

Title: Quantum Field Theory II - Lecture 14

Date: Nov 17, 2011 09:00 AM

URL: <http://pirsa.org/11110020>

Abstract:



$$S[A] = \frac{1}{2g^2} \int d^4x \sqrt{|g|} [F_{\mu\nu} F^{\mu\nu}] = \frac{1}{4g^2} \int d^4x F_{\mu\nu} F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad A_\mu = (A_\mu^a) \quad a = 1, \dots, \dim \mathfrak{g}$$



$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr} [F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

$$\partial_\mu A_\nu - \partial_\nu A_\mu - i [A_\mu, A_\nu] \quad A_\mu = A_\mu^a t_a \quad a=1, \dots, n = \dim G$$

↑ generators

$$g A_\mu g^{-1} - i g \partial_\mu g^{-1} \quad g \in G \quad g = 1 + i\alpha \quad \alpha = \alpha^a t_a$$



$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

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$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$



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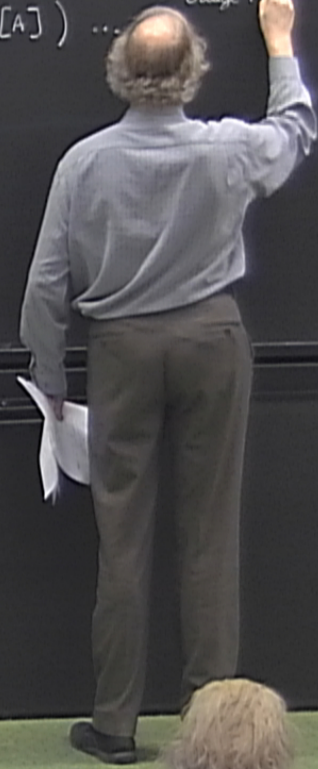
$t_a$  generators

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$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$\int D[A] \exp(+S[A]) \dots$$

Gauge Fixing





$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a{}^{\mu\nu}$$

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$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$\int D[A] \exp(+S[A]) \dots \int E[A] \quad \text{Gauge fixing condition}$$





$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu - i[A_\mu, A_\nu]$$

$$A_\mu = A_\mu^a t_a \quad a=1, \dots, n = \dim G$$

generators

$$A_\mu \rightarrow g A_\mu g^{-1} - i g \partial_\mu g^{-1} \quad g \in G$$

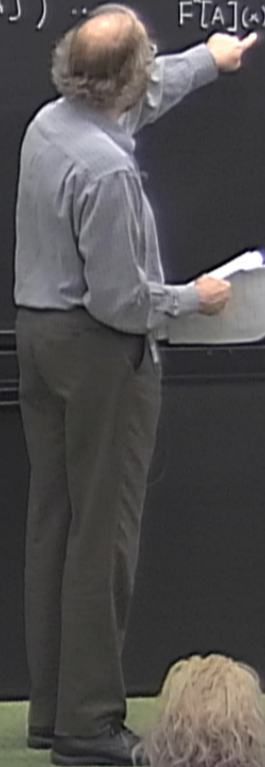
$$g = 1 + i\alpha \quad \alpha = \alpha^a t_a$$

$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$\int D[A] \exp(+S[A]) \dots$$

Gauge fixing condition

$$F[A](x) = 0$$





$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu - i[A_\mu, A_\nu] \quad A_\mu = A_\mu^a t_a \quad a=1, \dots, n = \dim G$$

$t_a$  generators

$$A_\mu \rightarrow g A_\mu g^{-1} \quad g \in G \quad g = 1 + i\alpha \quad \alpha = \alpha^a t_a$$

$$A_\mu \rightarrow A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$\int D[A] \exp(+S[A]) \dots$$

Gauge Fixing condition

$$F[A](x) = 0 \quad \text{Function of } A(x)$$

$\partial A(x)$



$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - i[A_\mu, A_\nu]$$

$$A_\mu = A_\mu^a t_a \quad a=1, \dots, n = \dim G$$

$$A_\mu \rightarrow g A_\mu g^{-1} - i g \partial_\mu g^{-1} \quad g \in G$$

$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$t_a$  generators  
 $g = 1 + i\alpha \quad \alpha = \alpha^a t_a$

$$\int D[A] \exp(+S[A]) \dots$$

Gauge Fixing condition

$$F[A](x) = 0 \quad \text{Function of } A(x)$$

$$\partial^\mu A_\mu^a(x) - \omega^a(x) \quad \text{need Locally Invariant}$$




$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a{}^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - i[A_\mu, A_\nu] \quad A_\mu = A_\mu^a t_a \quad a=1, \dots, n = \dim G$$

$t_a$  generators

$$A_\mu \rightarrow g A_\mu g^{-1} - i g \partial_\mu g^{-1} \quad g \in G \quad g = 1 + i\alpha \quad \alpha = \alpha^a t_a$$

$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$\int_{\mathcal{A}} \mathcal{D}[A] \exp(iS[A]) \dots$$

||

$$\int_{\mathcal{A}} \mathcal{D}[A]$$

Gauge Fixing condition

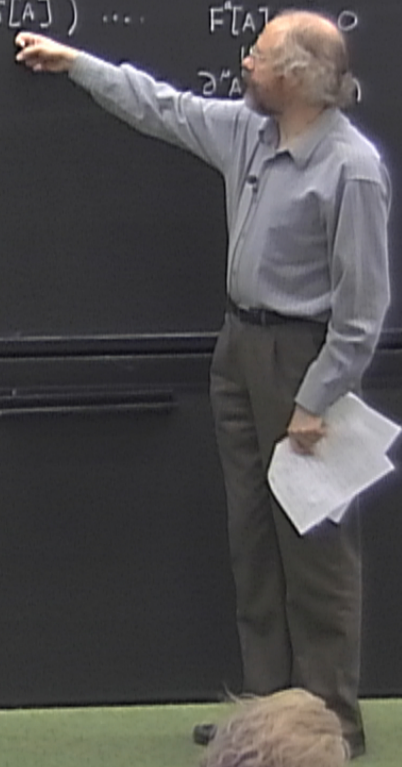
$$F[A] = 0$$

$$\partial^\mu A_\mu = 0$$

$$\partial^\mu A_\mu = 0$$

Function of  $A(x)$   
 $\partial A(x)$

$n$   $\omega^a(x)$  (need  
Locally Invariant)





$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu - i[A_\mu, A_\nu]$$

$$A_\mu \rightarrow g A_\mu g^{-1} - i g \partial_\mu g^{-1} \quad g \in G$$

$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$A_\mu = A_\mu^a t_a \quad a=1, \dots, n = \dim G$$

generators

$$g = 1 + i\alpha \quad \alpha = \alpha^a t_a$$

$$\int_{\mathcal{A}} \mathcal{D}[A] \exp(+S[A]) \dots$$

||

$$\int_{\mathcal{A}} \mathcal{D}[A]$$

Gauge Fixing condition

$$F[A](x) = 0 \quad \text{Function of } A(x)$$

||

$$\partial^\mu A_\mu^a(x) - \omega^a(x) \quad n \text{ } \omega^a(x) \text{ fixed}$$

Locally Invariant



$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu - i[A_\mu, A_\nu] \quad A_\mu = A_\mu^a t_a \quad a=1, \dots, n$$

generator

$$A_\mu \rightarrow g A_\mu g^{-1} - i g \partial_\mu g^{-1} \quad g \in G \quad g = 1 + i\alpha$$

$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$\int_{\mathcal{A}} \mathcal{D}[A] \exp(+S[A]) \dots$$

||

$$\int_{\mathcal{A}} \mathcal{D}[A] S[F[A]]$$

↑  
Dirac Function

Gauge Fixing condition

$$F[A](x) = 0 \quad \text{Function of } A(x)$$

||

$$\partial^\mu A_\mu^a(x) - \omega^a(x) \quad \text{if } \omega^a(x) \text{ fixed}$$

Locally Invariant



$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

$$\partial_\nu A_\mu - \partial_\mu A_\nu - i[A_\mu, A_\nu]$$

$$g A_\mu \bar{g}^{-1} - i g \partial_\nu \bar{g}^{-1} \quad g \in G$$

$$D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$A_\mu = A_\mu^a t_a \quad a=1, \dots, n = \dim G$$

$t_a$  generators

$$g = 1 + i\alpha \quad \alpha = \alpha^a t_a$$

$$\int_{\mathcal{A}} \mathcal{D}[A] \exp(+S[A]) \dots$$

||

$$\int_{\mathcal{A}} \mathcal{D}[A] \delta[F[A]] \left| \text{Det} \left[ \frac{\delta F[A]}{\delta h} \right] \right|$$

↑  
Dirac Function  
for all  $x$  and  $a$

Gauge Fixing condition

$$F[A](x) = 0$$

Function of  $A(x)$   
 $\frac{\delta}{\delta A(x)}$

$$\partial^\mu A_\mu^a(x) - \omega^a(x)$$

$n$   $\omega^a(x)$  fixed  
Locally Invariant



$$S[A] = -\frac{1}{2g^2} \int d^4x \text{Tr}[F_{\mu\nu} F^{\mu\nu}] = -\frac{1}{4g^2} \int d^4x F_{\mu\nu}^a F_a^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu - i[A_\mu, A_\nu] \quad A_\mu = A_\mu^a t_a \quad a=1, \dots, n = \dim G$$

generators

$$A \rightarrow A_g \quad A_\mu \rightarrow g A_\mu g^{-1} - i g \partial_\nu g^{-1} \quad g \in G$$

$$A_\mu \rightarrow A_\mu + D_\mu \alpha = A_\mu + \partial_\mu \alpha - i[A_\mu, \alpha]$$

$$g = 1 + i\alpha \quad \alpha = \alpha^a t_a$$

$$\int_{\mathcal{A}} D[A] \exp(iS[A]) \dots$$

Gauge Fixing condition

$$F[A](x) = 0 \quad \text{Function of } A(x)$$

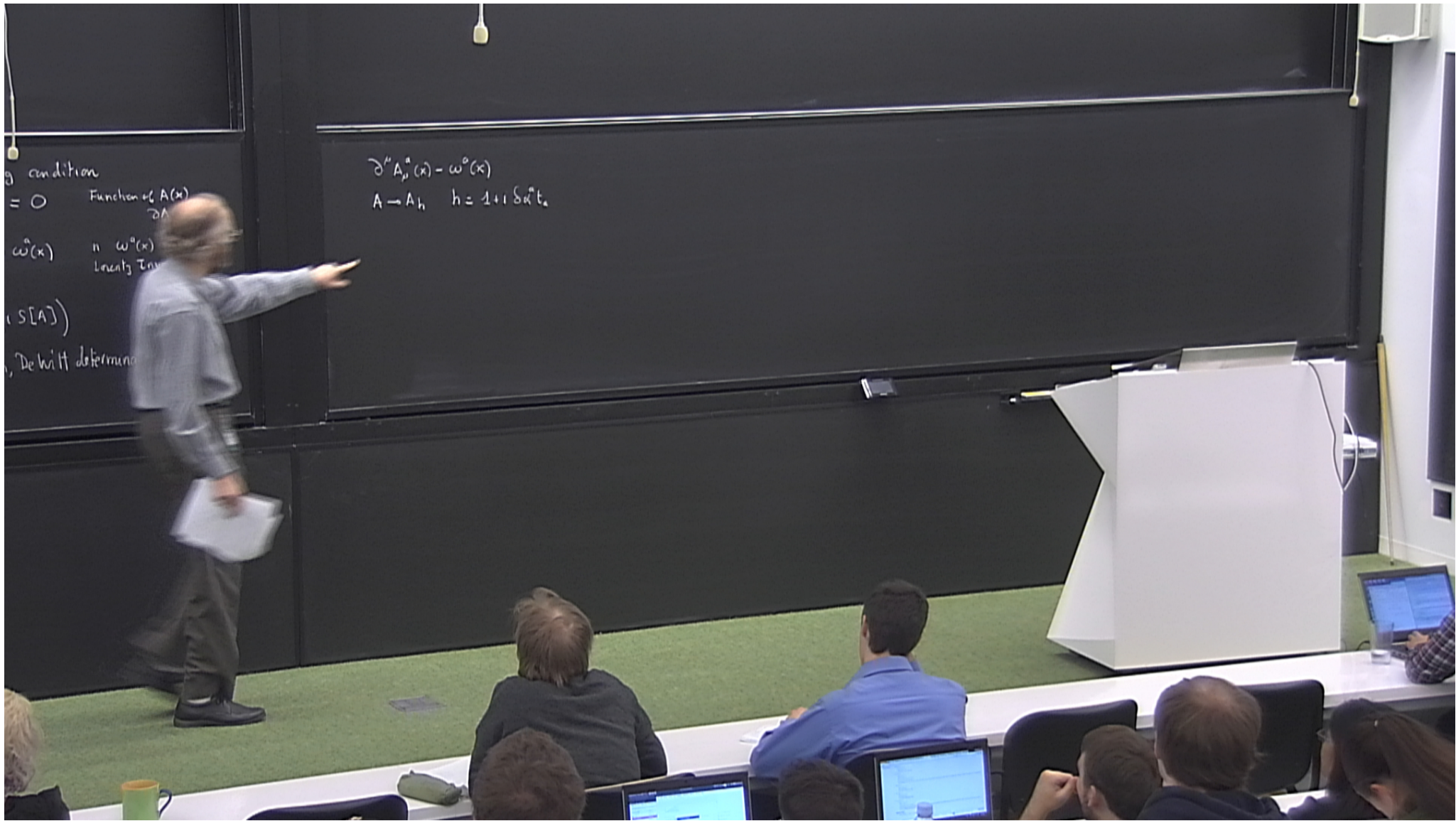
$$\partial^\mu A_\mu^a(x) - \omega^a(x) \quad n \omega^a(x) \text{ fixed}$$

Locally Invariant

$$\int_{\mathcal{A}} D[A] \exp(iS[A]) \left| \text{Det} \left[ \frac{\delta F[A]}{\delta \alpha} \right] \right| \exp(iS[A])$$

Faddeev-Popov, Feynman, De Witt determinant

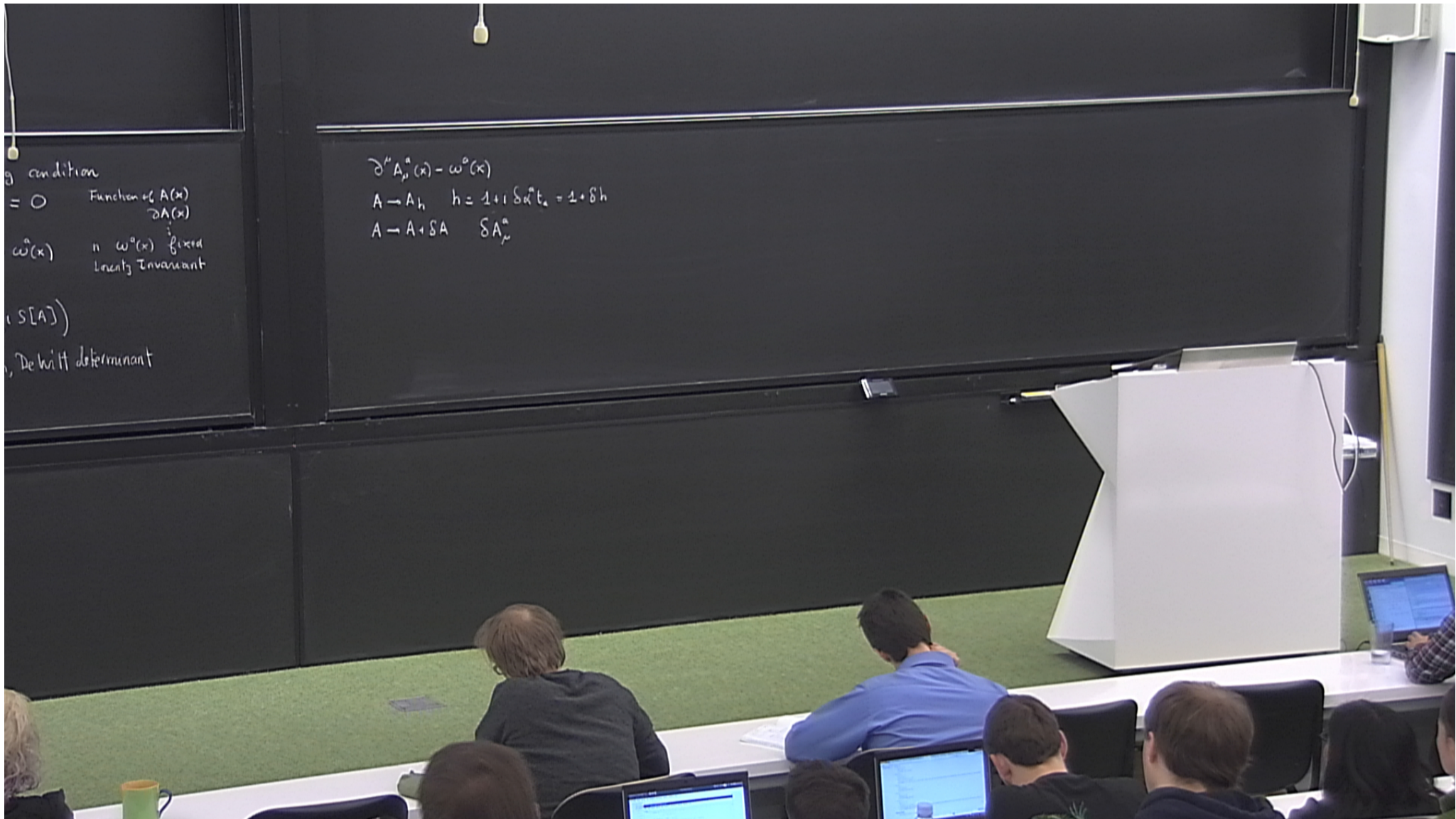




g condition  
= 0 Funktion  $\omega(A(x))$   
 $\omega(x)$  n  $\omega^0(x)$   
Lorentz Inv  
 $S[A]$   
De Witt determin

$$\frac{\delta^n A_{\mu\nu}(x) - \omega^0(x)}{\delta A}$$
$$A \rightarrow A_h \quad h = 1 + i S \alpha^a t.$$





g condition  
 $= 0$  Function of  $A(x)$   
 $\frac{\partial A(x)}{\partial A(x)}$   
 $\omega(x)$  is  $\omega^0(x)$  fixed  
 Locally Invariant  
 $S[A]$   
 De Witt determinant

$$\frac{\delta^n A_{\mu\nu}^a(x) - \omega^0(x)}{\delta A(x)}$$

$$A \rightarrow A_h \quad h = 1 + i \delta \alpha^a t_a = 1 + \delta h$$

$$A \rightarrow A + \delta A \quad \delta A_{\mu\nu}^a$$



$$h = 1 + \delta h$$

$$A \rightarrow A + \delta A$$

$$\delta h = \delta \alpha^a(t) t_a$$

$$\delta A_\mu^a(x) = D_\mu \alpha^a(x) = \partial_\mu \alpha^a(x) - i [$$



$$h = 1 + \delta h$$

$$A \rightarrow A + \delta A$$

$$\delta h = \delta \alpha^a(x) t_a$$

$$\delta A_\mu^a(x) = D_\mu \alpha^a(x) = \partial_\mu \alpha^a(x) - F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$



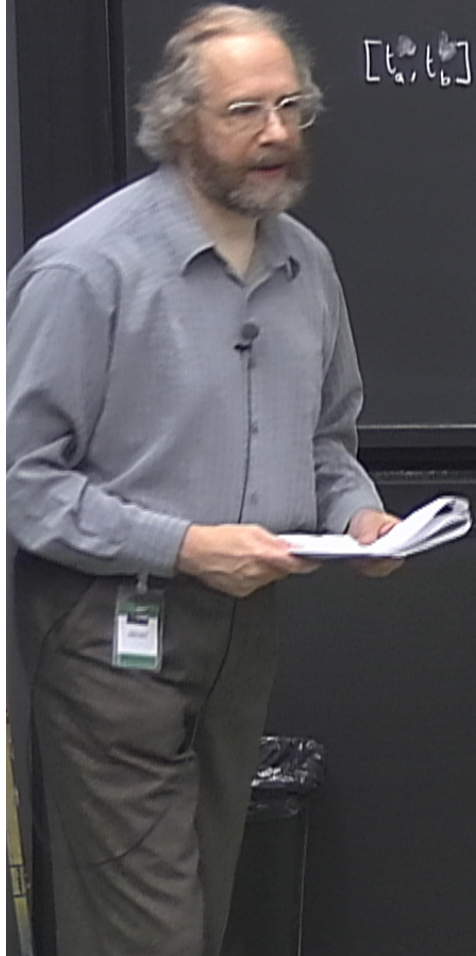
$$h = 1 + \delta h$$

$$\delta h = \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A$$

$$\delta A_\mu^a(x) = D_\mu \delta \alpha^a(x) = \partial_\mu \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c$$





$$\begin{aligned}
 h &= 1 + \delta h & \delta h &= i \delta \alpha^a(x) t_a \\
 A &\rightarrow A + \delta A & \delta A_\mu^a(x) &= D_\mu \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x) \\
 [t_a, t_b] &= i F_{ab}^c t_c
 \end{aligned}$$

$$F^a(x) = \partial^\rho A_\rho^a(x) - \omega^a(x)$$

$$A \rightarrow A_h \quad h = 1 + i \delta \alpha^a t_a = 1 + \delta h$$

$$A \rightarrow A + \delta A \quad \delta A_\rho^a$$



$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \delta \alpha^a(x) = \partial_\mu^a \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) =$$



$$h = 1 + \delta h$$

$$\delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A$$

$$\delta A_\mu^a(x) = D_\mu \alpha^a(x) = \partial_\mu \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c$$

$$\delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{i \delta \alpha^b(y)}$$



$$h = 1 + \delta h$$

$$\delta h = i \delta \alpha^a(x) t_a$$

$$\rightarrow A + \delta A$$

$$\delta A_\mu^a(x) = D_\mu \delta \alpha^a(x) = \partial_\mu \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c$$

$$\delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{F^a[A_h](x)}{i \delta \alpha^b(y)} = \text{Integral Kernel of an operator}$$



