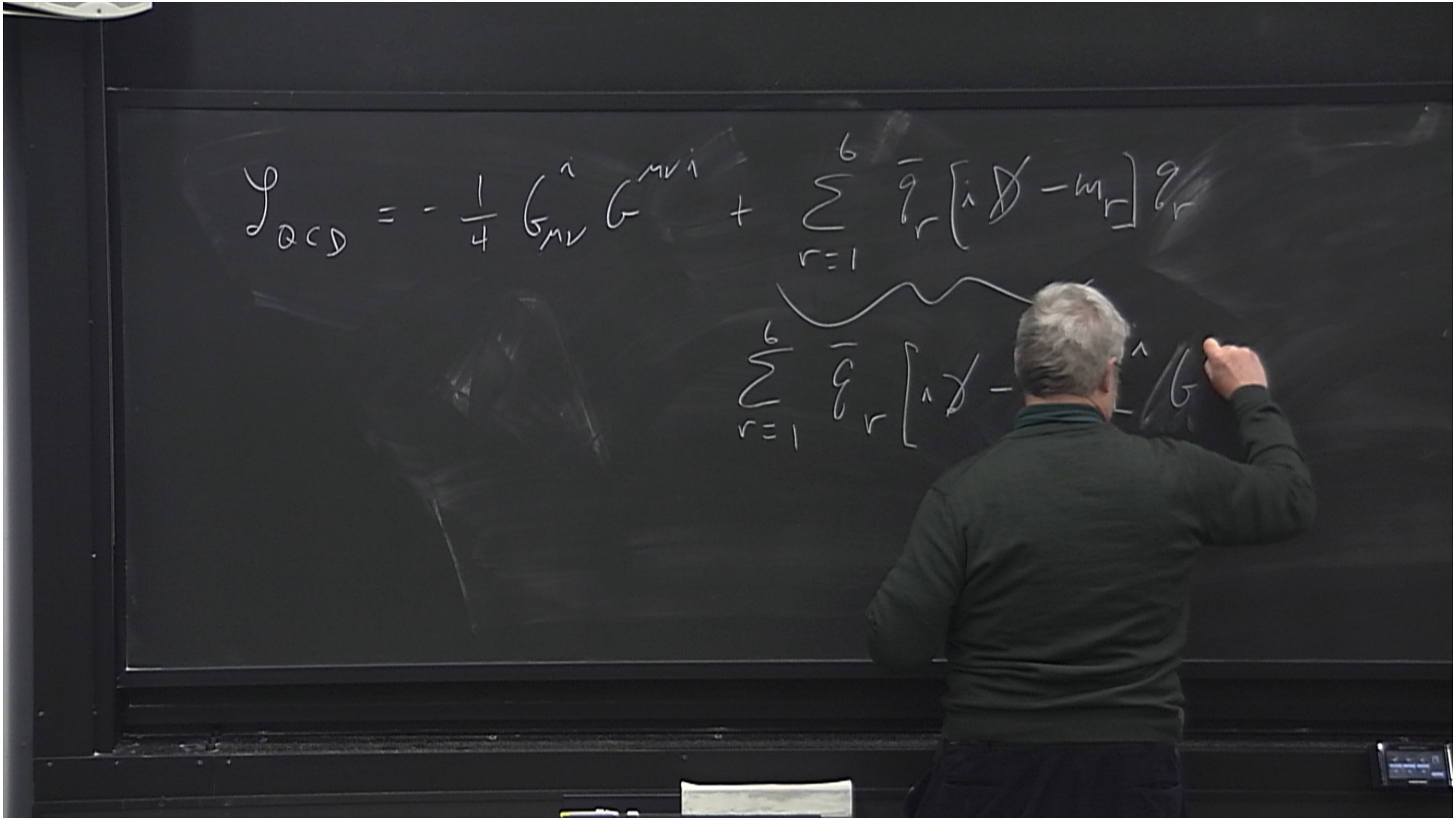
each q_r is an 3 IRREP

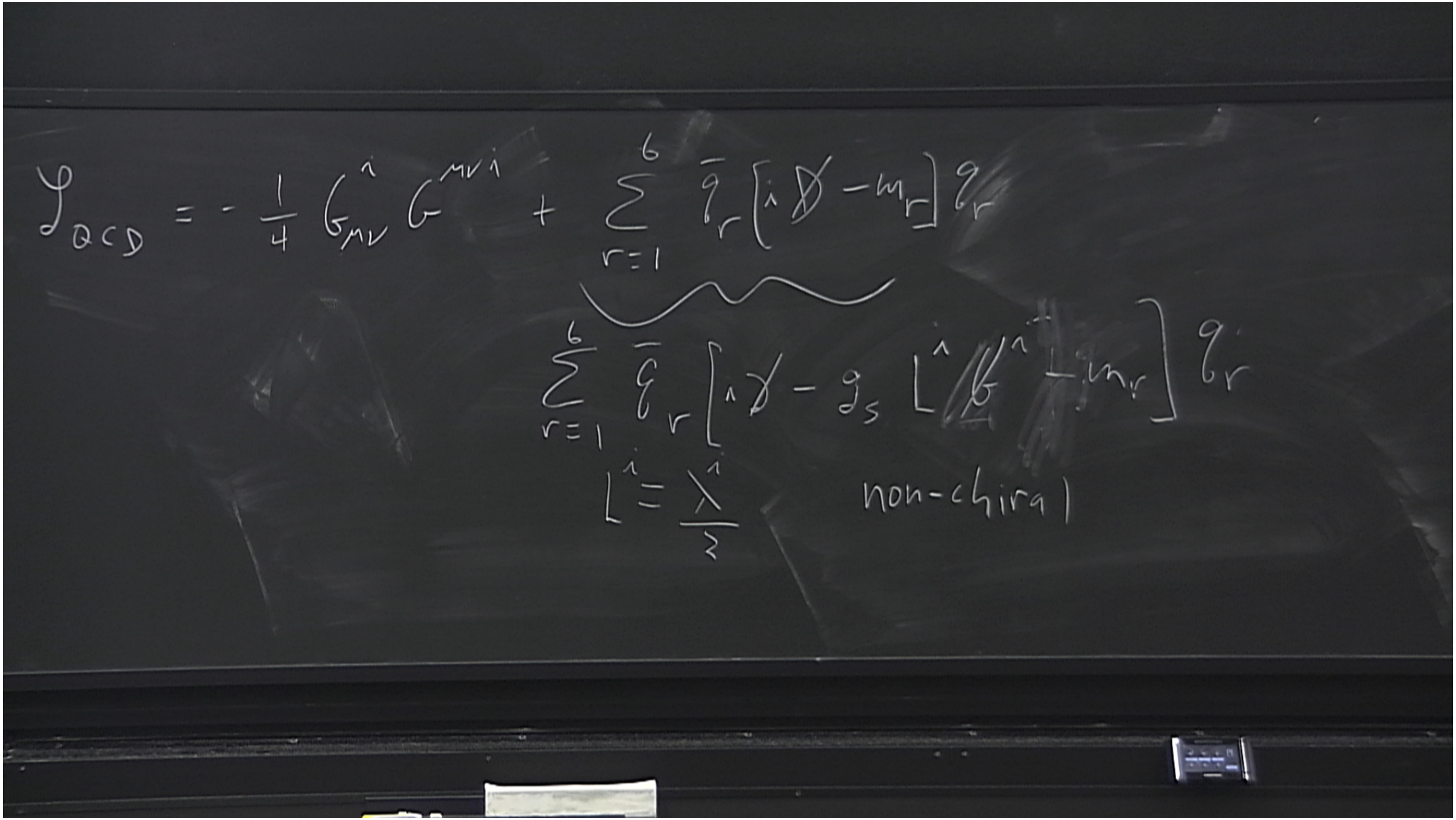
G_μ^i $\quad i = 1, \ldots 8$

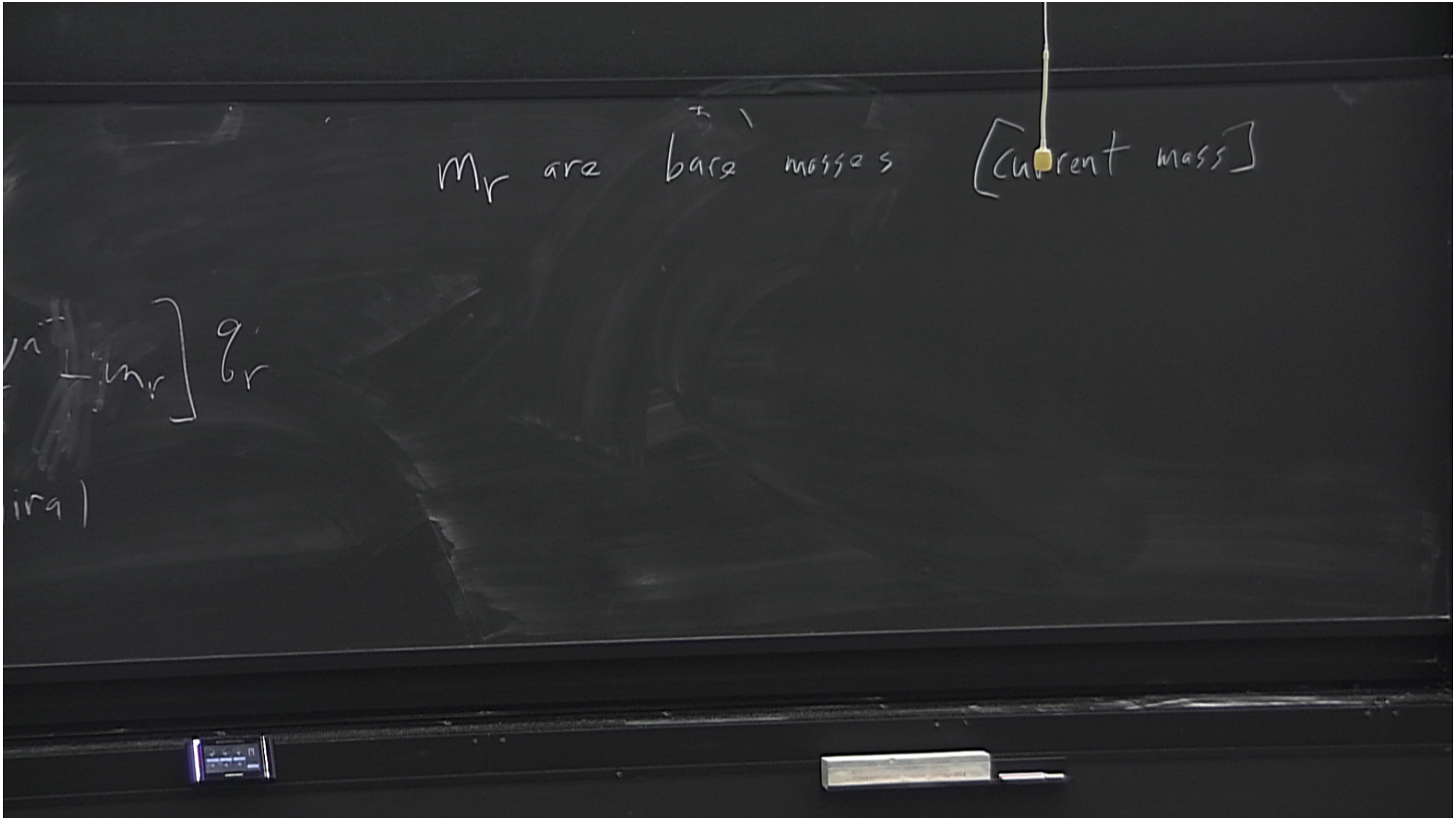
$$G_{\mu\nu}^i = \partial_\mu G_\nu^i - \partial_\nu G_\mu^i - g_s f_{ijk} G_\mu^j G_\nu^k$$

$\alpha_s = \frac{g_s^2}{4\pi}$


$\mathcal{L}_{QCD} = -\frac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu a} + \sum_{r=1}^{6} \bar{q}_r \left[i \not{D} - m_r \right] q_r$

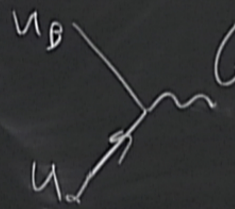

$\mathcal{L}_{QCD} = -\frac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu a} + \sum_{r=1}^{6} \bar{q}_r [i\not{D} - m_r] q_r$
$\sum_{r=1}^{6} \bar{q}_r [i\not{D} -$