$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \delta \alpha^a(x) = \partial_\mu^a \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{i \delta \alpha^b(y)} = \text{Integral Kernel of an operator} = J_b^a(x, y) =$$



$$\begin{aligned}
 h &= 1 + \delta h & \delta h &= i \delta \alpha^a(x) t_a \\
 A &\rightarrow A + \delta A & \delta A_\mu^a(x) &= D_\mu \alpha^a(x) = \partial_\mu \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x) \\
 [t_a, t_b] &= i F_{ab}^c t_c & \delta F^a(x) &= \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \alpha^a(x) + \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))
 \end{aligned}$$

$$\frac{\delta F^a[A_\mu](x)}{i \delta \alpha^b(y)} = \text{Integral Kernel of an operator} =$$



$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \delta \alpha^a(x) = \partial_\mu^a \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu^a \delta \alpha^a(x) + F_{bc}^a \partial^\mu \delta \alpha^c(x)$$

$$\frac{\delta F^a[A_n](x)}{i \delta \alpha^a(y)} = \text{Integral Kernel of an operator} = J_c^a(x, y) = \delta_c^a$$



$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \delta \alpha^a(x) = \partial_\mu^a \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_n](x)}{i \delta \alpha^a(y)} = \text{Integral Kernel of an operator} = J_c^a(x, y) = \delta_c^a \Delta + F_{bc}^a \overrightarrow{\partial}_\mu A_\mu^b$$

$\uparrow$   
 Laplace operator  
 $\partial^\mu \cdot \partial_\mu$



$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \delta \alpha^a(x) = \partial_\mu^a \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial^\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_n](x)}{i \delta \alpha^a(y)} = \text{Integral Kernel of an operator} = J_c^a(x, y) = \left[ \delta^a_c \partial^\mu \partial_\mu \delta(x-y) + F_{bc}^a \partial^\mu (A_\mu^b(x) \delta(x-y)) \right]$$



$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu \alpha^a(x) = \partial_\mu \alpha^a(x) + F_{bc}^a A^b$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_n](x)}{i \delta \alpha^a(y)} = \text{Integral Kernel} = \text{Differential operator}$$

$$J^a = \partial_\mu \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

↑  
Laplace operator  
 $\partial^\mu \cdot \partial_\mu$



Dirac function, Dirac delta, Faddeev-Popov, Feynman, Hessian determinant

$$h = 1 + \delta h$$

$$\delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A$$

$$\delta D_\mu \alpha^a(x) = \partial_\mu \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c$$

$$= \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

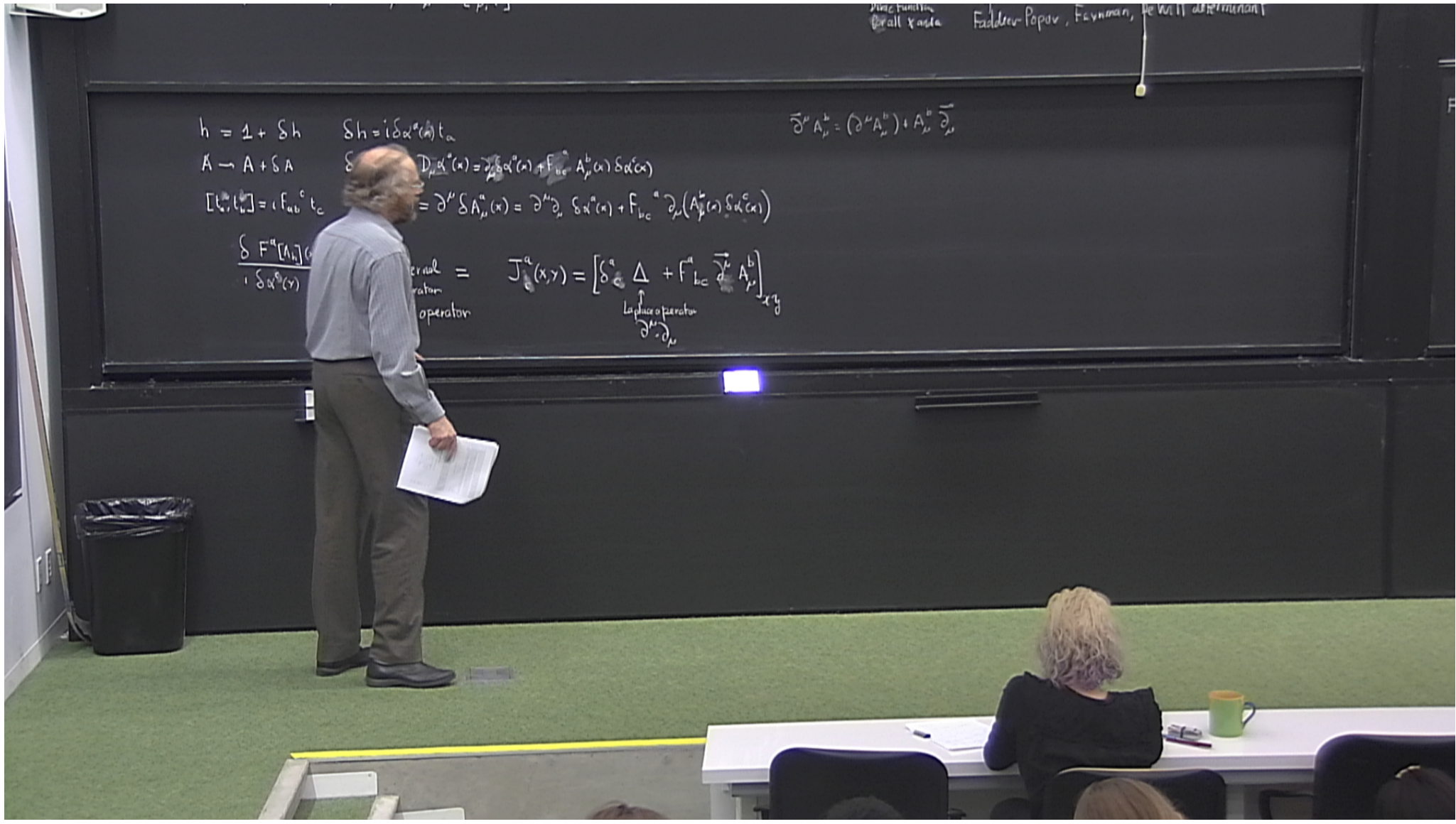
$$\vec{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \vec{\partial}_\mu$$

$$\frac{\delta F^a[A_\mu]}{\delta \alpha^a(x)}$$

functional operator

$$J_a^a(x, y) = \left[ \delta_{ab}^a \Delta + F_{bc}^a \vec{\partial}_\mu A_\mu^b \right]_{xy}$$

Laplace operator  
 $\partial^\mu \partial_\mu$





$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a(x) \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

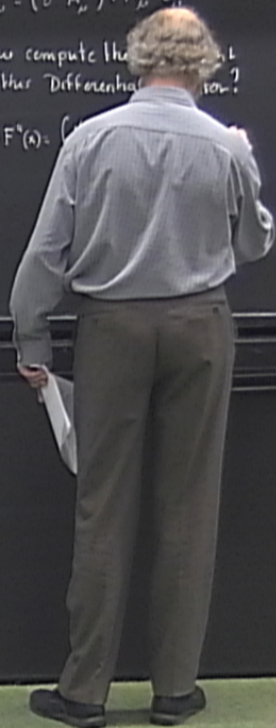
$$\overline{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^a \overline{\partial}_a^\mu$$

How compute the determinant of this differential operator?

$$\delta F^a(x) = \dots$$

$$\frac{\delta F^a[A_\mu^b](x)}{\delta \alpha^a(y)} = \text{Integral Kernel of a differential operator} = J_{ab}^a(x, y) = \left[ \delta_{ab}^a \Delta + F_{bc}^a \overline{\partial}_c^\mu A_\mu^b \right]_{xy}$$

Laplace operator  
 $\partial^\mu \partial_\mu$





Dirac function, Grassmann, Faddeev-Popov, Feynman, Higgs determinant

$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = \partial_\nu \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F_{bc}^a(x) = \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\nu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{\delta \alpha^a(y)} = J_a^a(x, y) = \left[ \delta_{ab}^a \Delta + F_{bc}^a \overleftrightarrow{\partial}_\mu A_\nu^b \right]_{xy}$$

Laplace operator  
 $\partial^\mu \partial_\mu$

$$\overleftrightarrow{\partial}^\mu A_\nu^b = (\partial^\mu A_\nu^b) + A_\nu^b \overleftrightarrow{\partial}^\mu$$

How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$



$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a(x) \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$\frac{\delta F^a[A_\mu^b](x)}{\delta \alpha^a(y)}$  = Integral Kernel of an operator  
Differential operator

$$J_c^a(x, y) = \left[ \delta_c^a \Delta + F_{bc}^a \overleftrightarrow{\partial}_\mu A_\mu^b \right]_{xy}$$

Laplace operator  
 $\overleftrightarrow{\partial}_\mu = \partial^\mu \partial_\mu$

$$\overleftrightarrow{\partial}_\mu A_\nu^b = (\partial^\mu A_\nu^b) + A_\nu^b \overleftrightarrow{\partial}_\mu$$

How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int d^4y J_c^a(x, y) \delta \alpha^c(y)$$



$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a(x) \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{\delta \alpha^a(y)} = \text{Integral Kernel of an operator Differential operator}$$

$$J_a^a(x, y) = \left[ \delta_a^a \Delta + F_{bc}^a \partial_\mu \right]$$

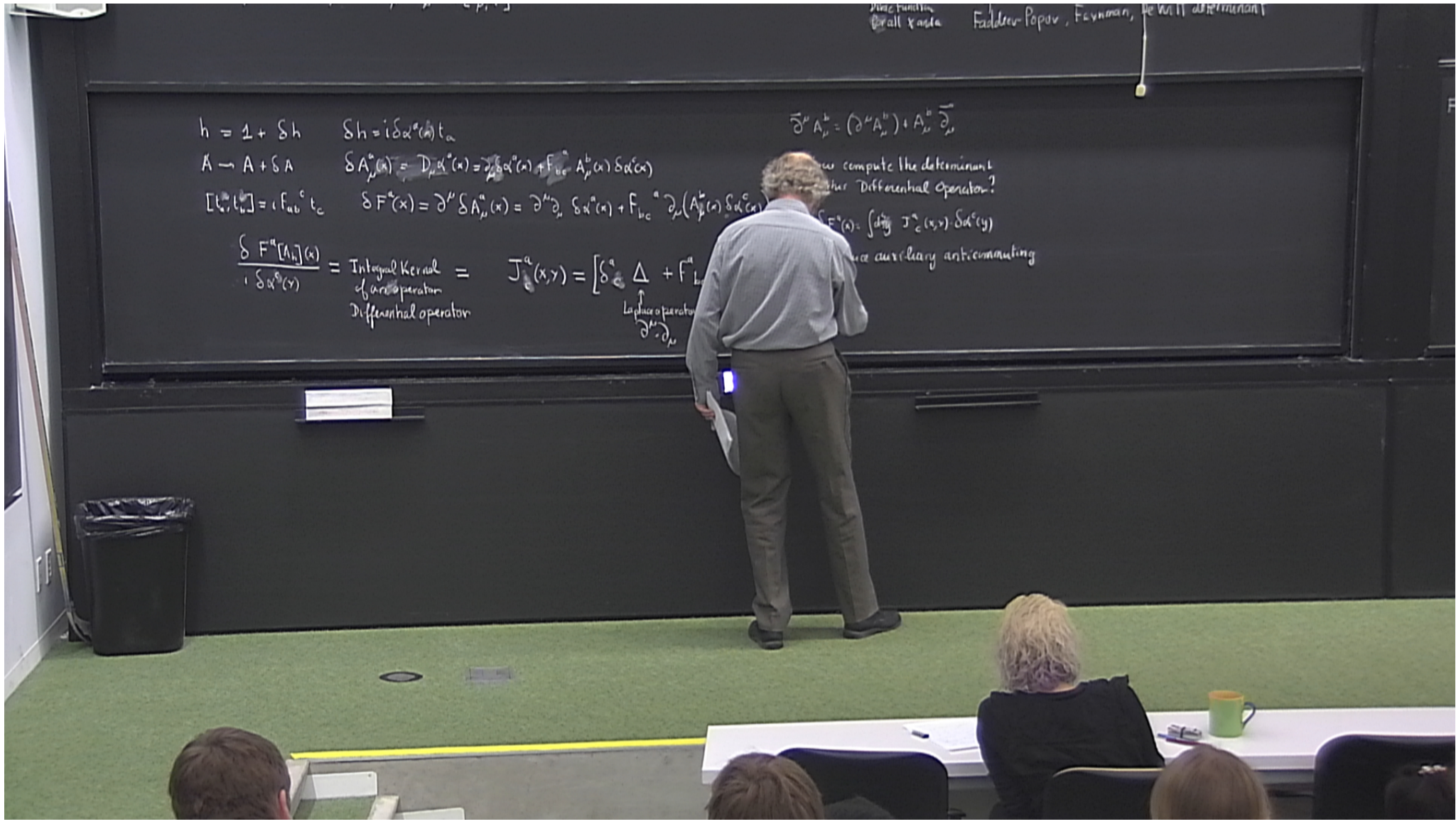
Laplace operator  
 $\partial^\mu \partial_\mu$

$$\overline{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \overline{\partial}^\mu$$

How compute the determinant of the Differential Operator?

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$

are auxiliary anticommuting





$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{\delta \alpha^a(y)} = \text{Integral Kernel of a differential operator} = J_{ab}^a(x, y) = \left[ \delta_{ab}^a \Delta + F_{bc}^a \overleftrightarrow{\partial}_\mu A_\mu^b \right]_{xy}$$

Laplace operator  
 $\partial^\mu \partial_\mu$

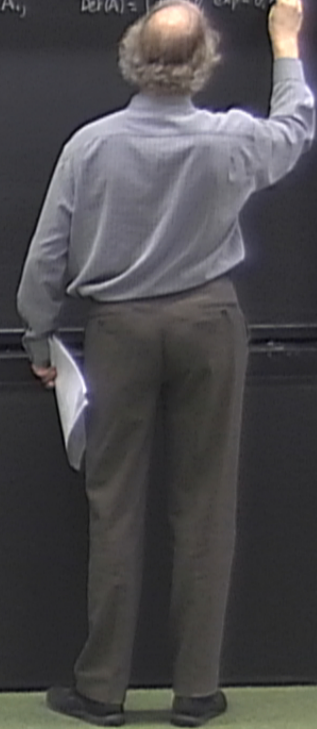
$$\overleftrightarrow{\partial}_\mu A_\nu^b = (\partial^\mu A_\nu^b) + A_\nu^b \overleftrightarrow{\partial}_\mu$$

$$\theta, \bar{\theta}, A, \text{Det}(A) = \int \exp(-\theta^T A \theta)$$

How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int dy J_{ab}^a(x, y) \delta \alpha^b(y)$$

Introduce auxiliary anticommuting fields: Ghosts and antighosts fields





$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a(x) \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

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Laplace operator  
 $\overleftrightarrow{\partial}_\mu = \partial^\mu \partial_\mu$

$$\overleftrightarrow{\partial}_\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \overleftrightarrow{\partial}_\mu$$

$$\theta_i, \bar{\theta}_i = A_i, \quad \text{Det}(A) = \int d\bar{\theta}_i d\theta_i \exp(\bar{\theta}_i A_i \theta_i)$$

How compute the determinant of this Differential Operator?

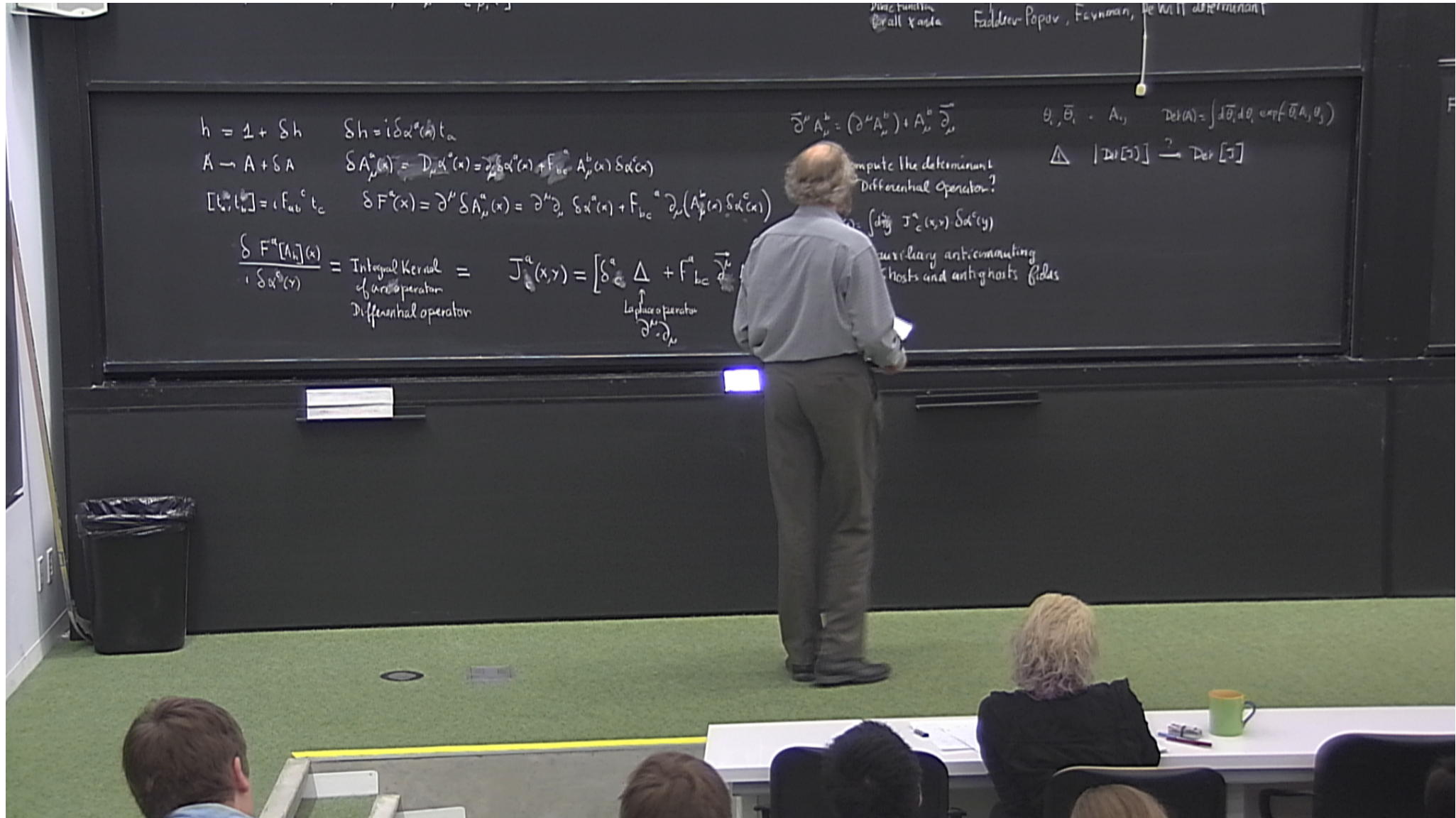
$$\Delta \quad |\text{Det}[\Delta]| \xrightarrow{?} \text{Det}[J]$$

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$

Introduce auxiliary anticommuting fields: Ghosts and antighosts fields







Dirac function, Faddeev-Popov, Feynman, We'll determine

$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a(x) \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{\delta \alpha^a(y)} = \text{Integral Kernel of an operator Differential operator} = J_a^a(x, y) = \left[ \delta_{ab}^a \Delta + F_{bc}^a \partial_\mu^a \right]$$

Laplace operator  
 $\partial^\mu \partial_\mu$

$$\bar{\partial}^\mu A_\mu^a = (\partial^\mu A_\mu^a) + A_\mu^a \bar{\partial}_\mu$$

compute the determinant  
Differential Operator?

$$\int \text{d}x J_a^a(x, y) \delta \alpha^a(y)$$

auxiliary anticommuting  
ghosts and antighosts fields

$$\theta_i, \bar{\theta}_i = A_i, \quad \text{Det}(A) = \int \text{d}\bar{\theta}_i \text{d}\theta_i \exp(-\bar{\theta}_i A_i \theta_i)$$

$$\Delta \quad |\text{Det}[\Delta]| \xrightarrow{?} \text{Det}[J]$$



Dirac function, Grassmann, Faddeev-Popov, Feynman, We'll determine

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Laplace operator  
 $\partial^\mu \partial_\mu$

$$\vec{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \vec{\partial}_\mu$$

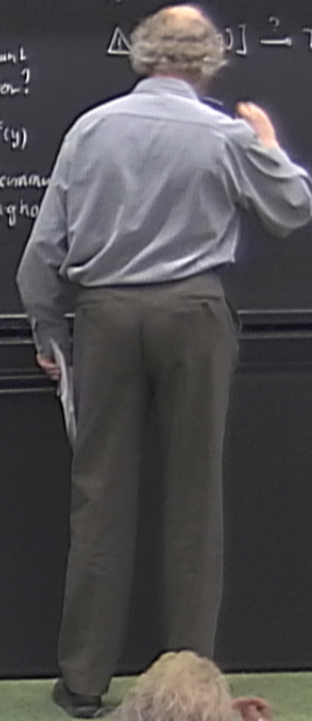
How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$

Introduce auxiliary anticommuting fields: Ghosts and antighosts

$$\theta, \bar{\theta}, A, \quad \text{Det}(A) = \int d\bar{\theta} d\theta \exp(\bar{\theta} A \theta)$$

$$\Delta \rightarrow \text{Det}[\Delta] \rightarrow \text{Det}[J]$$





Dirac function, Faddeev-Popov, Feynman, We'll determine

$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \alpha^a(x) = \partial_\mu^a \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

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$$\frac{\delta F^a[A_\mu](x)}{\delta \alpha^a(y)} = \text{Integral Kernel of an operator Differential operator} = J_a^a(x, y) = \left[ \delta_{ab}^a \Delta + F_{bc}^a \partial_\mu^b A_\mu^c \right]_{xy}$$

Laplace operator  
 $\partial^\mu \partial_\mu$

$$\bar{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \bar{\partial}_\mu$$

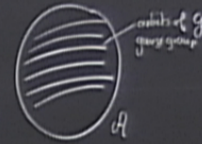
How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$

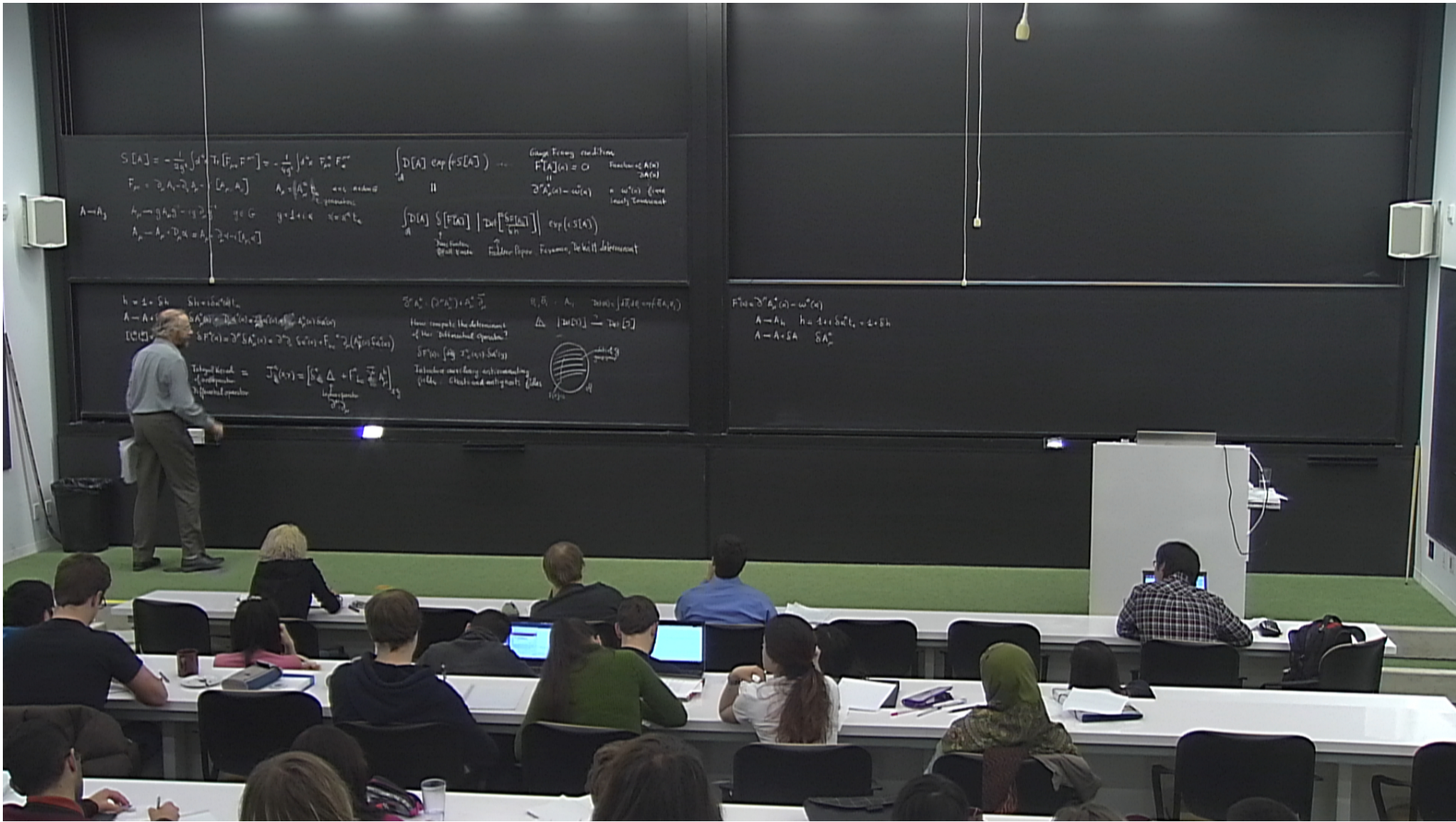
Introduce auxiliary anticommuting fields: Ghosts and antighosts fields

$$\theta_i, \bar{\theta}_i = A_i, \quad \text{Det}(A) = \int d\bar{\theta}_i d\theta_i \exp(-\bar{\theta}_i A_i \theta_j)$$

$$\Delta [\text{Det}(A)] \xrightarrow{?} \text{Det}[J]$$









$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \alpha^a(x) = \partial_\mu^a \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{\delta \alpha^a(y)} = \text{Integral Kernel of an operator Differential operator} = J_a^a(x, y) = \left[ \delta_{ab}^a \Delta + F_{bc}^a \partial_\mu A_\mu^b \right]_{xy}$$

$\Delta \leftarrow \text{Laplace operator } \partial^\mu \partial_\mu$

$$\bar{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \bar{\partial}^\mu$$

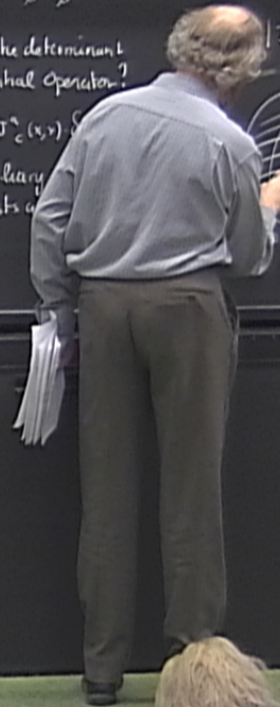
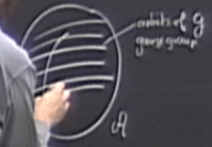
$$\theta, \bar{\theta}, A, \quad \text{Det}(A) = \int d\theta_1 d\theta_2 \exp(-\bar{\theta} A \theta)$$

How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$

Introduce auxiliary fields: Ghosts

$$|\text{Det}[D]| \xrightarrow{2} \text{Det}[J]$$





Dirac function, Faddeev-Popov, Feynman, DeWitt determinant

$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a(x) \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{\delta \alpha^a(y)} = \text{Integral Kernel of an operator Differential operator} = J_a^a(x, y) = \left[ \delta_{ab}^a \Delta + F_{bc}^a \partial_\mu \vec{A}_\mu^b \right]_{xy}$$

Laplace operator  
 $\partial^\mu \partial_\mu$

$$\vec{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \vec{\partial}_\mu$$

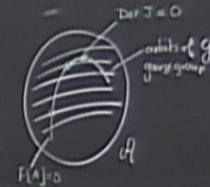
How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$

Introduce auxiliary anticommuting fields: Ghosts and antighosts fields

$$\theta_i, \bar{\theta}_i, A_i, \quad \text{Det}(A) = \int d\bar{\theta}_i d\theta_i \exp(-\bar{\theta}_i A_i \theta_j)$$

$$\Delta [ \text{Det}[D] ]^2 \xrightarrow{?} \text{Det}[J]$$





Dirac function, overall constant, Faddeev-Popov, Feynman, We'll determine

$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a \alpha^a(x) = \partial_\mu^a \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \alpha^a(x) + F_{bc}^a \partial_\mu (A_\mu^b(x) \delta \alpha^c(x))$$

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Laplace operator  
 $\partial^\mu \partial_\mu$

$$\bar{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \bar{\partial}_\mu$$

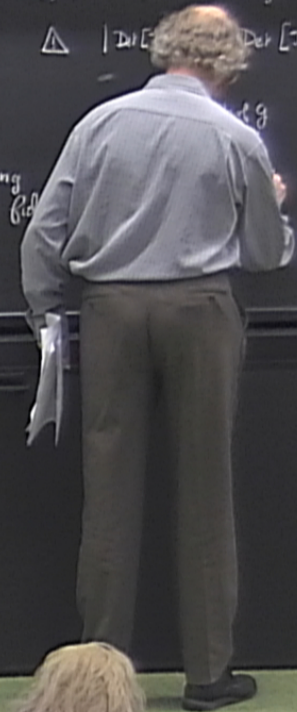
How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$

Introduce auxiliary anticommuting fields: Ghosts and antighosts fields

$$\theta_i, \bar{\theta}_i \cdot A_i, \quad \text{Det}(A) = \int d\bar{\theta}_i d\theta_i \exp(-\bar{\theta}_i A_i \theta_i)$$

$$\Delta \quad | \text{Det}[A] \quad \text{Det}[J]$$





$$h = 1 + \delta h \quad \delta h = i \delta \alpha^a(x) t_a$$

$$A \rightarrow A + \delta A \quad \delta A_\mu^a(x) = D_\mu^a(x) \delta \alpha^a(x) + F_{bc}^a A_\mu^b(x) \delta \alpha^c(x)$$

$$[t_a, t_b] = i F_{ab}^c t_c \quad \delta F^a(x) = \partial^\mu \delta A_\mu^a(x) = \partial^\mu \partial_\mu \delta \alpha^a(x) + F_{bc}^a \partial_\mu (\delta \alpha^b(x) A_\mu^c(x))$$

$$\frac{\delta F^a[A_\mu](x)}{\delta \alpha^a(y)} = \text{Integral Kernel of an operator Differential operator} = J_a^a(x, y) = \left[ \delta_a^a \Delta \right]$$

$$\bar{\partial}^\mu A_\mu^a = (\partial^\mu A_\mu^a) + A_\mu^b \bar{\partial}_\mu^a$$

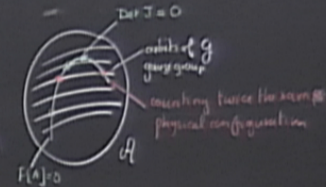
How compute the determinant of this Differential Operator?

$$\delta F^a(x) = \int d^4y J_a^a(x, y) \delta \alpha^a(y)$$

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$$\theta_i, \bar{\theta}_i = A_i, \quad \text{Det}(A) = \int d\bar{\theta}_i d\theta_i \exp(-\bar{\theta}_i A_{ij} \theta_j)$$

$$\Delta [ \text{Det}(S) ]^2 = \text{Det}[J]$$





$$\vec{\partial}^\mu A_\mu^b = (\partial^\mu A_\mu^b) + A_\mu^b \vec{\partial}_\mu$$

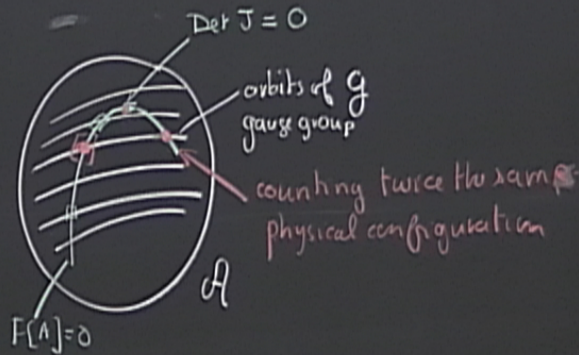
How compute the determinant of this Differential operator?

$$\delta F^a(x) = \int d^4y J_c^a(x,y) \cdot \delta \alpha^c(y)$$

Introduce auxiliary anticommuting fields: Ghosts and antighosts fields

$$\theta_i, \bar{\theta}_i \cdot A_{ij} \quad \text{Det}(A) = \int d\bar{\theta}_i d\theta_i \exp(-\bar{\theta}_i A_{ij} \theta_j)$$

$$\triangle \quad |\text{Det}[J]| \xrightarrow{?} \text{Det}[J]$$



$$F^a(x) = \vec{\partial}^\mu A_\mu^a(x)$$

$$A \rightarrow A_h$$

$$A \rightarrow A +$$



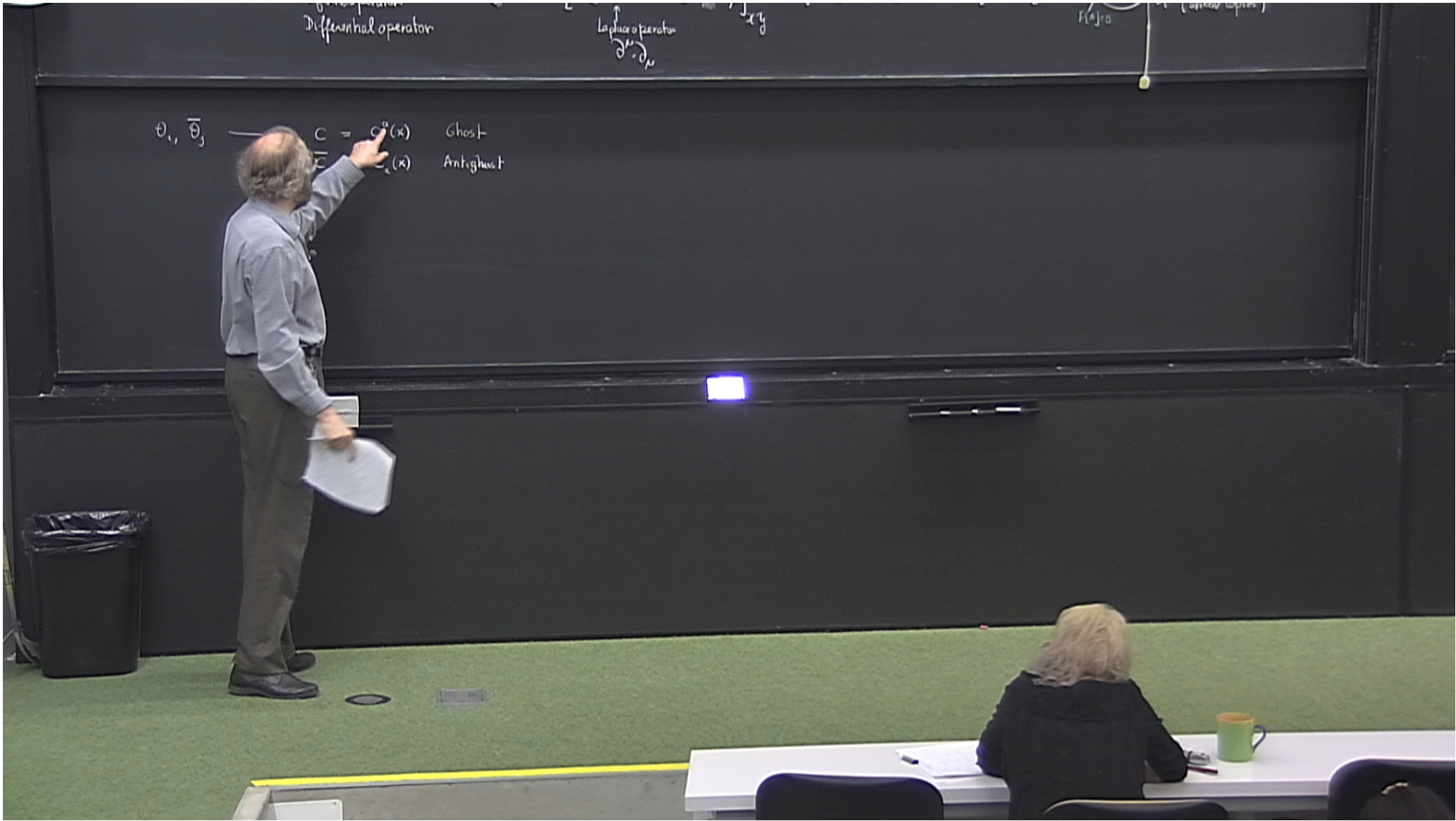
Differential operator

Laplace operator  
 $\partial^m = \partial_{x_1}^{m_1} \dots \partial_{x_n}^{m_n}$

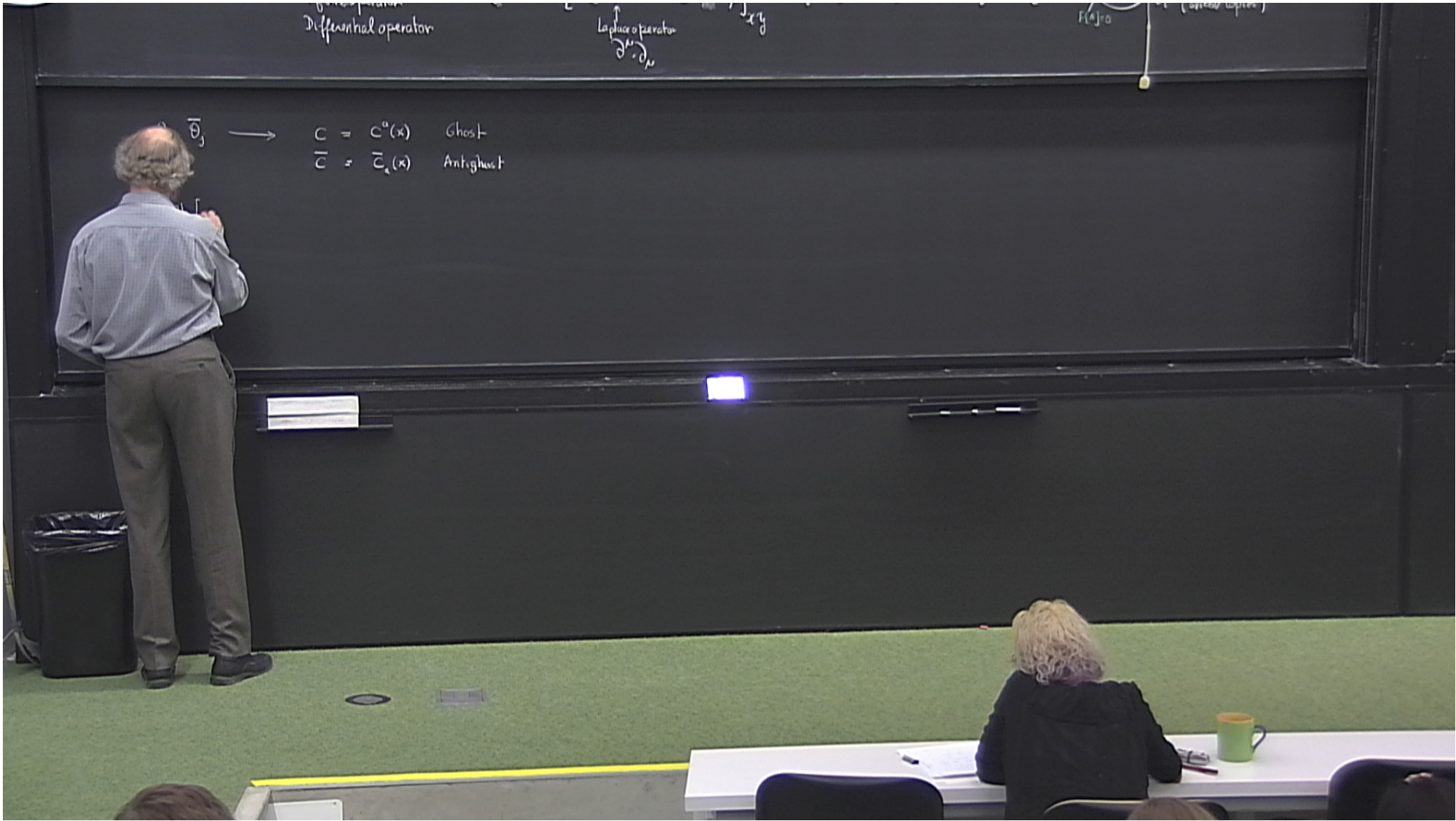
$f(x) = 0$

$$\begin{aligned} \partial_i, \bar{\partial}_j &\longrightarrow C = C^a(x) \quad \text{Ghost} \\ &\bar{C} = \bar{C}_a(x) \quad \text{Antighost} \end{aligned}$$