$\mathcal{L}_{QCD} = -\frac{1}{4} \hat{G}_{\mu\nu} G^{\mu\nu} + \sum_{r=1}^{6} \bar{q}_r [i\not{\partial} - m_r] q_r$
$\sum_{r=1}^{6} \bar{q}_r [i\not{\partial} - g_s \hat{L} \not{G}^{\hat{a}} - m_r] q_r$
$\hat{L} = \frac{\hat{\lambda}}{2}$
non-chiral


m_r are bare masses [current mass]
$-im_r]q_r$
iral

m_r are bare masses [current mass]

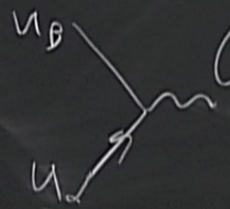
flavor SU(2), SU(3)



m_r are bare masses [current mass]

flavor SU(2), SU(3)

$m_u = m_d = 0$

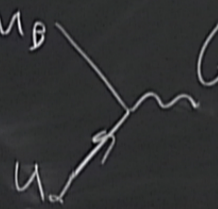


$\Rightarrow$ flavor $SU(2)_L \times SU(2)_R \times U(1)_B \times U(1)$

m_r are bare masses [current mass]

$-m_r]\, q_r$

flavor $SU(2)$, $SU(3)$



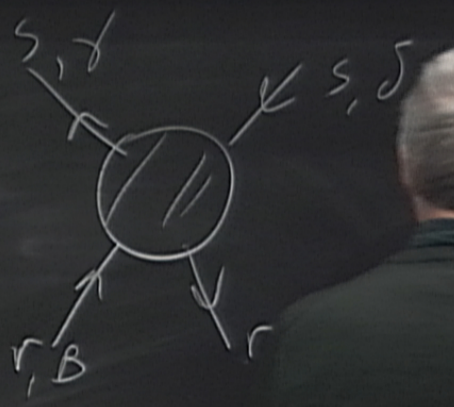
$m_u = m_d = 0$

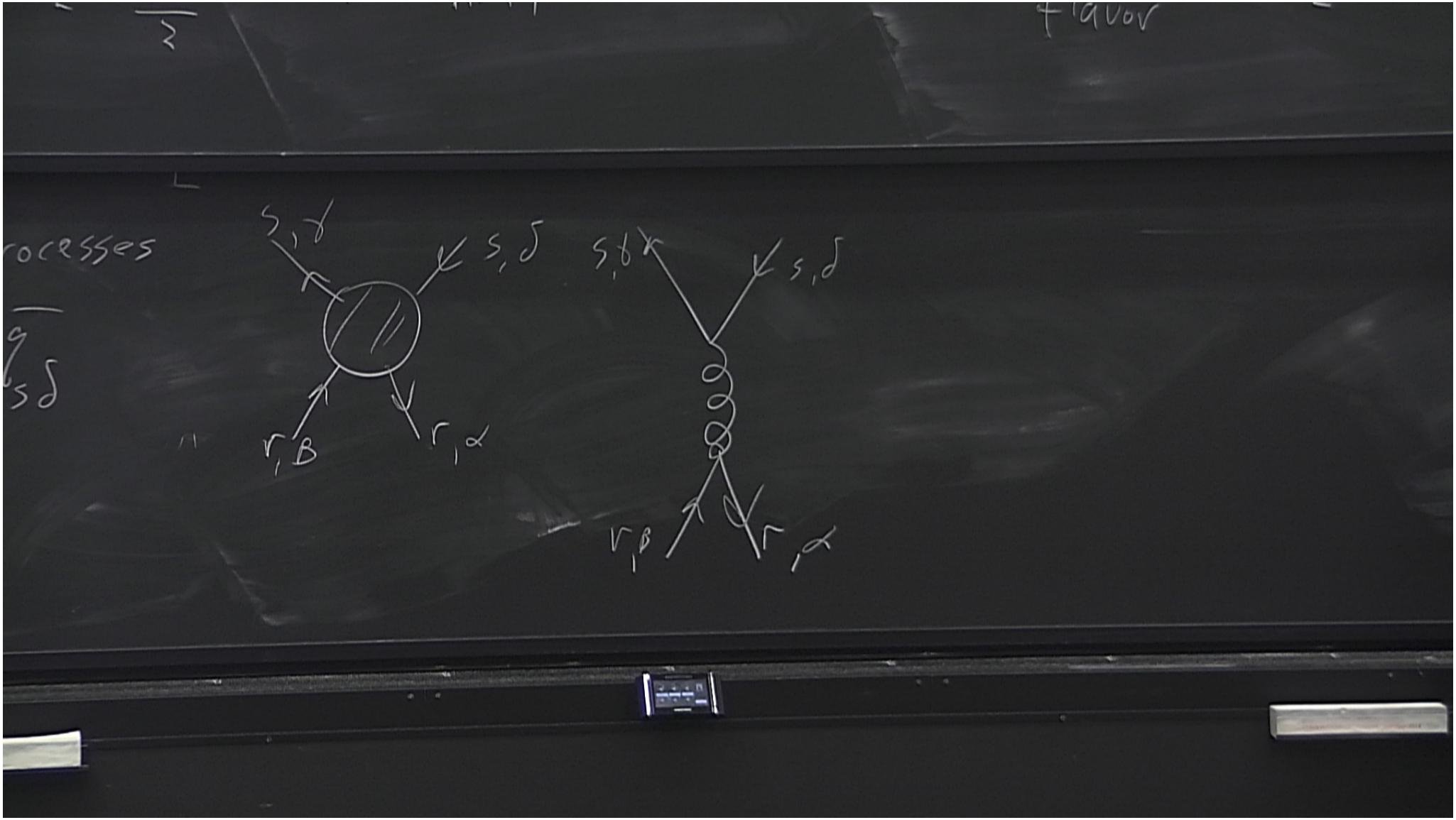
$\Rightarrow SU(2)_L \times SU(2)_R \times U(1)_B \times \cancel{U(1)_{B_A}}$