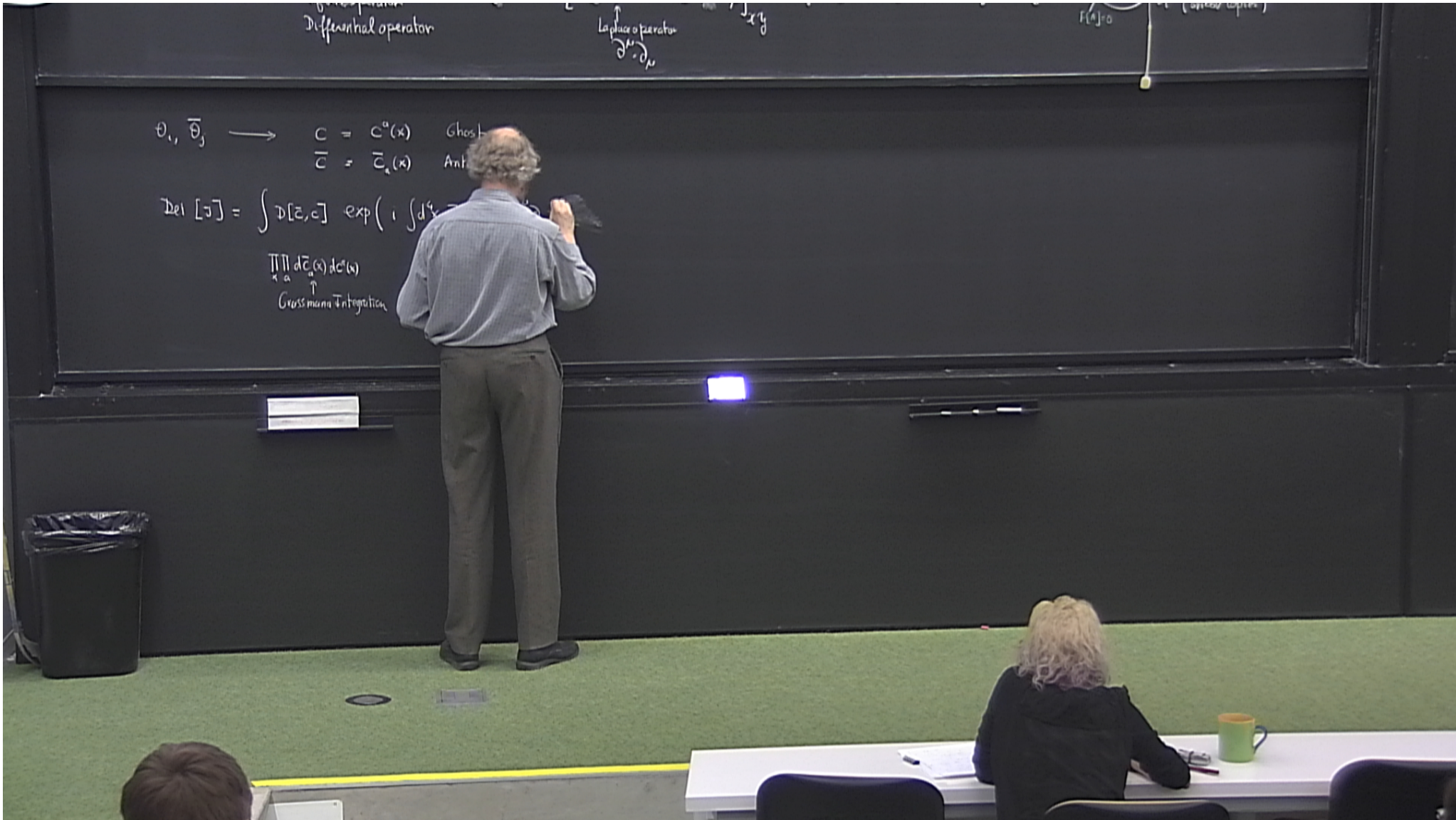












Differential operator

Laplace operator  
 $\partial^{\mu}\partial_{\mu}$

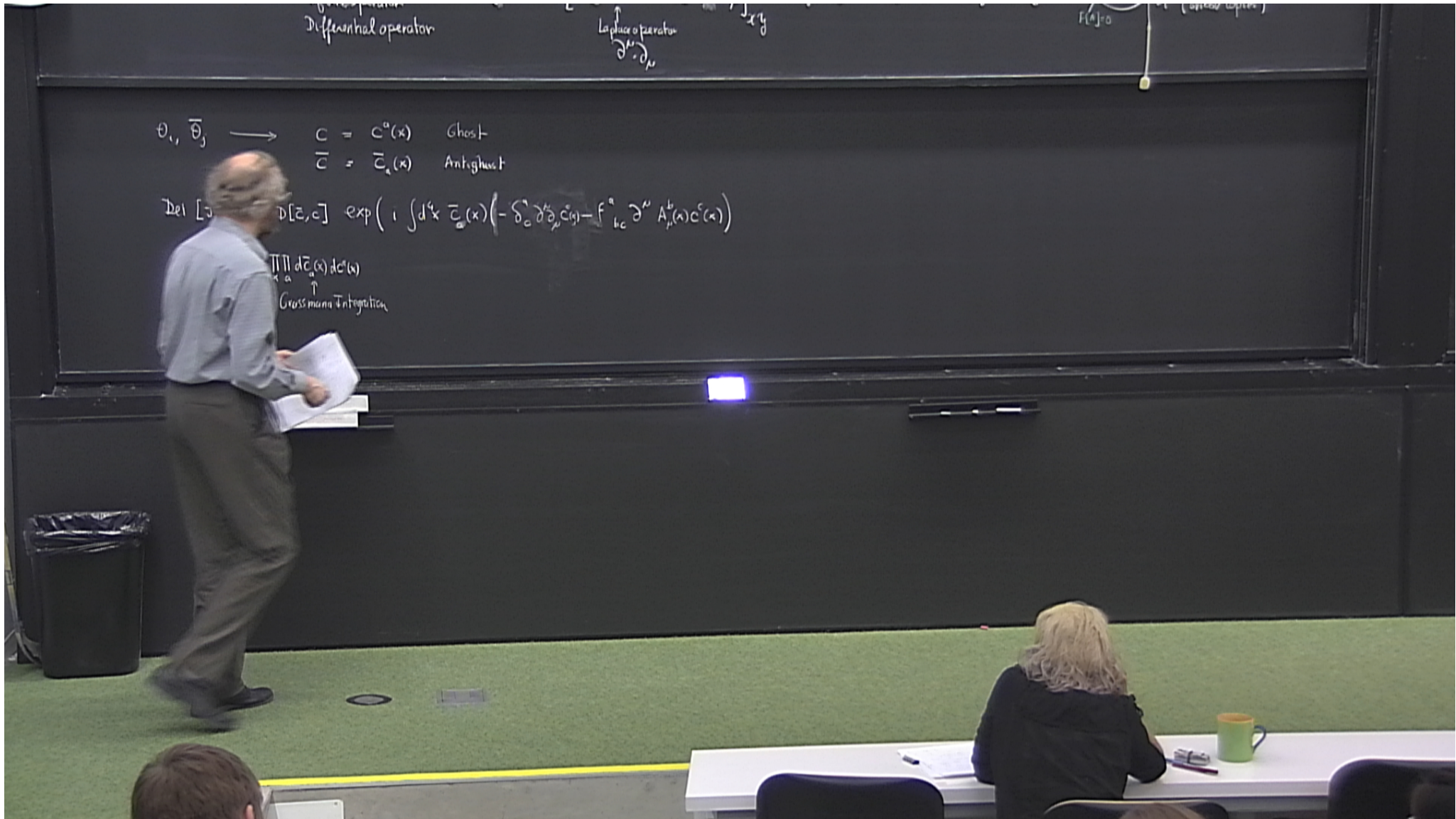
$$\theta_i, \bar{\theta}_j \longrightarrow \begin{aligned} c &= c^a(x) && \text{Ghost} \\ \bar{c} &= \bar{c}_a(x) && \text{Anti} \end{aligned}$$

$$\text{Det } [D] = \int \mathcal{D}[c, \bar{c}] \exp\left(i \int d^4x \dots\right)$$

$$\prod_a \int d\bar{c}_a(x) dc^a(x)$$

↑  
Grossmann Integration





Differential operator

Laplace operator  
 $\partial^{\mu}\partial_{\mu}$

$$\theta_i, \bar{\theta}_j \longrightarrow \begin{aligned} c &= c^a(x) && \text{Ghost} \\ \bar{c} &= \bar{c}_a(x) && \text{Antighost} \end{aligned}$$

$$\text{Det} [D] = \text{Det} [D[z, c]] \exp \left( i \int d^4x \bar{c}_a(x) \left( -\delta_{ab} \partial^{\mu}\partial_{\mu} c_b - f_{bc}^a \partial^{\mu} A_{\mu}^c(x) c^b(x) \right) \right)$$

$$\prod_a \int d\bar{c}_a(x) dc^a(x)$$

↑  
Grossmann Integration



Differential operator

Laplace operator  
 $\partial^{\mu}\partial_{\mu}$

$F[A]=0$

$$\theta_i, \bar{\theta}_j \longrightarrow \begin{array}{l} c = c^a(x) \text{ Ghost} \\ \bar{c} = \bar{c}_a(x) \text{ Ant.} \end{array}$$

$$\text{Det } [J] = \int \mathcal{D}[z, c] \exp\left(i \int d^4x \left[ -\partial^{\mu}\partial_{\mu} \bar{c}_a c_a - F^a_{bc} \partial^{\mu} A_{\mu}^b c^c(x) \right]\right)$$

$\prod_a \int d\bar{c}_a(x) dc_a(x)$   
↑  
Grassmann Integration



Differential operator

Laplace operator  
 $\partial^2 = \partial_\mu \partial^\mu$

$F[A]=0$  (Ghosts)

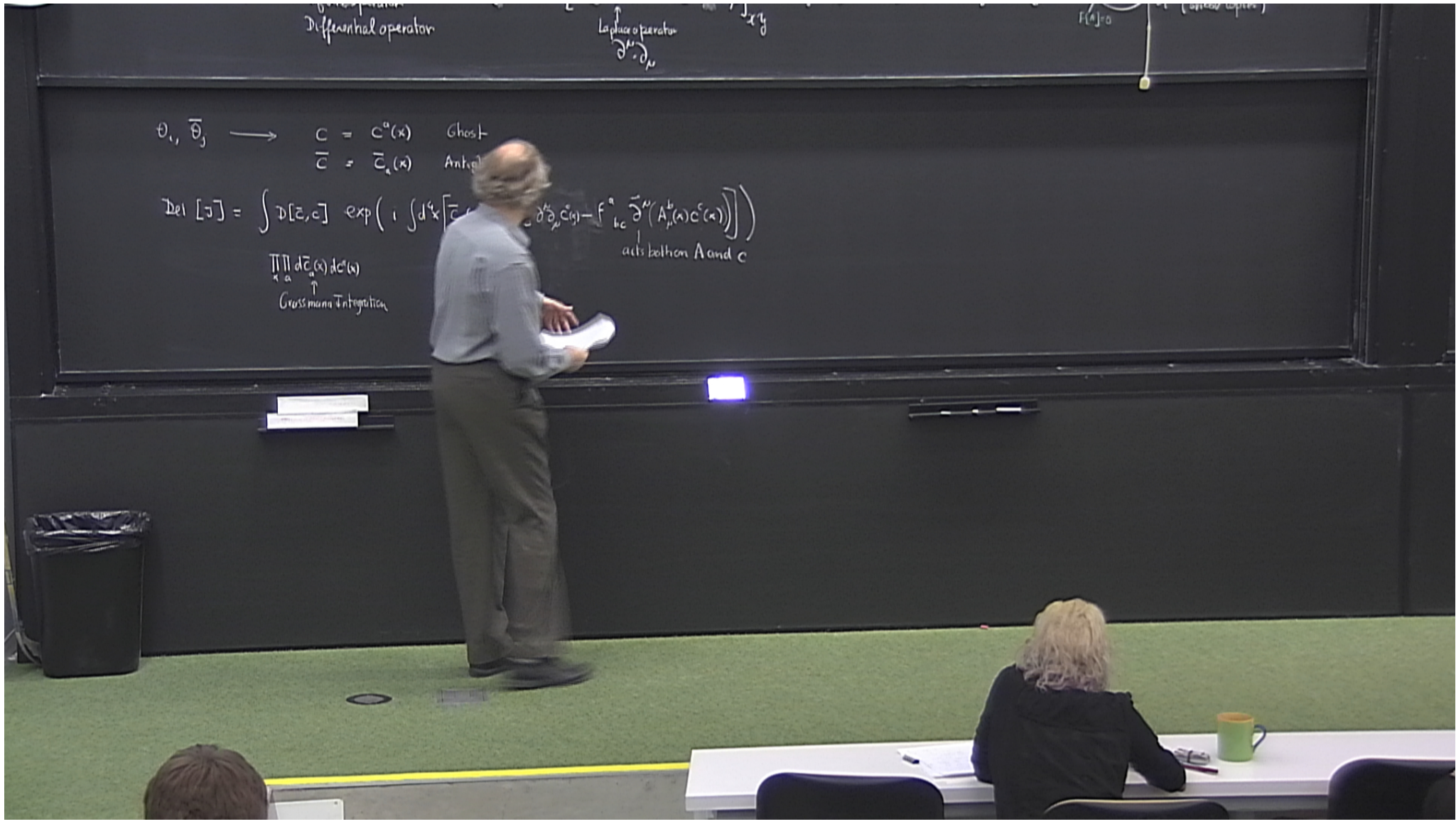
$$\theta_i, \bar{\theta}_j \longrightarrow \begin{aligned} c &= c^a(x) && \text{Ghost} \\ \bar{c} &= \bar{c}_a(x) && \text{Antigh} \end{aligned}$$

$$\text{Det } [J] = \int \mathcal{D}[z, c] \exp \left( i \int d^4x \left[ \bar{c} \left( \partial^2 \delta_{bc} - f_{bc}^a \partial^\mu (A_\mu^a c^c) \right) \right] \right)$$

acts both on A and c

$$\prod_a \int d\bar{c}_a(x) dc^a(x)$$

↑  
Grassmann Integration





Differential operator

Laplace operator  
 $\partial^2 = \partial_\mu \partial^\mu$

$F[A]=0$

$\theta_i, \bar{\theta}_j \rightarrow$   
 $c = c^a(x)$  Ghost charge  
 $\bar{c} = \bar{c}_a(x)$  Antighost but no spin

$$\text{Det } [J] = \int \mathcal{D}[c, \bar{c}] \exp \left( i \int d^4x \left[ \bar{c}_a(x) \left( -\delta_{ab} \partial^2 c_b(x) + f^a_{bc} \partial^2 (A^b_\mu(x) c^c(x)) \right) \right] \right)$$

$\prod_a \int d\bar{c}_a(x) dc^a(x)$   
↑  
Grassmann Integration

acts both on A and c  
or only on  $\bar{c}$



Differential operator

Laplace operator  
 $\partial^\mu \partial_\mu$

$F(A)=0$  (antisymmetric)

$\theta_i, \bar{\theta}_j \rightarrow c = c^a(x)$  Ghost charge  $\odot$  Spin-Statistics  
 $\bar{c} = \bar{c}_a(x)$  Antighost but no spin

$$\text{Det } [J] = \int \mathcal{D}[c, \bar{c}] \exp \left( i \int d^4x \left[ \bar{c}_a(x) \left( -\delta_c^a \partial^\mu \partial_\mu c_a + f_{bc}^a \partial^\mu (A_\mu^b c^c) \right) \right] \right)$$

$\prod_a \int d\bar{c}_a(x) dc^a(x)$   
↑  
Grassmann Integration

acts both on A and c  
or only on  $\bar{c}$



Differential operator

Laplace operator  
 $\partial^\mu \partial_\mu$

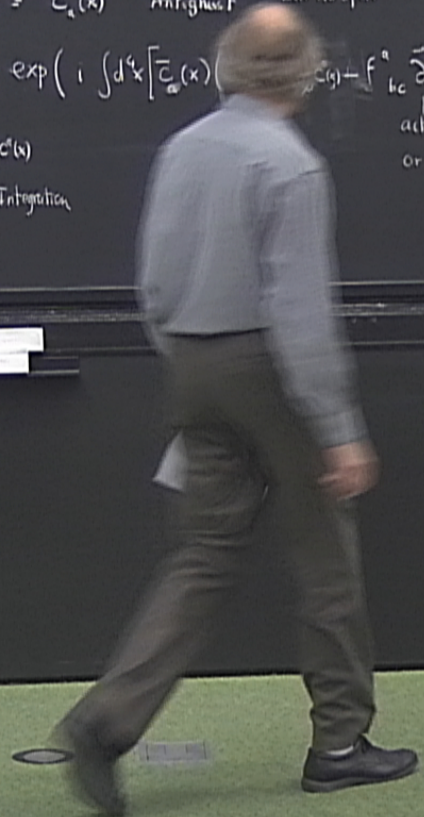
$F(\lambda) = 0$

$\theta_i, \bar{\theta}_j \rightarrow c = c^a(x)$  Ghost charge  $\odot$  Spin-Statistics  
 $\bar{c} = \bar{c}_a(x)$  Antighost but no spin

$$\text{Det } [J] = \int \mathcal{D}[c, \bar{c}] \exp \left( i \int d^4x \left[ \bar{c}_a(x) \left( \square \delta_{ab} - f_{bc}^a \partial^\mu \partial_\mu \right) c^b(x) \right] \right)$$

acts both on A and c  
or only on  $\bar{c}$

$\prod_a \int d\bar{c}_a(x) dc^a(x)$   
↑  
Grassmann Integration





Differential operator

Laplace operator  
 $\partial^2 = \partial_\mu \partial^\mu$

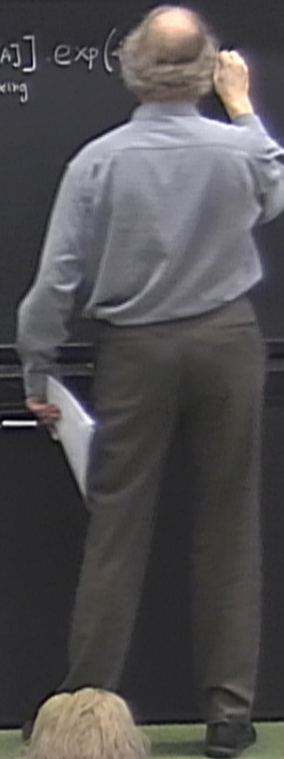
$\theta_i, \bar{\theta}_j \rightarrow c = c^a(x)$  Ghost charge  $\odot$  Spin-Statistics  
 $\bar{c} = \bar{c}_a(x)$  Antighost but no spin

$\int \mathcal{D}[A] \mathcal{D}[\bar{c}, c] \delta[F[A]] \exp(\dots)$   
gauge fixing

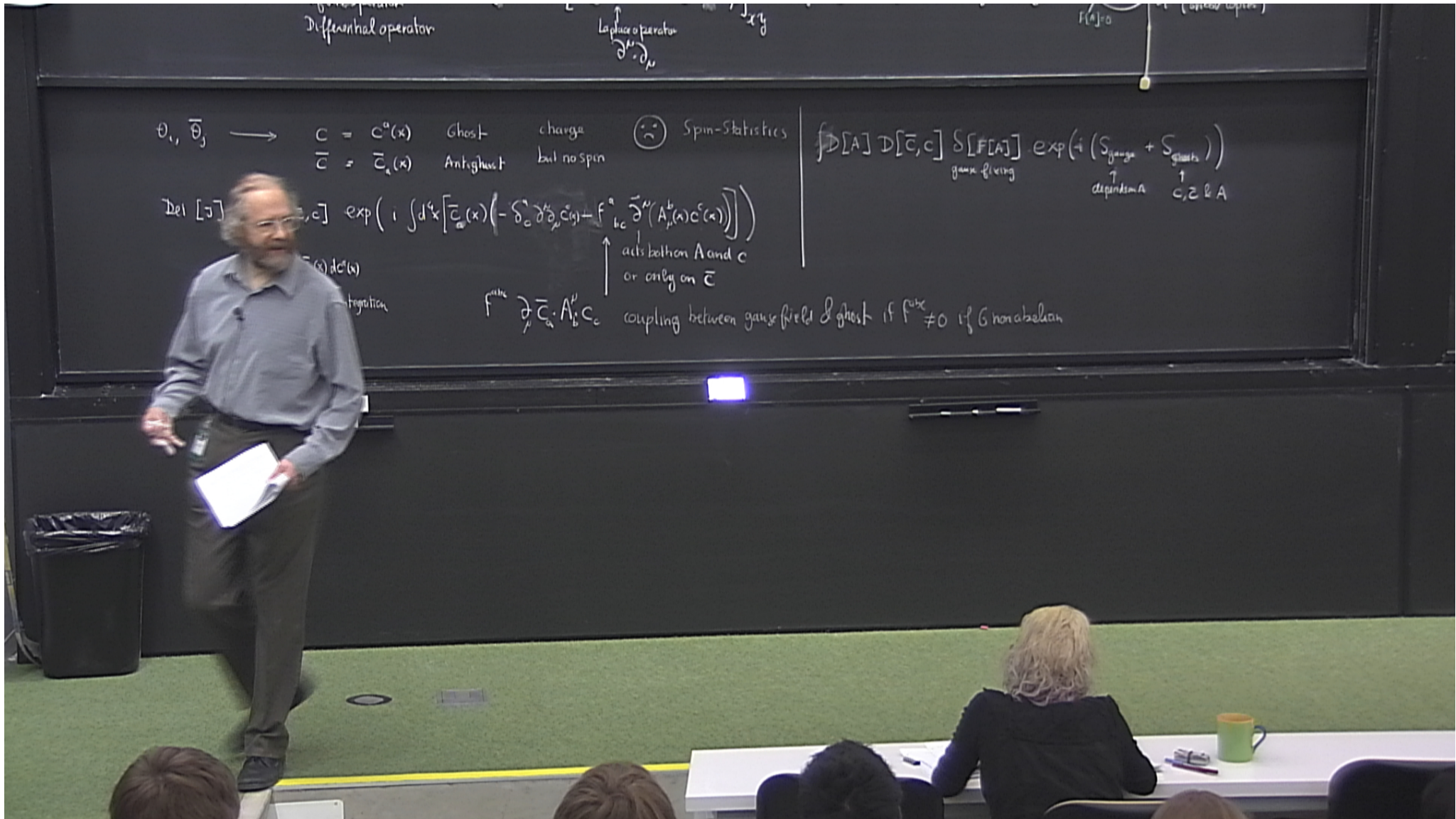
$$\text{Det}[J] = \int \mathcal{D}[\bar{c}, c] \exp\left(i \int d^4x \left[ \bar{c}_a(x) \left( -\delta_c^a \partial_\mu^2 c^a(x) + f_{bc}^a \partial_\mu^2 (A_\mu^b(x) c^c(x)) \right) \right]\right)$$

$\prod_x d\bar{c}_a(x) dc^a(x)$   
Grassmann Integration

acts both on A and c  
or only on  $\bar{c}$







Differential operator  $\Delta = \partial^\mu \partial_\mu$  Laplace operator  $\Delta = \partial^\mu \partial_\mu$   $F[A]=0$  (gauge fixing)

$\theta_i, \bar{\theta}_j \rightarrow c = c^a(x)$  Ghost charge  $\odot$  Spin-Statistics  
 $\bar{c} = \bar{c}_a(x)$  Antighost but no spin

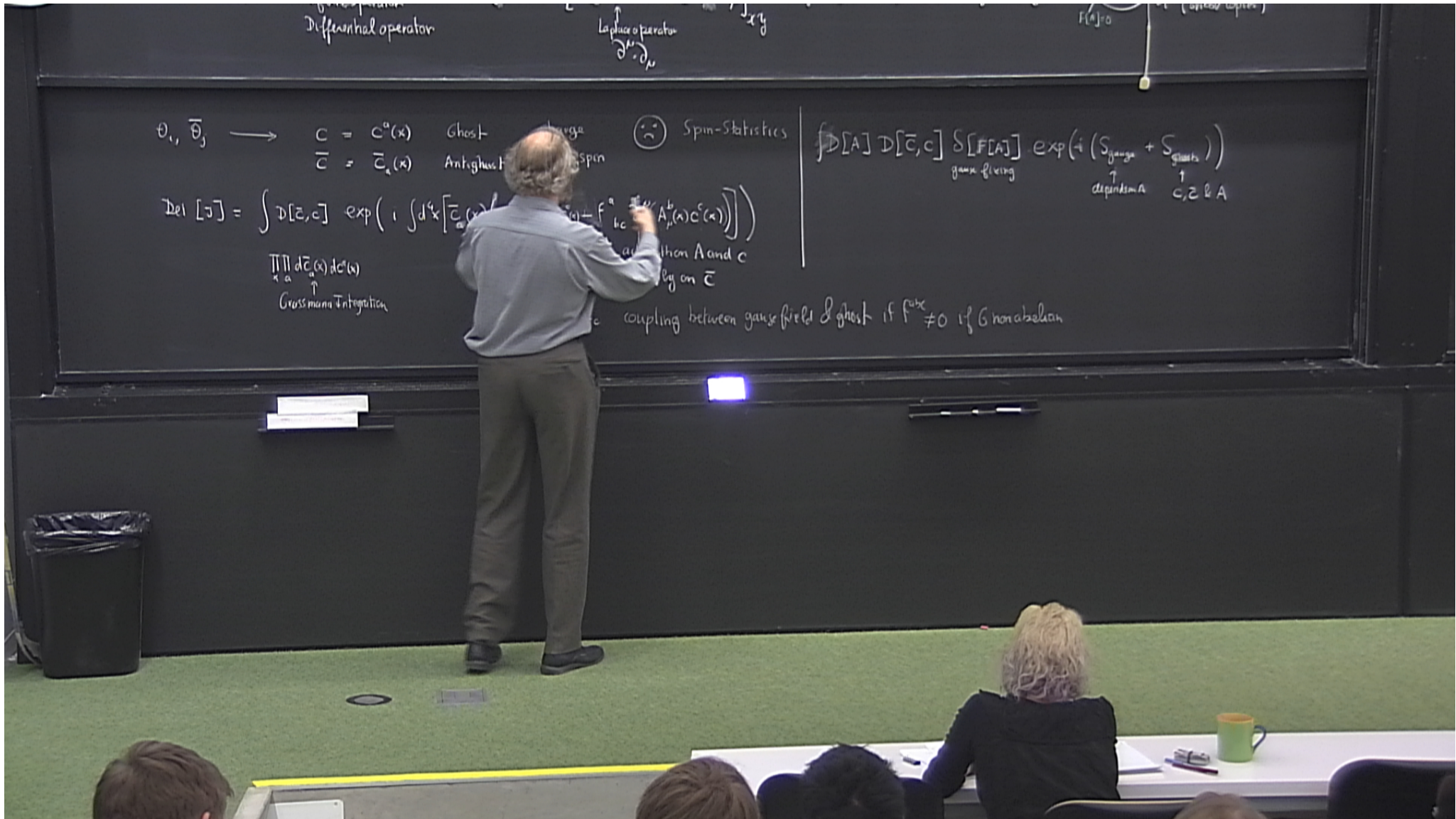
$$\int \mathcal{D}[A] \mathcal{D}[\bar{c}, c] \delta[F[A]] \exp(i(S_{\text{gauge}} + S_{\text{ghost}}))$$

$\uparrow$  gauge fixing  $\uparrow$  depends on A  $\uparrow$  c, z & A

$$\text{Det} [D] = \int \mathcal{D}[\bar{c}, c] \exp\left(i \int d^4x \left[ \bar{c}_a(x) \left( -\delta_{ab} \partial_\mu \partial^\mu c_b(x) + f_{bc}^a \partial^\mu (A_\mu^b(x) c_c(x)) \right) \right]\right)$$

$f_{bc}^a \partial^\mu \bar{c}_a \cdot A_\mu^b c_c$  acts both on A and c or only on  $\bar{c}$   
 coupling between gauge field & ghost if  $f_{bc}^a \neq 0$  if G nonabelian





Differential operator

Laplace operator  
 $\partial^2 = \partial_\mu \partial^\mu$

$\theta_i, \bar{\theta}_j \rightarrow c = c^a(x)$  Ghost  
 $\bar{c} = \bar{c}_a(x)$  Antighost

Spin-Statistics

$$\int \mathcal{D}[A] \mathcal{D}[\bar{c}, c] \delta[F[A]] \exp(i(S_{\text{gauge}} + S_{\text{ghost}}))$$

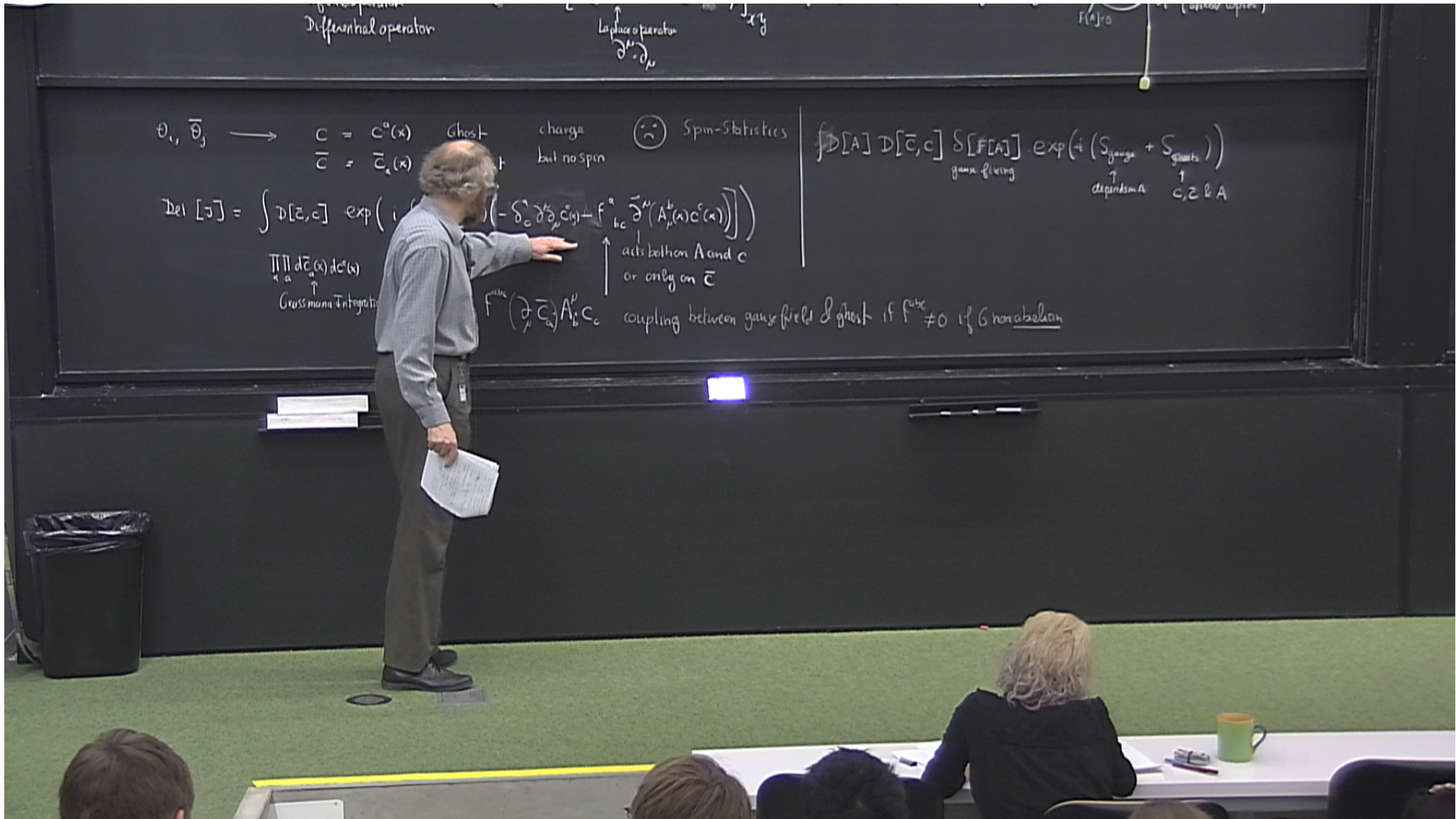
$\uparrow$  gauge fixing       $\uparrow$  depends on A       $\uparrow$  c, z & A

$$\text{Det}[J] = \int \mathcal{D}[z, c] \exp(i \int d^4x [\bar{c}_a(x) \left( \partial^2 + f_{bc}^a A_\mu^b(x) \partial^\mu \right) c^c(x)])$$

$\prod_a \int d\bar{c}_a(x) dc^a(x)$   
 Grassmann Integration

coupling between gauge field & ghost if  $f_{bc}^a \neq 0$  if G nonabelian





Differential operator  
 Laplace operator  $\partial^{\mu}\partial_{\mu}$   
 $F[A]=0$  (Gauss eqn)

$\theta_i, \bar{\theta}_j \rightarrow c = c^a(x)$  Ghost charge but no spin  $\odot$  Spin-Statistics  
 $\bar{c} = \bar{c}_a(x)$

$$\int \mathcal{D}[A] \mathcal{D}[\bar{c}, c] \delta[F[A]] \exp(i(S_{\text{gauge}} + S_{\text{ghost}}))$$

$\uparrow$  gauge fixing       $\uparrow$  depends on A       $\uparrow$  c, z & A

$$\text{Det}[D] = \int \mathcal{D}[z, c] \exp(i \int d^4x \left( -\delta_c \partial^{\mu} \bar{c}_a \partial_{\mu} c^a + f_{bc}^a \partial^{\mu} (A_{\mu}^b c^c) \right))$$

$\prod_a \int d\bar{c}_a(x) dc^a(x)$   
 Grassmann Integration

$f_{bc}^a (\partial_{\mu} \bar{c}_a) A_{\mu}^b c_c$  acts both on A and c or only on  $\bar{c}$   
 coupling between gauge field & ghost if  $f_{bc}^a \neq 0$  if G non-abelian







Differential operator

Laplace operator  
 $\partial^\mu \partial_\mu$

$F[A]=0$  (gauge fixing)

$\theta_i, \bar{\theta}_j \rightarrow c = c^a(x)$  Ghost charge  $\odot$  Spin-Statistics  
 $\bar{c} = \bar{c}_a(x)$  Antighost but no spin

$$\int \mathcal{D}[A] \mathcal{D}[\bar{c}, c] \delta[F[A]] \exp(i(S_{\text{gauge}} + S_{\text{ghost}}))$$

$\delta[F[A]]$  gauge fixing  
 $S_{\text{gauge}}$  depends on A  
 $S_{\text{ghost}}$  depends on c, z & A

$$\text{Det } [\mathcal{D}] = \int \mathcal{D}[\bar{c}, c] \exp\left(i \int d^4x \left[ \bar{c}_a(x) \left( -\delta_{ab} \partial^\mu \partial_\mu c_b(x) + f_{bc}^a \partial^\mu (A_\mu^b(x) c^c(x)) \right) \right]\right)$$

$\prod_a \int d\bar{c}_a(x) dc^a(x)$   
 Grassmann Integration

$f_{bc}^a$  acts both on A and c or only on  $\bar{c}$   
 coupling between gauge field & ghost if  $f_{bc}^a \neq 0$  if G nonabelian



...one last trick  
 $F[A] = \partial \cdot A - \omega$



...one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$



☹ Spin-Statistics

spin

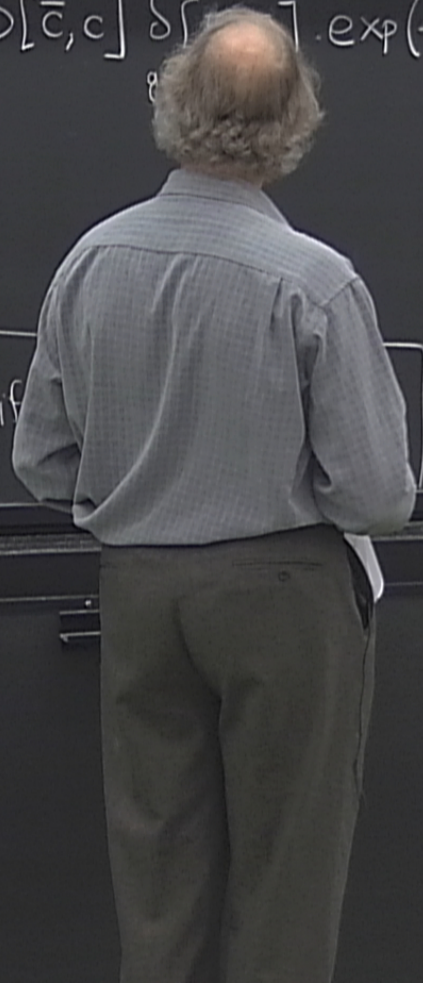
$$-f_{bc}^a \bar{\partial}^\nu (A_\mu^b(x) c^c(x))$$

↑ acts both on A and c or only on  $\bar{c}$

$c_c$  coupling between gauge field & ghost if

$$\int \mathcal{D}[A] \mathcal{D}[\bar{c}, c] \delta[\dots] \exp(i(S_{\text{gauge}} + S_{\text{ghosts}}))$$

$\uparrow$  depends on A       $\uparrow$   $\bar{c}, c$  & A





one last trick

$$F[A] = \int \mathcal{D}[A] e^{-i \int d^4x (\partial_\mu A)^2 - \omega A}$$

The integral is independent of  $\omega$  (invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp(-i \int d^4x \omega A)$$



...one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over

$$\int \mathcal{D}[\omega] \exp \left( \prod_x \int_a d\omega^a(x) \exp \left( -i \int d^4x \frac{\omega^a(x) \omega_a(x)}{2\xi} \right) \right)$$



one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x \prod_a d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right)$$

$\xi$  just a real number



↓ can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \left( \prod \prod d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right) \right)$$

↑  
 $\xi$  just a

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right)$$



I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right)$$

real number (

$$\int \mathcal{D}[\omega] \exp(-i \dots) \cdot \delta[\partial A \cdot -\omega]$$



I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x \prod_a d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right)$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial A \cdot \omega] = \exp\left(-i \int d^4x \frac{(\partial A)^2}{2\xi}\right)$$







...one last trick

$$F[A] = \int \mathcal{D}A \exp(-i \int d^4x \mathcal{L})$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

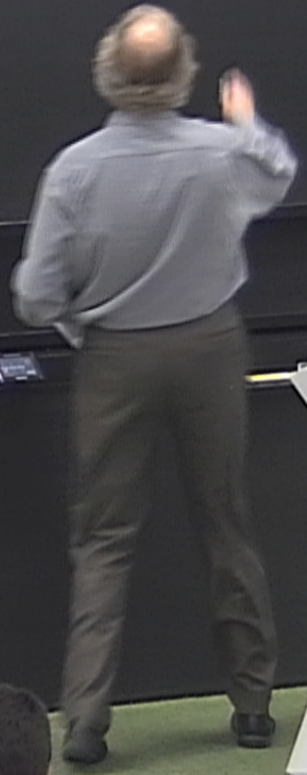
$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x \prod_a d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right)$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial A - \omega] = \exp\left(-i \int d^4x \frac{(\partial A)^2}{2\xi}\right)$$

which final action?

$$\frac{1}{g^2} \left[ \frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu)^2 \right]$$



$$(\partial_\mu A_\nu - \partial_\nu A_\mu)^2$$



...one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x \prod_a d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right)$$

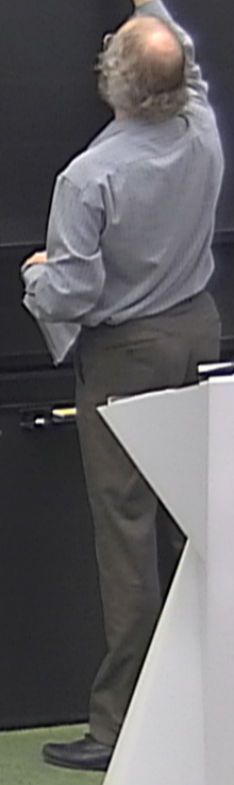
$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial \cdot A - \omega] = \exp\left(-i \int d^4x \frac{(\partial \cdot A)^2}{2\xi}\right)$$

which final action?

$$\frac{1}{g^2} \left[ \frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu)^2 \right] \rightarrow \frac{1}{2} \partial_\mu^2$$

$$(\partial_\mu A_\nu - \partial_\nu A_\mu)^2$$





...one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x \prod_a d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right)$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial A - \omega] = \exp\left(-i \int d^4x \frac{(\partial A)^2}{2\xi}\right)$$

which final action?

$$\frac{1}{g^2} \left[ \frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu)^2 \right] \rightarrow \frac{1}{2} [\partial_\mu A_\nu - \partial_\nu A_\mu] A_\mu^b A_\nu^c F^{abc}$$

$$(\partial_\mu A_\nu^a)^2$$



one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x \prod_a d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right)$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial \cdot A - \omega] = \exp\left(-i \int d^4x \frac{(\partial \cdot A)^2}{2\xi}\right)$$

$$(\partial^\mu A_\mu^a)^2$$

which final action?

$$\frac{1}{g^2} \left[ \frac{1}{4} (\partial_\mu A_\nu^a - \partial_\nu A_\mu^a)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu^a)^2 \right] \rightarrow \frac{1}{2} [\partial_\mu A_\nu^a - \partial_\nu A_\mu^a] A_\mu^b A_\nu^c F^{abc} \rightarrow \frac{1}{4} F^{abc} F^{ade} A_\mu^a A_\nu^b A_\mu^c A_\nu^d$$





one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x \prod_a d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi}\right)$$

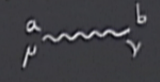
$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial \cdot A - \omega] \int \mathcal{D}[A] \exp\left(-i \int d^4x \frac{(\partial A)^2}{2\xi}\right)$$

which final action?  $A \rightarrow gA$

$$\left[ \frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu)^2 \right] \rightarrow \frac{g^2}{2} [\partial_\mu A_\nu - \partial_\nu A_\mu] A_\mu^b A_\nu^c F^{abc} \rightarrow \frac{g^2}{4} F^{abc} F^{cde} A_\mu^a A_\nu^b A_\rho^c A_\sigma^d$$

propagator



$$(\partial_\mu A_\nu^a)^2$$



one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int D[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \int \prod_x \prod_a d\omega^a(x) \exp\left(-i \int d^4x \frac{\omega^a(x) \omega_a(x)}{2\xi}\right)$$