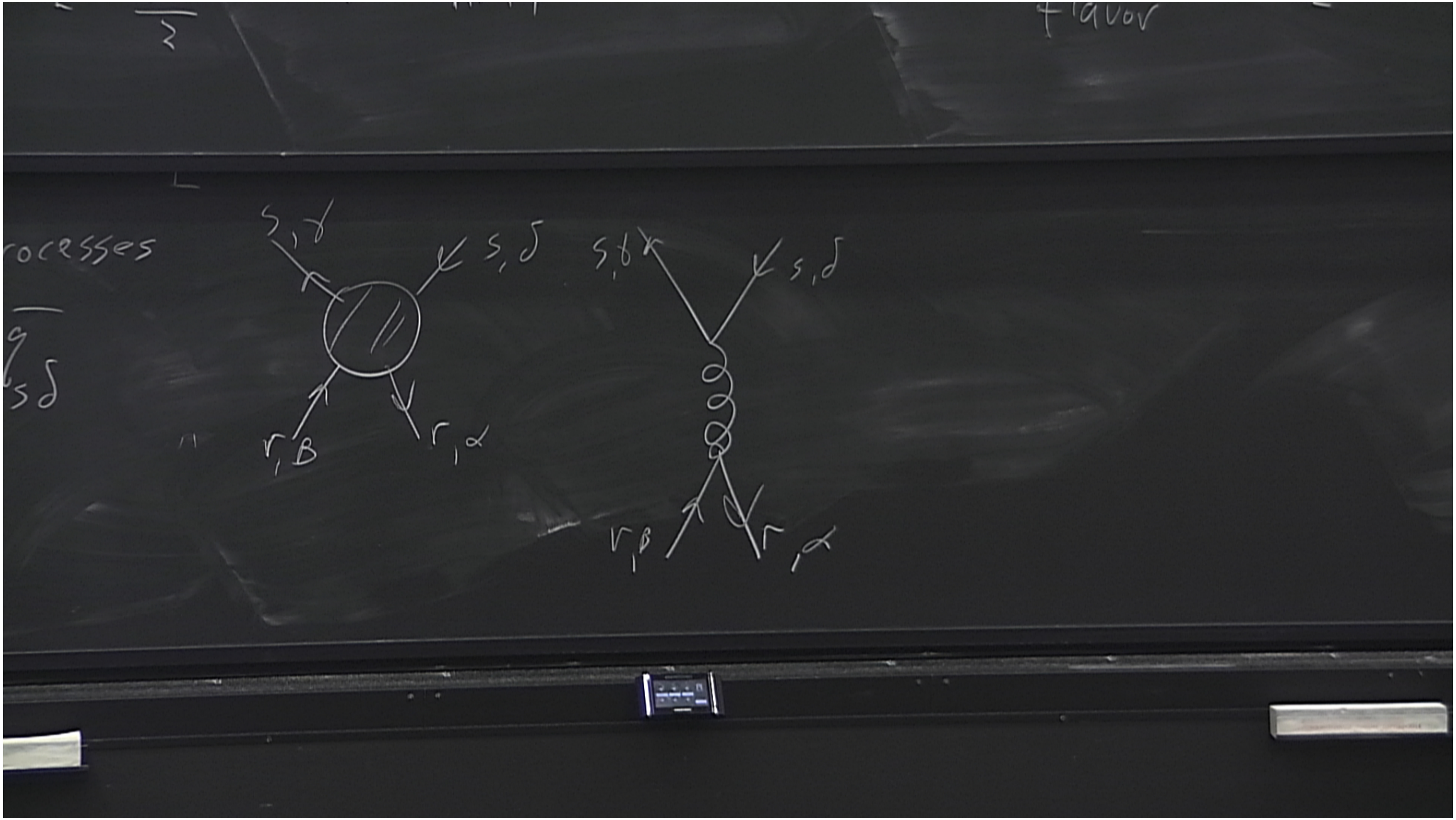
flavor

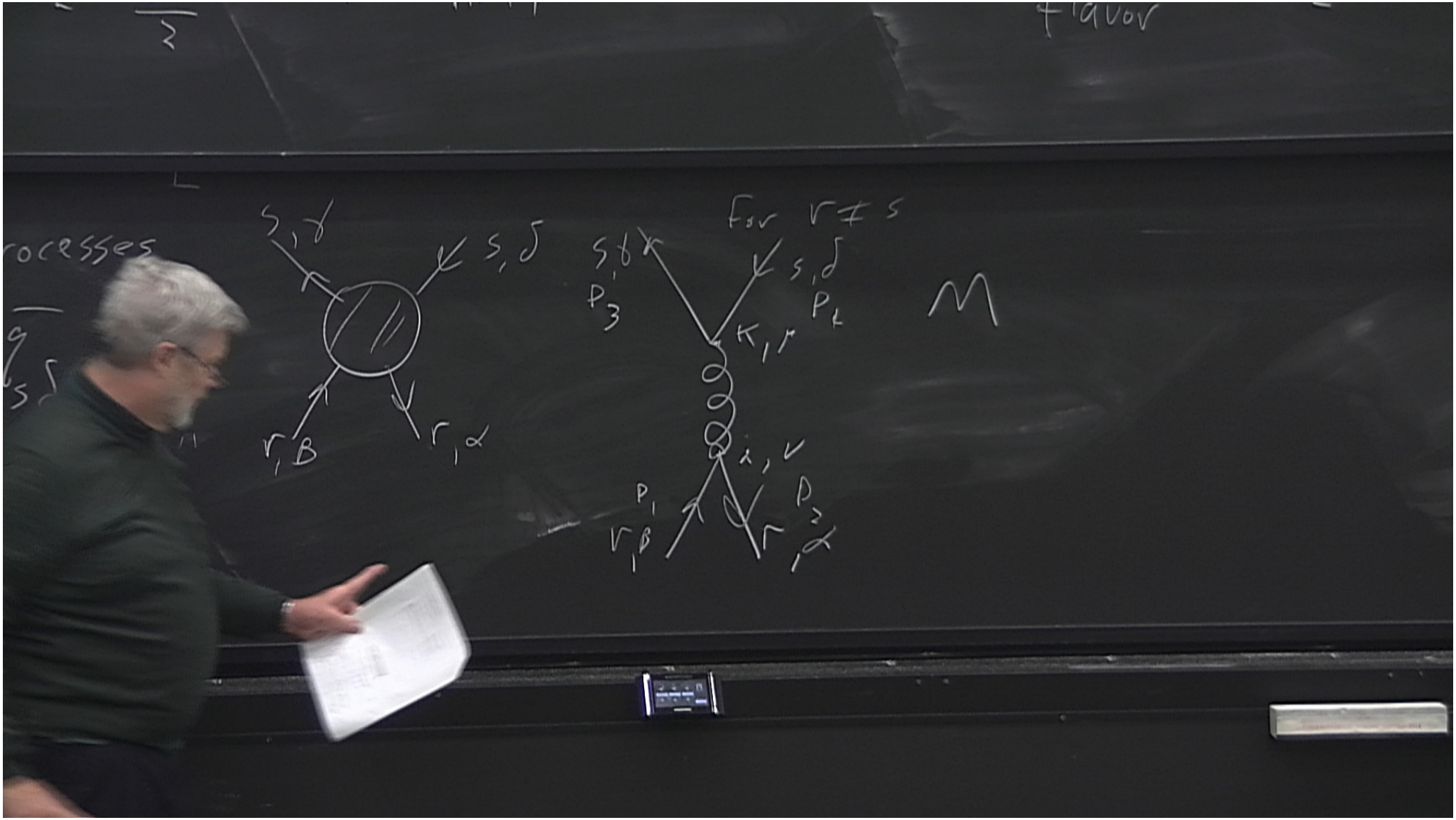
Simple QCD processes

$$q_{rB}\,\bar{q}_{r\alpha} \longrightarrow q_{s\gamma}\,\bar{q}_{s\delta}$$



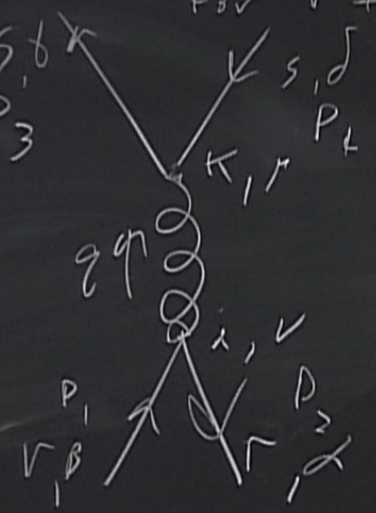

flavor
rocesses
s,γ
s,δ
r,β
r,α
s,δ
r,β
r,α


flavor
rocesses
s,γ
s,δ
r,B
r,α
s,δ
s,δ
r,B
r,α


flavor
processes
For r ≠ s
M

flavor

For $r \neq s$

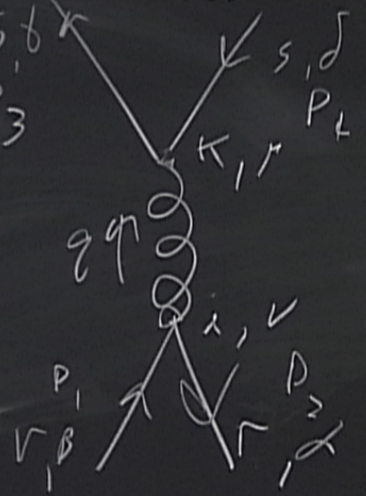


$$\mathcal{M} = \left(-i g_s \bar{u}_3 \gamma_\mu L^k_{\gamma\delta} V_4\right)\left[\frac{-i g^{\mu\nu}}{q^2}\delta^{\lambda k}\right]$$

$$\left(-i g_s \bar{V}_2 \gamma_\nu \hat{L}_{\alpha\beta} u_1\right)$$

flavor

For $r \neq s$

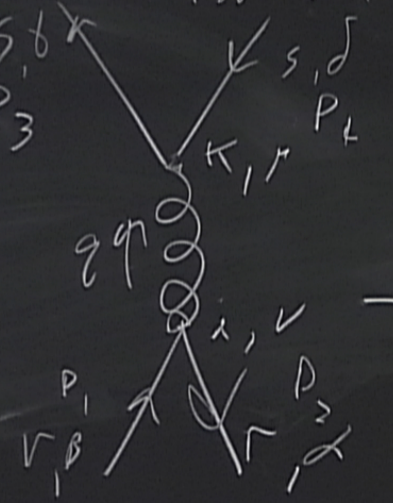


$$\mathcal{M} = \left(-i g_s \bar{u}_3 \gamma_\mu L^K_{\gamma\delta} V_4\right)\left[\frac{-i g^{\mu\nu}}{q^2}\delta^{\lambda K}\right]$$

$$\left(-i g_s \bar{V}_2 \gamma_\nu \hat{L}_{\alpha\beta} u_1\right)$$

flavor

For $r \neq s$



$$\mathcal{M} = \left(-i g_s \bar{u}_3 \gamma_\mu L^K_{\gamma\delta} V_4\right)\left[\frac{-i g^{\mu\nu}}{q^2}\delta^{\lambda K}\right]$$

$$- \left(-i g_s \bar{V}_2 \gamma_\nu \hat{L}_{\alpha\beta} u_1\right)$$