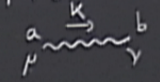
↑  
just a real number

$$\int D[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial A - \omega] = \exp\left(-i \int d^4x \frac{(\partial A)^2}{2\xi}\right)$$

which final action?  $A \rightarrow gA$

$$\left[ \frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu)^2 \right] \rightarrow \frac{g^2}{2} [\partial_\mu A_\nu - \partial_\nu A_\mu] A_\mu^b A_\nu^c F^{abc} \rightarrow \frac{g^2}{4} F^{abc} F^{cde} A_\mu^a A_\nu^b A_\rho^c A_\sigma^d$$

propagator (momentum space)





one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \prod_x \int d\omega(x) \exp\left(-i \int d^4x \frac{\omega(x) \omega(x)}{2\xi}\right)$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial \cdot A - \omega] = \exp\left(-i \int d^4x \frac{(\partial \cdot A)^2}{2\xi}\right)$$

$$(\partial^\nu A_\mu^a)^2$$

which final action?  $A \rightarrow gA$

$$\left[ \frac{1}{4} (\partial_\nu A_\mu^a - \partial_\mu A_\nu^a)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu^a)^2 \right] \rightarrow \frac{g^2}{2} [\partial_\mu A_\nu^a - \partial_\nu A_\mu^a] A_\mu^b A_\nu^c F^{abc} \rightarrow \frac{g^2}{4} F^{abc} F^{ade} A_\mu^a A_\nu^b A_\mu^c A_\nu^d$$

propagator (momentum space)

$$\frac{-i}{k^2 - i\epsilon} \left( \eta_{\mu\nu} + (\xi - 1) \frac{k_\mu k_\nu}{k^2} \right)$$



one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \prod_x \int d\omega(x) \exp\left(-i \int d^4x \frac{\omega(x) \omega(x)}{2\xi}\right)$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial \cdot A - \omega] = \exp\left(-i \int d^4x \frac{(\partial \cdot A)^2}{2\xi}\right)$$

$$(\partial_\mu A_\nu^a)^2$$

which final action?  $A \rightarrow gA$

$$\left[ \frac{1}{4} (\partial_\mu A_\nu^a - \partial_\nu A_\mu^a)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu^a)^2 \right] \rightarrow \frac{g^2}{2} [\partial_\mu A_\nu^a - \partial_\nu A_\mu^a] A_\mu^b A_\nu^c F^{abc} \rightarrow \frac{g^2}{4} F^{abc} F^{cde} A_\mu^a A_\nu^b A_\mu^c A_\nu^d$$

propagator (momentum space)

$$\begin{array}{c} a \xrightarrow{k} b \\ \mu \quad \quad \quad \nu \end{array} \quad \frac{-i}{k^2 - i\epsilon} \left( \eta_{\mu\nu} + (\xi - 1) \frac{k_\mu k_\nu}{k^2} \right) \delta^{ab}$$



...one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int D[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \int D[A] \exp\left(-i \int d^4x \frac{\omega^a(x) \omega_a(x)}{2\xi}\right)$$

$$\int D[\omega] \exp\left(-i \int d^4x \frac{(\partial A)^2}{2\xi}\right)$$

which final action?  $A \rightarrow gA$

$$\left[ \frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu)^2 \right] \rightarrow \frac{g^2}{2} [\partial_\mu A_\nu - \partial_\nu A_\mu] A_\mu^b A_\nu^c F^{abc} \rightarrow \frac{g^2}{4} F^{abc} F^{ade} A_\mu^b A_\nu^c A_\mu^a A_\nu^d$$

propagator (momentum space)

$$\begin{array}{c} a \xrightarrow{k} b \\ \mu \quad \quad \quad \nu \end{array} \quad \frac{-i}{k^2 - i\epsilon} \left( \eta_{\mu\nu} + (\xi - 1) \frac{k_\mu k_\nu}{k^2} \right) \delta^{ab}$$



one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \prod_x \int d\omega(x) \exp\left(-i \int d^4x \frac{\omega(x) \omega(x)}{2\xi}\right)$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial A - \omega] = \exp\left(-i \int d^4x \frac{(\partial A)^2}{2\xi}\right)$$

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$$\left[ \frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \frac{1}{2\xi} (\partial_\mu A_\mu)^2 \right] \rightarrow \frac{g^2}{2} [\partial_\mu A_\nu - \partial_\nu A_\mu] A_\mu^b A_\nu^c F^{abc} \rightarrow \frac{g^2}{4} F^{abc} F^{ade} A_\mu^a A_\nu^b A_\mu^c A_\nu^d$$

propagator (momentum space)

$$a \xrightarrow{\mu} \overset{k}{\sim} \xrightarrow{\nu} b \quad \frac{-i}{k^2 - i\epsilon} \left( \eta_{\mu\nu} + (\xi - 1) \frac{k_\mu k_\nu}{k^2} \right) \delta^{ab}$$

Lorentz gauge  $\partial^\mu A_\mu = 0 \Leftrightarrow \xi = 0$   $\left( \eta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} \right)$  = projector on transverse polarization states

$$A_\mu = \epsilon_\mu e^{ikx} \quad \epsilon_\mu$$

$$(\partial^\mu A_\mu)^2$$



one last trick

$$F[A] = \partial \cdot A - \omega$$

The integral is independent of  $\omega$  (gauge invariance)

I can integrate over  $\omega$

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) = \prod_x \int d\omega(x) \exp\left(-i \int d^4x \frac{\omega(x) \omega(x)}{2\xi}\right)$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp\left(-i \int d^4x \frac{\omega^2}{2\xi}\right) \cdot \delta[\partial \cdot A - \omega] = \exp\left(-i \int d^4x \frac{(\partial \cdot A)^2}{2\xi}\right)$$

$$(\partial^\nu A_\mu^a)^2$$

which final action?  $A \rightarrow gA$

$$\left[ \frac{1}{4} (\partial_\nu A_\mu^a - \partial_\mu A_\nu^a)^2 - \frac{1}{2\xi} (\partial_\nu A_\mu^a)^2 \right] \rightarrow \frac{g^2}{2} [\partial_\nu A_\mu^a - \partial_\mu A_\nu^a] A_\mu^b A_\nu^c F^{abc} \rightarrow \frac{g^2}{4} F^{abc} F^{ade} A_\mu^a A_\nu^b A_\mu^c A_\nu^d$$

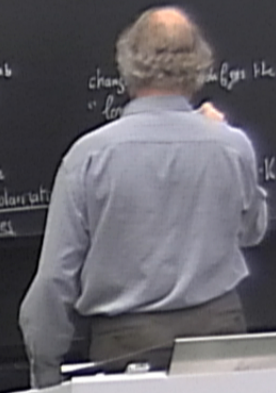
propagator (momentum space)

$$a \xrightarrow{\mu} \overset{k}{\sim} \xrightarrow{\nu} b \quad \frac{-i}{k^2 - i\epsilon} \left( \eta_{\mu\nu} + (\xi - 1) \frac{k_\mu k_\nu}{k^2} \right) \delta^{ab}$$

changes the propagation of

Lorentz gauge  $\partial^\nu A_\nu = 0 \Leftrightarrow \xi = 0$   $\left( \eta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} \right) =$  projector on transverse polarizations

$$k^\mu = 0$$





$$\int \mathcal{D}[\omega] \exp(-i \int d^4x \frac{\omega^2}{2\xi}) = \int \prod_x \prod_a d\omega^a(x) \exp(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi})$$

$\xi$  just a real number

$$\int \mathcal{D}[\omega] \exp(-i \int d^4x \frac{\omega^2}{2\xi}) \cdot \delta[\partial A - \omega] = \exp(-i \int d^4x \frac{(\partial A)^2}{2\xi})$$

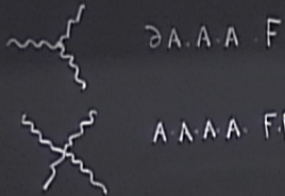
Lorentz gauge  $\partial^\mu A_\mu = 0 \Leftrightarrow \xi = 0$

$$\frac{-i}{k^2 - i\epsilon} \left( \eta_{\mu\nu} + (\xi - 1) \frac{k_\mu k_\nu}{k^2} \right) \delta$$

changing  $\xi$  modifies the propagator of longitudinal polarization states "unphysical"

$\left( \eta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} \right) =$  projector on transverse polarization states

$A_\mu = \epsilon_\mu e^{ikx} \quad \epsilon_\mu \cdot k^\mu = 0$





$$\int \mathcal{D}[\omega] \exp(-i \int d^4x \frac{\omega^2}{2\xi}) = \int \prod_x \prod_a d\omega^a(x) \exp(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi})$$

$\xi$  just a real number

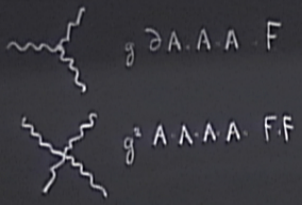
$$\int \mathcal{D}[\omega] \exp(-i \int d^4x \frac{\omega^2}{2\xi}) \cdot \delta[\partial A \cdot \omega] = \exp(-i \int d^4x \frac{(\partial A)^2}{2\xi})$$

Lorentz gauge  $\partial^\mu A_\mu = 0 \Leftrightarrow \xi = 0$

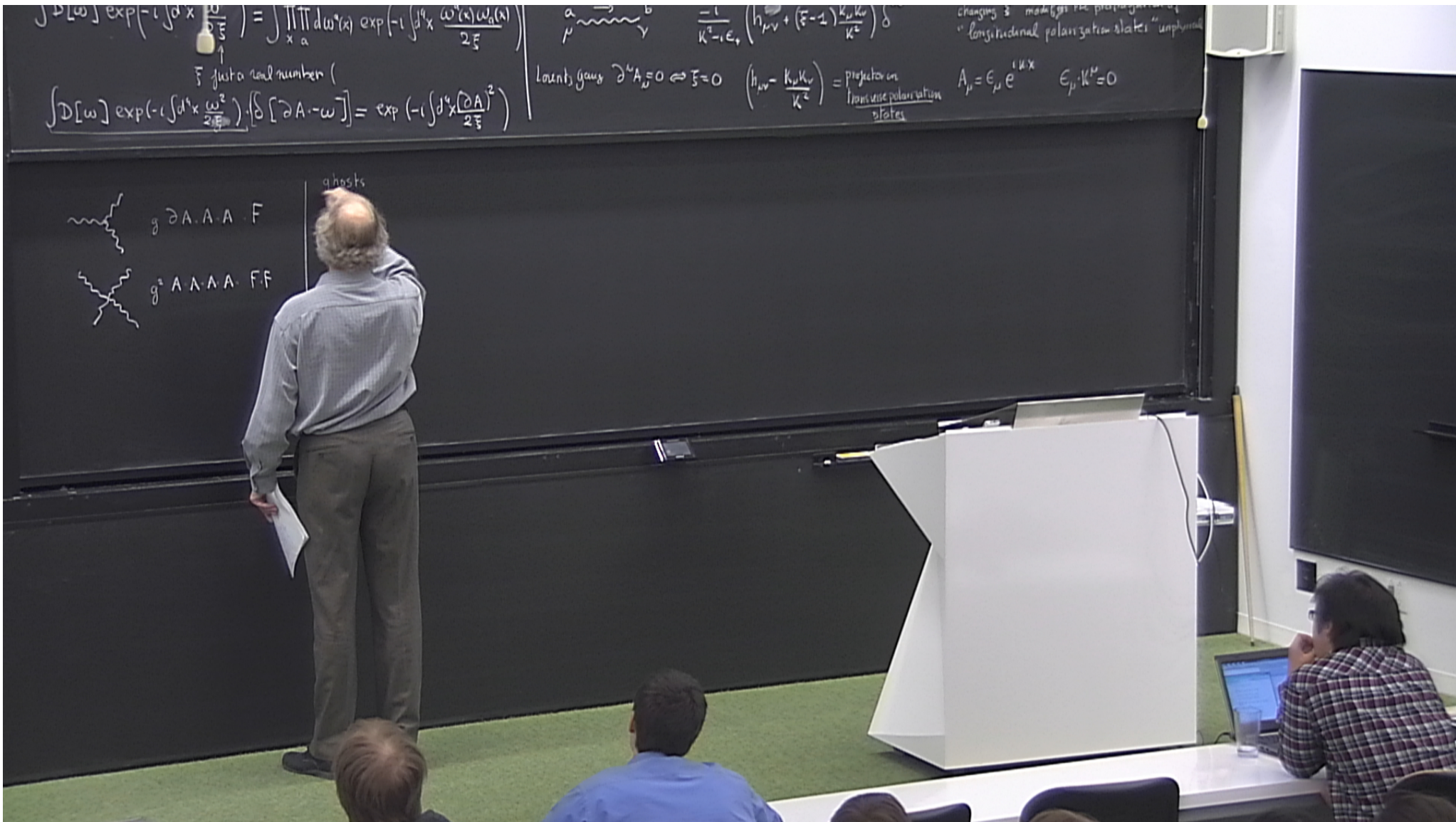
$$\frac{-i}{k^2 - i\epsilon} \left( \eta_{\mu\nu} + (\xi - 1) \frac{k_\mu k_\nu}{k^2} \right) \delta$$

$\eta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}$  = projector on transverse polarization states

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 $A_\mu = \epsilon_\mu e^{ikx}$      $\epsilon_\mu \cdot k^\mu = 0$



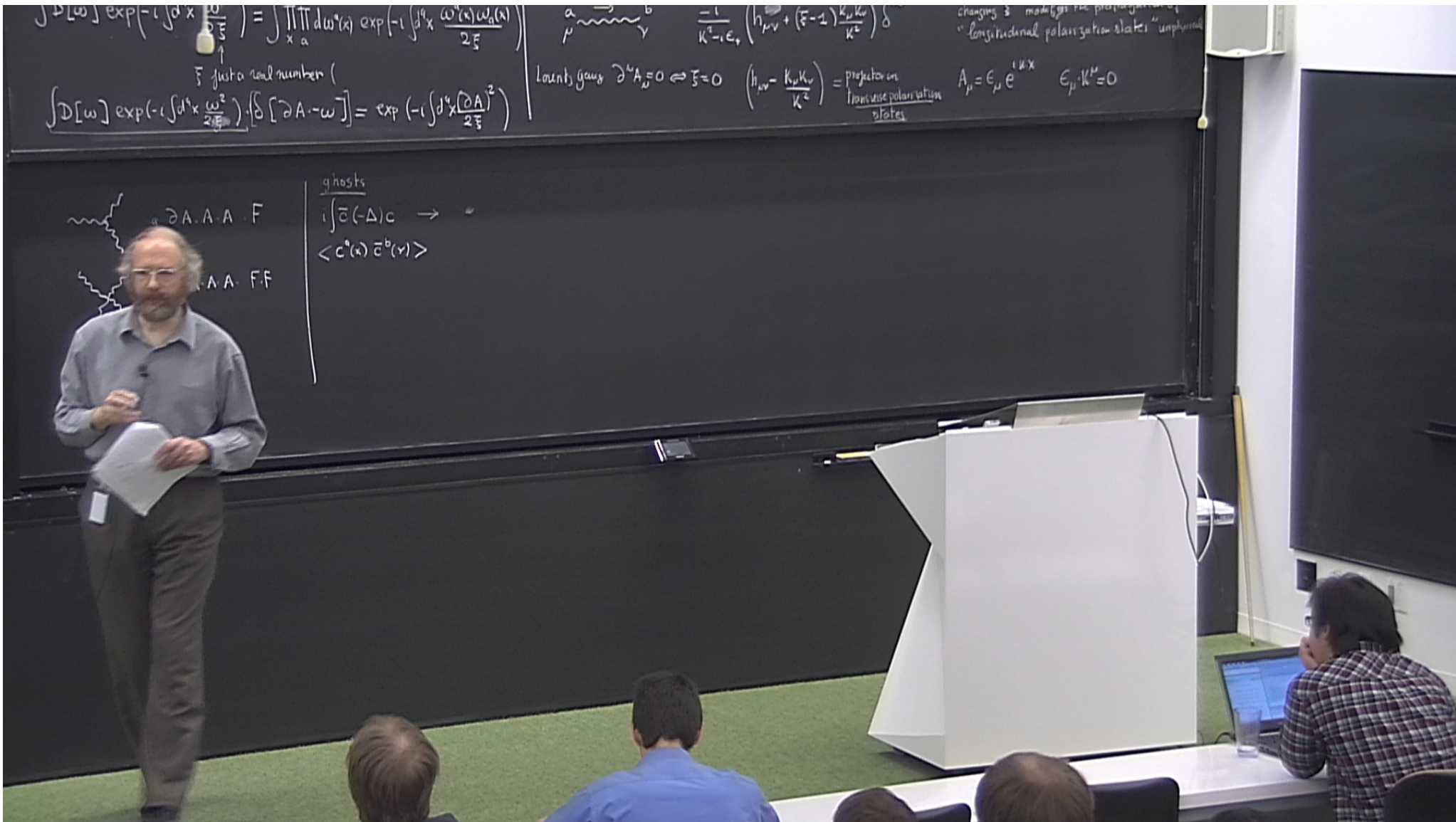




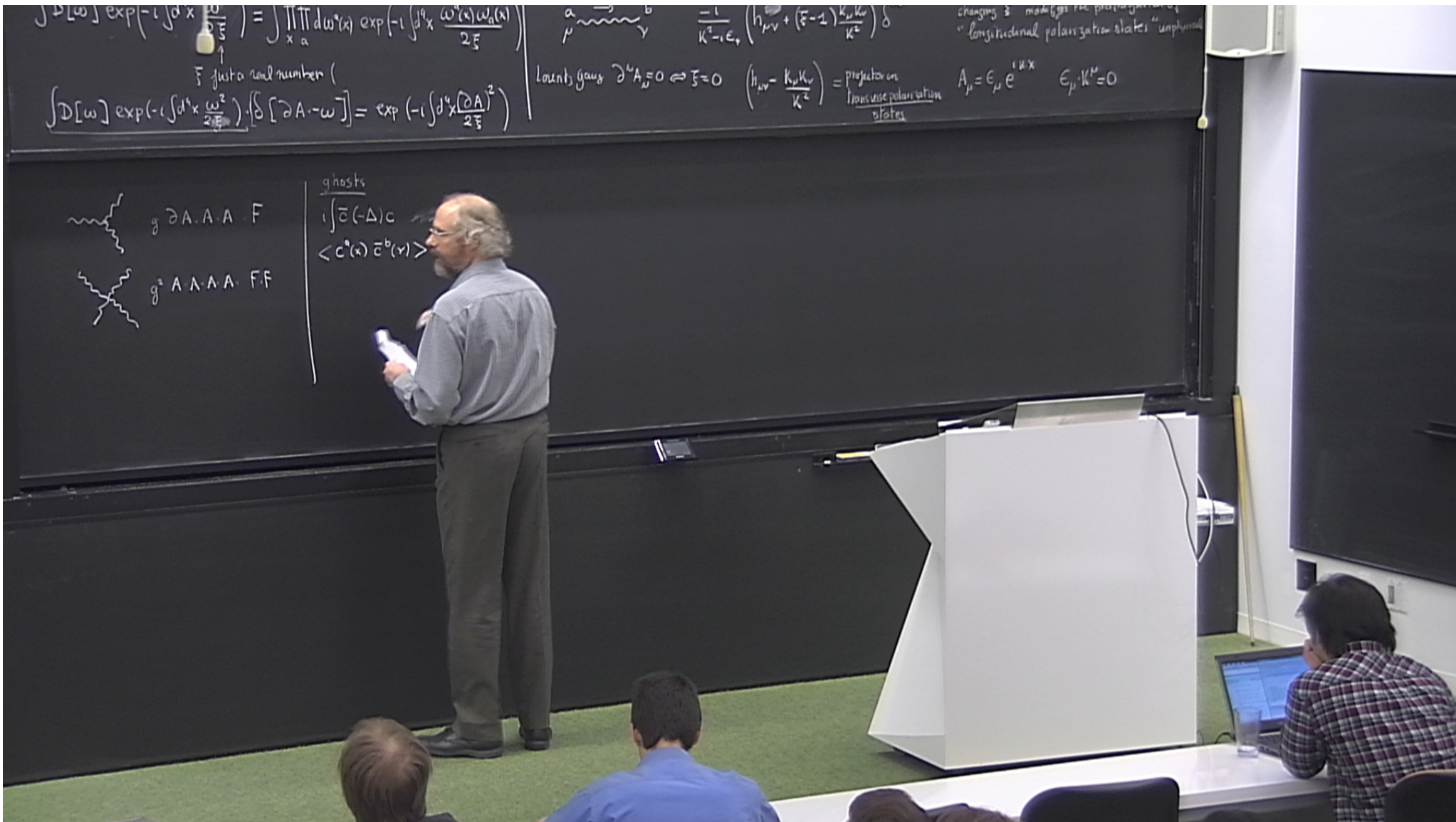














$$\int \mathcal{D}[\omega] \exp(-i \int d^4x \frac{\omega^2}{2\xi}) = \int \prod_x \prod_a d\omega^a(x) \exp(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi})$$

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changing  $\xi$  modifies the propagator of "longitudinal polarization states" unphysical

$$A_\mu = \epsilon_\mu e^{ikx} \quad \epsilon_\mu \cdot k^\mu = 0$$

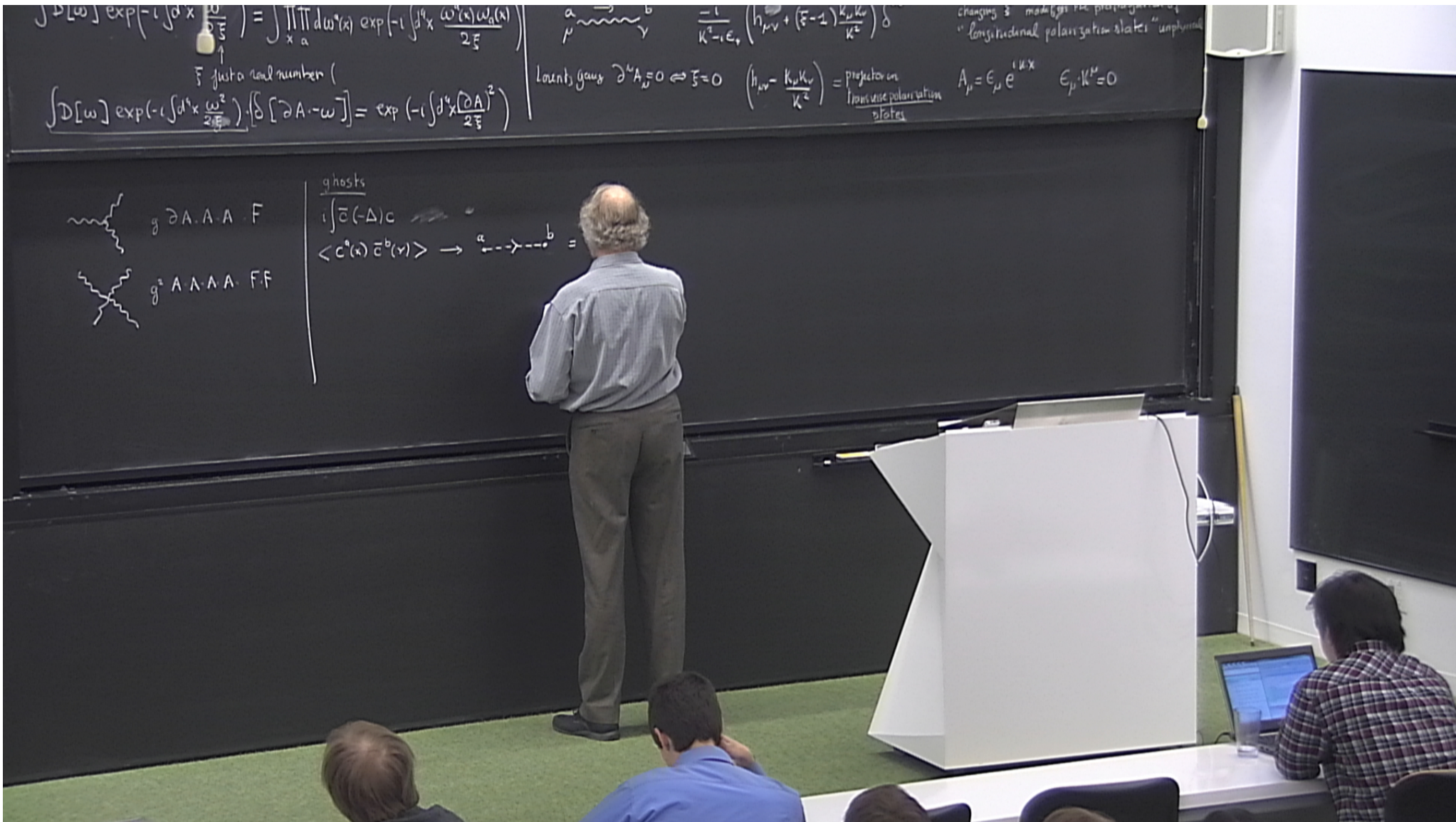
ghosts

$$i \int \bar{c}(-\Delta) c$$

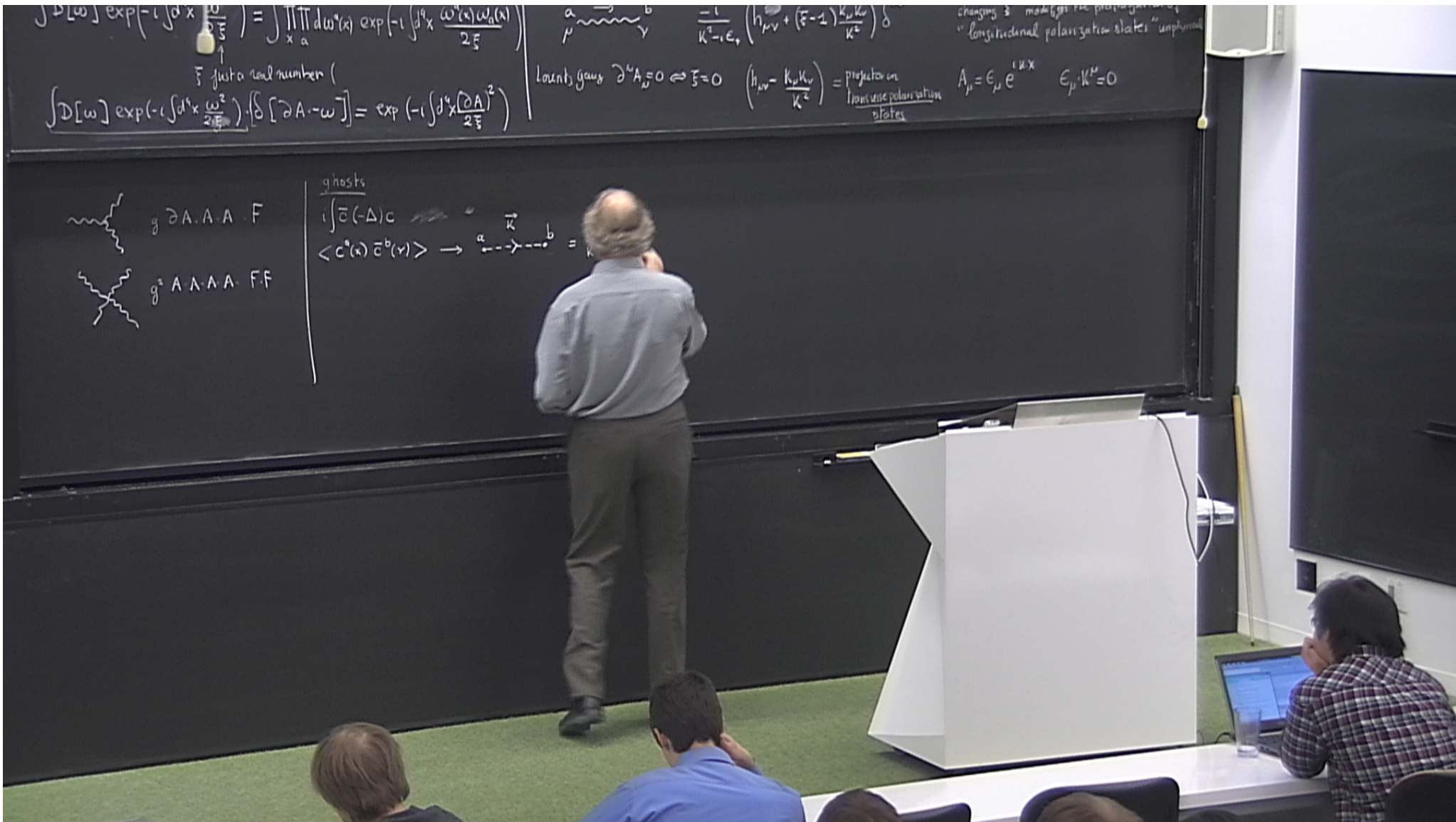
$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \text{---} \rightarrow \text{---}$$

$g \partial A \cdot A \cdot A \cdot F$   
 $g^2 A \cdot A \cdot A \cdot F F$

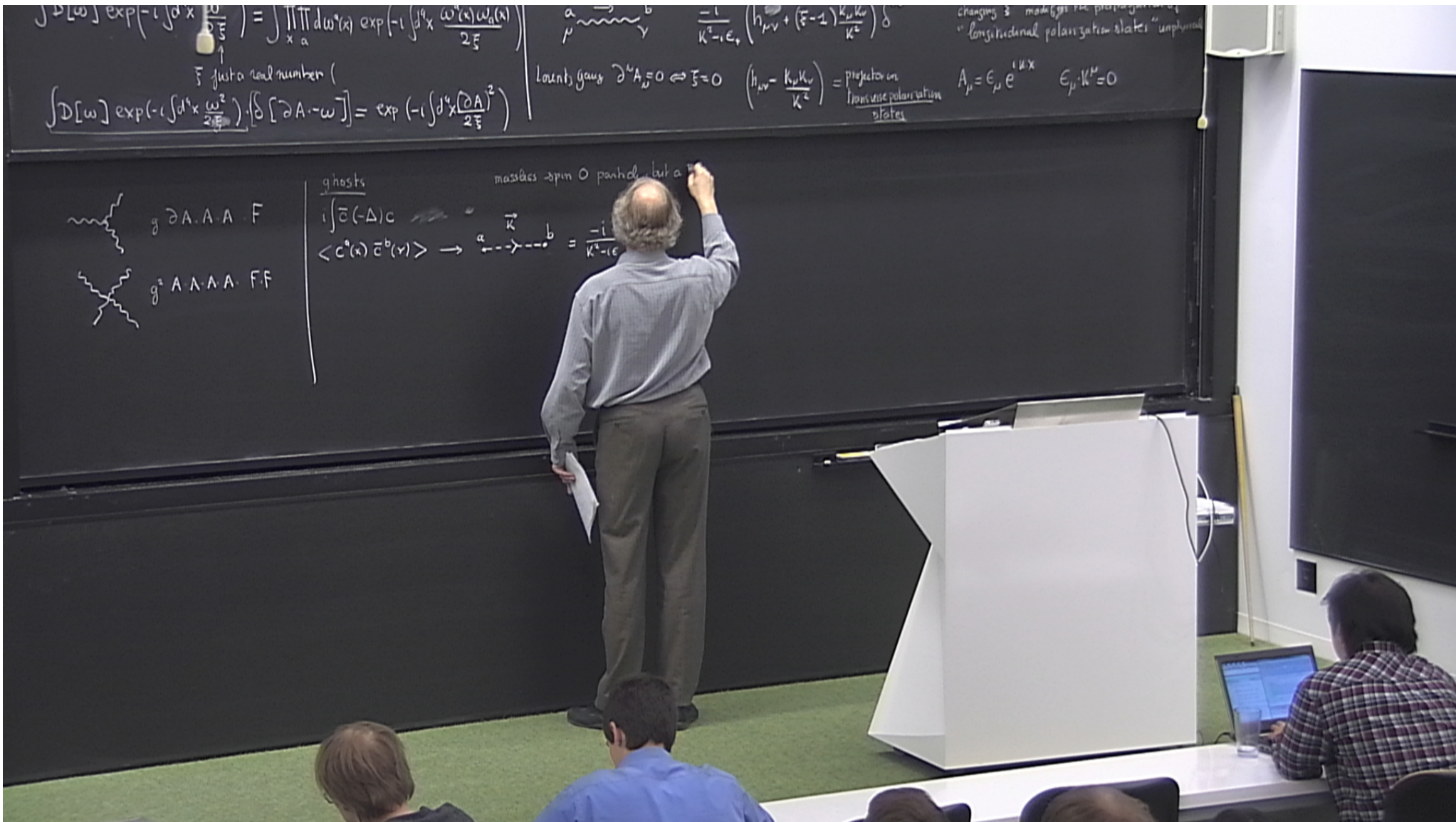














$$\int \mathcal{D}[\omega] \exp(-i \int d^4x \frac{\omega^2}{2\xi}) = \int \prod_x \prod_a d\omega^a(x) \exp(-i \int d^4x \frac{\omega^a(x)\omega_a(x)}{2\xi})$$

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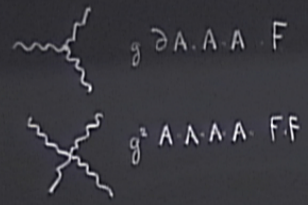
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$$A_\mu = \epsilon_\mu e^{ikx} \quad \epsilon_\mu \cdot k^\mu = 0$$



ghosts      massless spin 0 particle, but a Fermion

$$i \int \bar{c}(-\Delta) c$$

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \overset{a}{\text{---}} \xrightarrow{\vec{k}} \overset{b}{\text{---}} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$



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$$\int \mathcal{D}[\omega] \exp(-i \int d^4x \frac{\omega^2}{2\xi}) \cdot \delta[\partial A \cdot \omega] = \exp(-i \int d^4x \frac{(\partial A)^2}{2\xi})$$

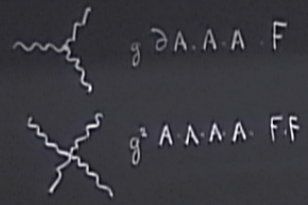
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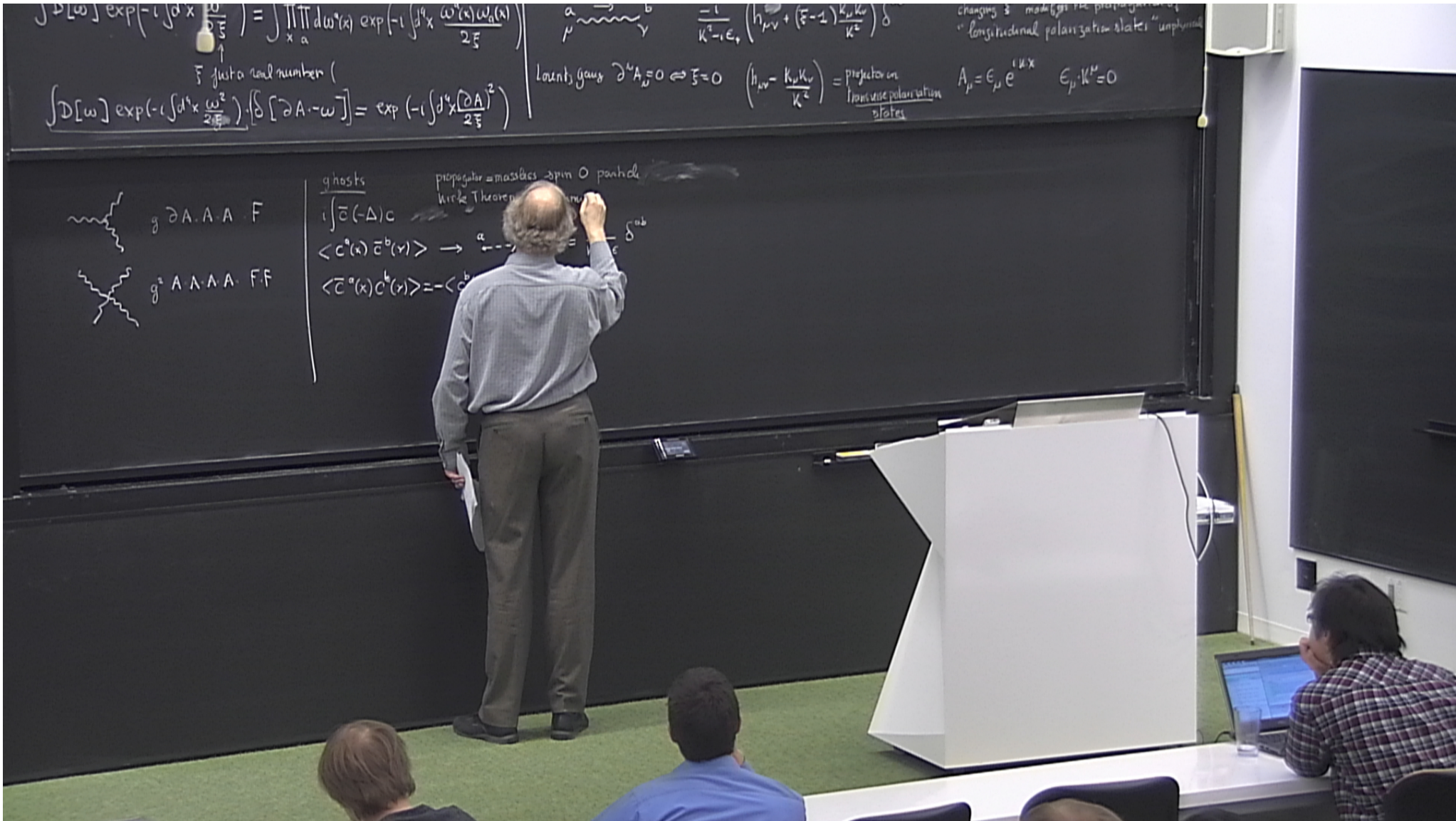
ghosts                      massless spin 0 particle, but a Fermion

$$i \int \bar{c}(-\Delta) c$$

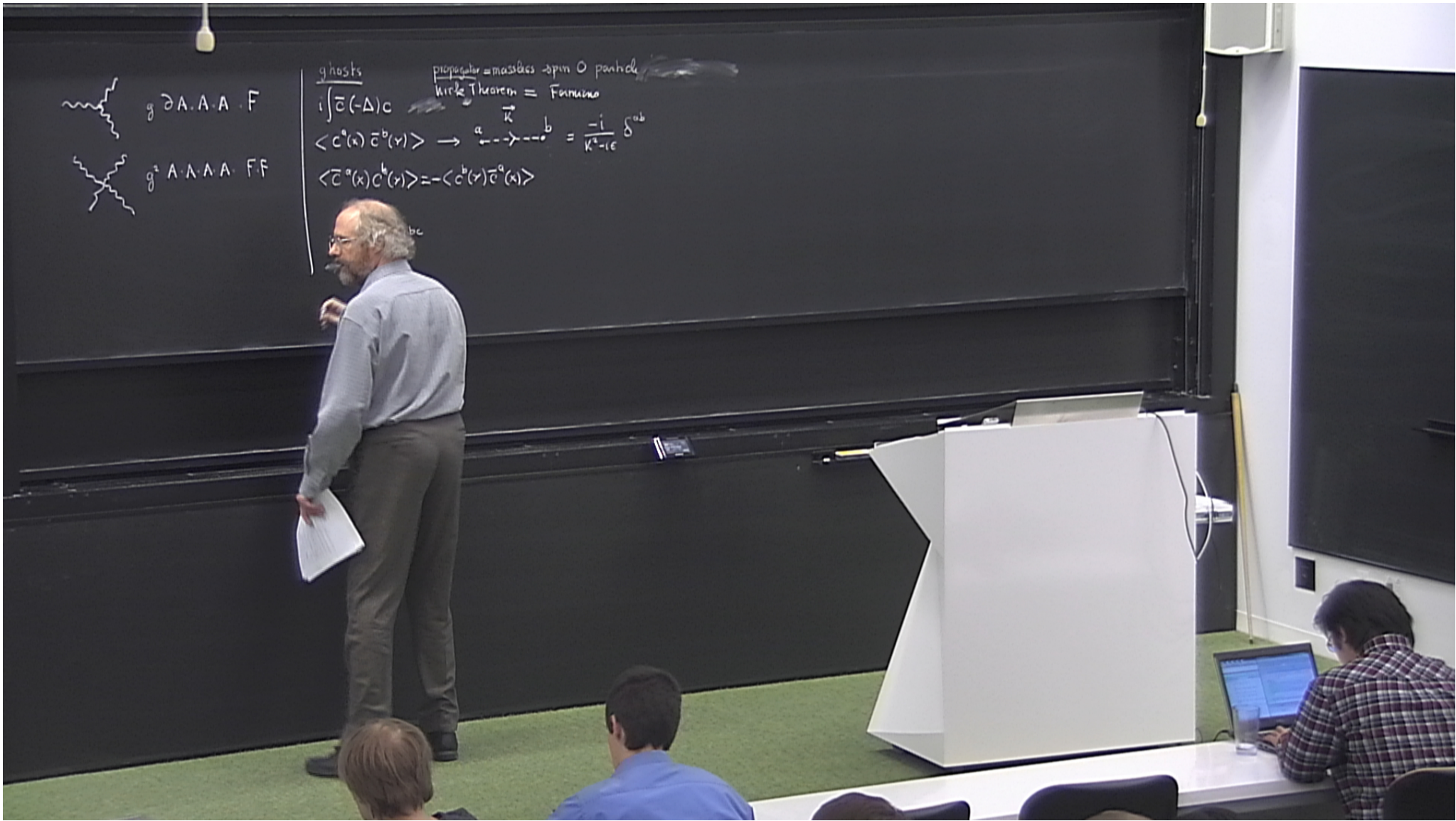
$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \overset{a}{\text{---}} \xrightarrow{\vec{k}} \overset{b}{\text{---}} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

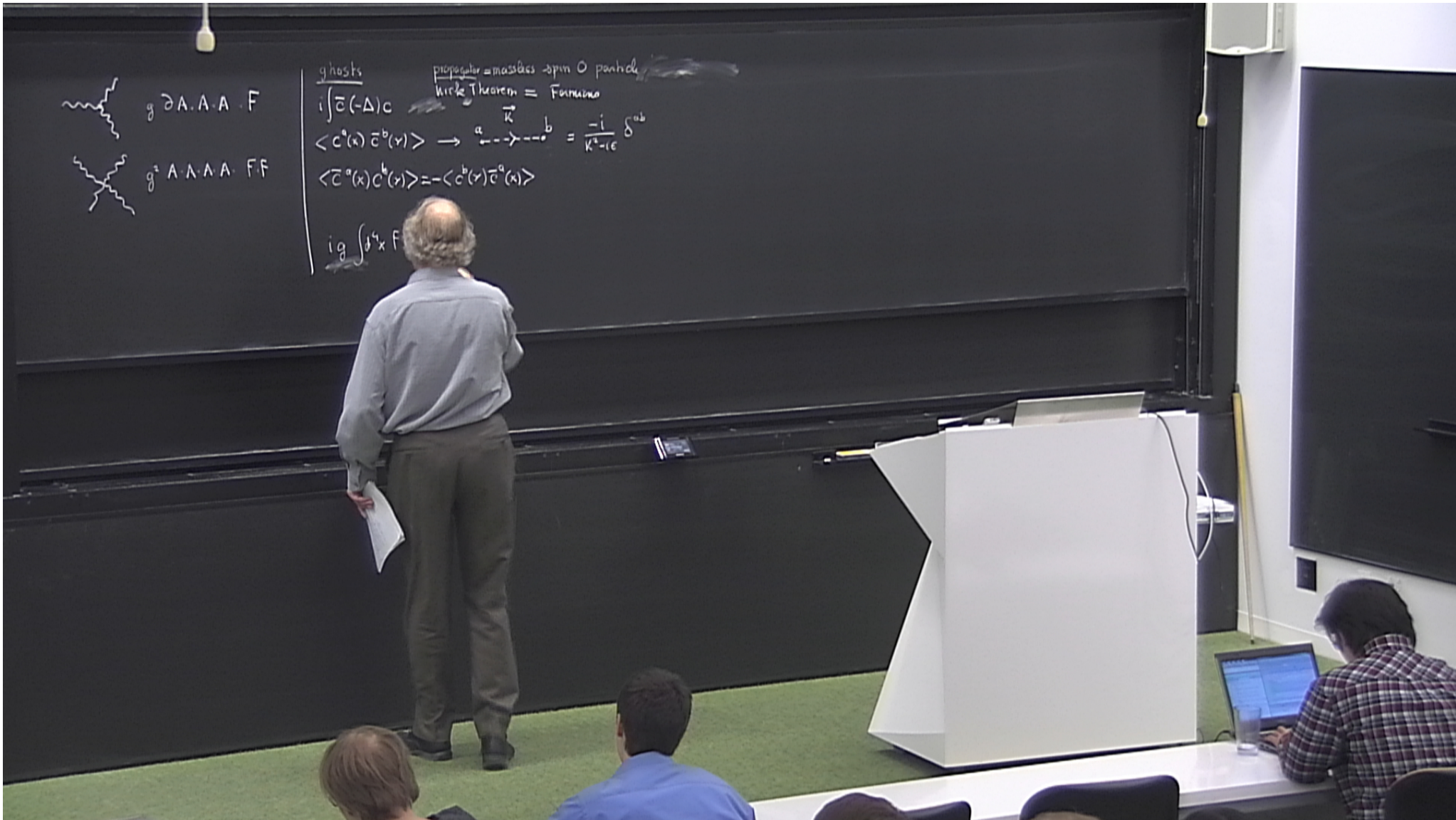




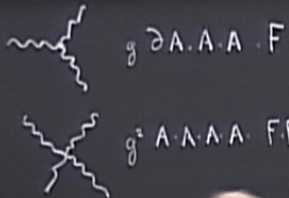












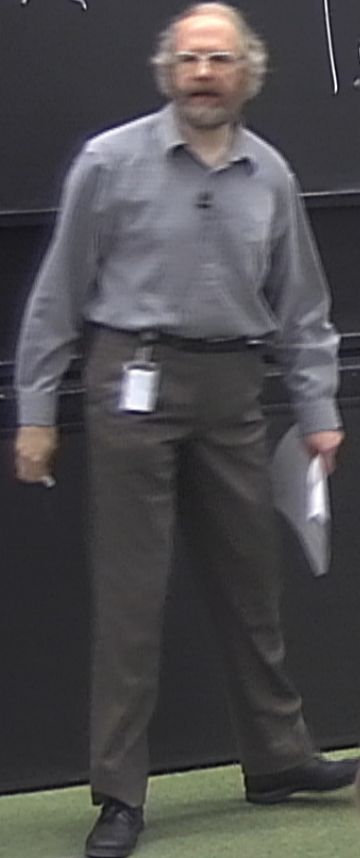
ghosts propagator = massless spin 0 particle  
 Wicks Theorem = Furry's

$$i \int \bar{c}(-\Delta) c$$

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \overset{a}{\text{---}} \xrightarrow{\vec{k}} \overset{b}{\text{---}} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$ig \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$





$$g \partial A \cdot A \cdot A \cdot F$$

$$g^2 A \cdot A \cdot A \cdot A \cdot F \cdot F$$

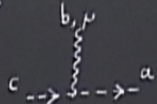
ghosts propagator = massless spin 0 particle  
 Wick's Theorem = Furry's

$$i \int \bar{c}(x) (-\Delta) c$$

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow a \dashrightarrow b = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$ig \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$





$$g \partial A \cdot A \cdot A \cdot F$$

$$g^2 A \cdot A \cdot A \cdot A \cdot F \cdot F$$

ghosts propagator = massless spin 0 particle  
 Wicks Theorem = Furry's

$$i \int \bar{c}(-\Delta) c$$

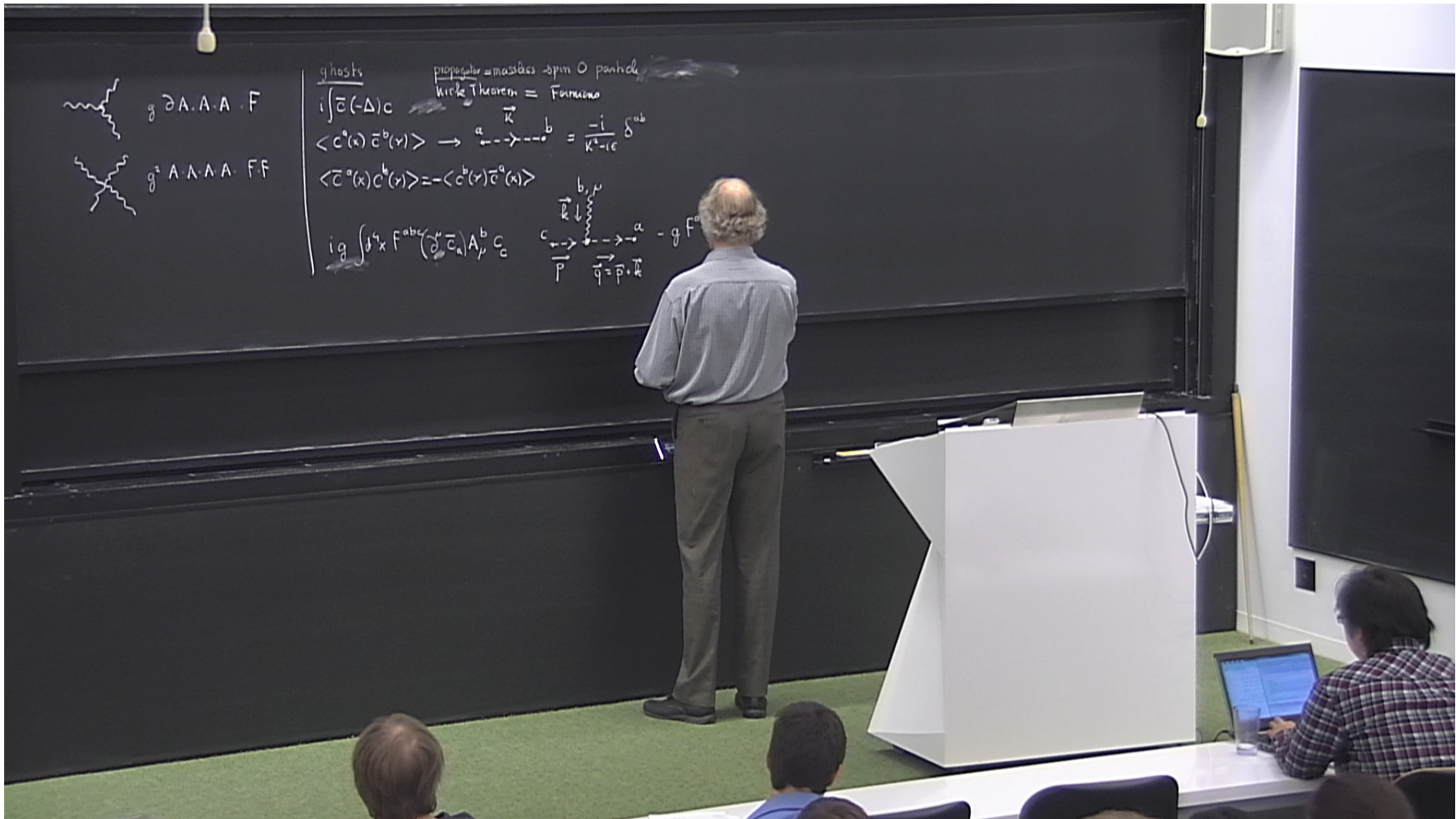
$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \overset{a}{\text{---}} \overset{\vec{k}}{\text{---}} \overset{b}{\text{---}} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$ig \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$

$\vec{k}$   
 $\vec{q} = \vec{p} + \vec{k}$





$$g \partial A \cdot A \cdot A \cdot F$$

$$g^2 A \cdot A \cdot A \cdot A \cdot F \cdot F$$

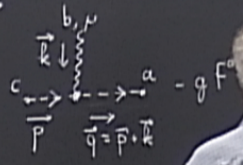
ghosts  
 propagator = massless spin 0 particle  
 Wick's Theorem = Furry's

$$i \int \bar{c}(x) (-\Delta) c$$

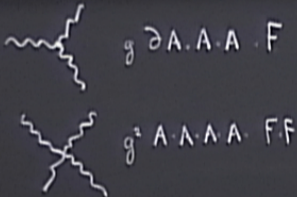
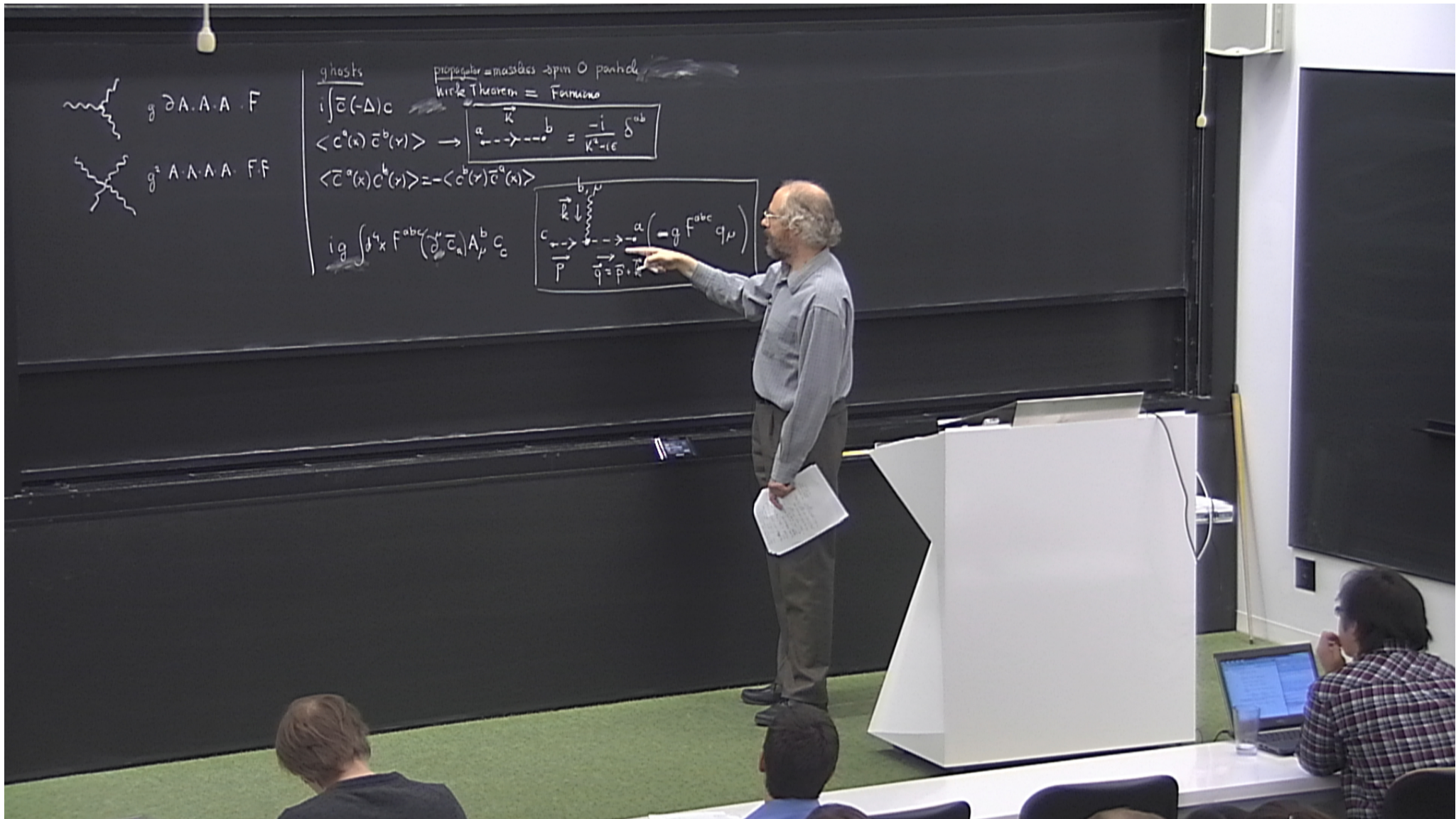
$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \overset{a}{\text{---}} \overset{\vec{k}}{\text{---}} \overset{b}{\text{---}} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$i g \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$







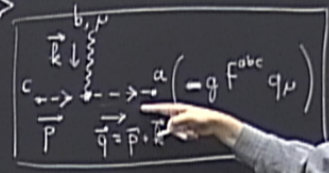
ghosts propagator = massless spin 0 particle  
 Wick's Theorem = Furry's

$$i \int \bar{c}(-\Delta) c$$

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \begin{array}{c} \vec{k} \\ a \text{---} \text{---} \text{---} b \\ \text{---} \end{array} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$i g \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$





$$g \partial A \cdot A \cdot F$$

$$g^2 A \cdot A \cdot A \cdot F F$$

ghosts  
 propagator = massless spin 0 particle  
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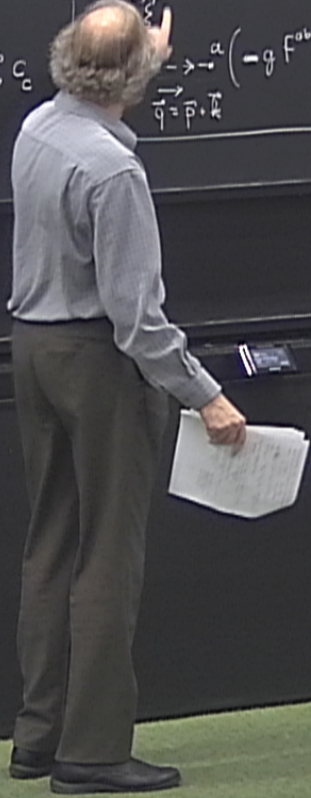
$$i \int \bar{c}(-\Delta) c$$

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \begin{array}{c} \vec{k} \\ a \text{---} \text{---} \text{---} b \\ \text{---} \end{array} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

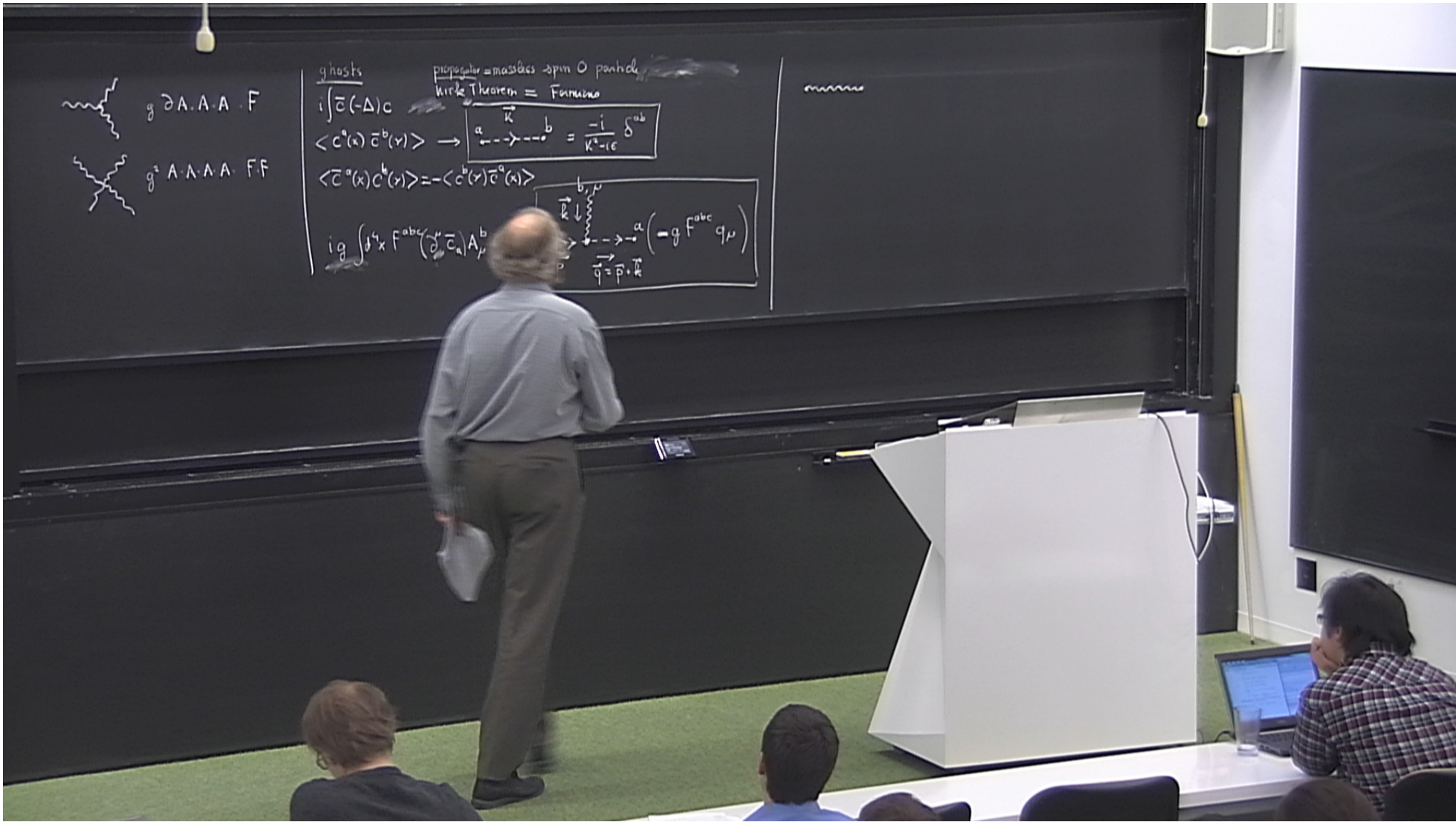
$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$i g \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c \rightarrow \begin{array}{c} b, \mu \\ a \text{---} \text{---} \end{array} \left( -g F^{abc} q_\mu \right)$$

$$\vec{q} = \vec{p} + \vec{k}$$









$g \partial A \cdot A \cdot A \cdot F$   
 $g^2 A \cdot A \cdot A \cdot A \cdot F F$

ghosts propagator = massless spin 0 particle

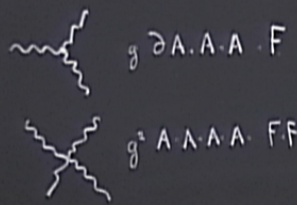
$i \int \bar{c}(-\Delta) c$   
 $\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \frac{\vec{k}}{k^2 - i\epsilon} = \frac{-i \delta^{ab}}{k^2 - i\epsilon}$

$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$

$i g \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$   
 $\frac{b, \mu}{\vec{k}} \downarrow$   
 $\frac{c}{\vec{p}} \rightarrow \frac{a}{\vec{q} = \vec{p} + \vec{k}} \left( -g F^{abc} q_\mu \right)$

$\text{wavy line} + g^2$





Fermion  $\psi^i \bar{\psi}_i \quad i=1, \dots, \dim(R)$

ghosts  $i \int \bar{c}(-\Delta)c$

propagator = massless spin 0 particle  
Wick's Theorem = Fermions

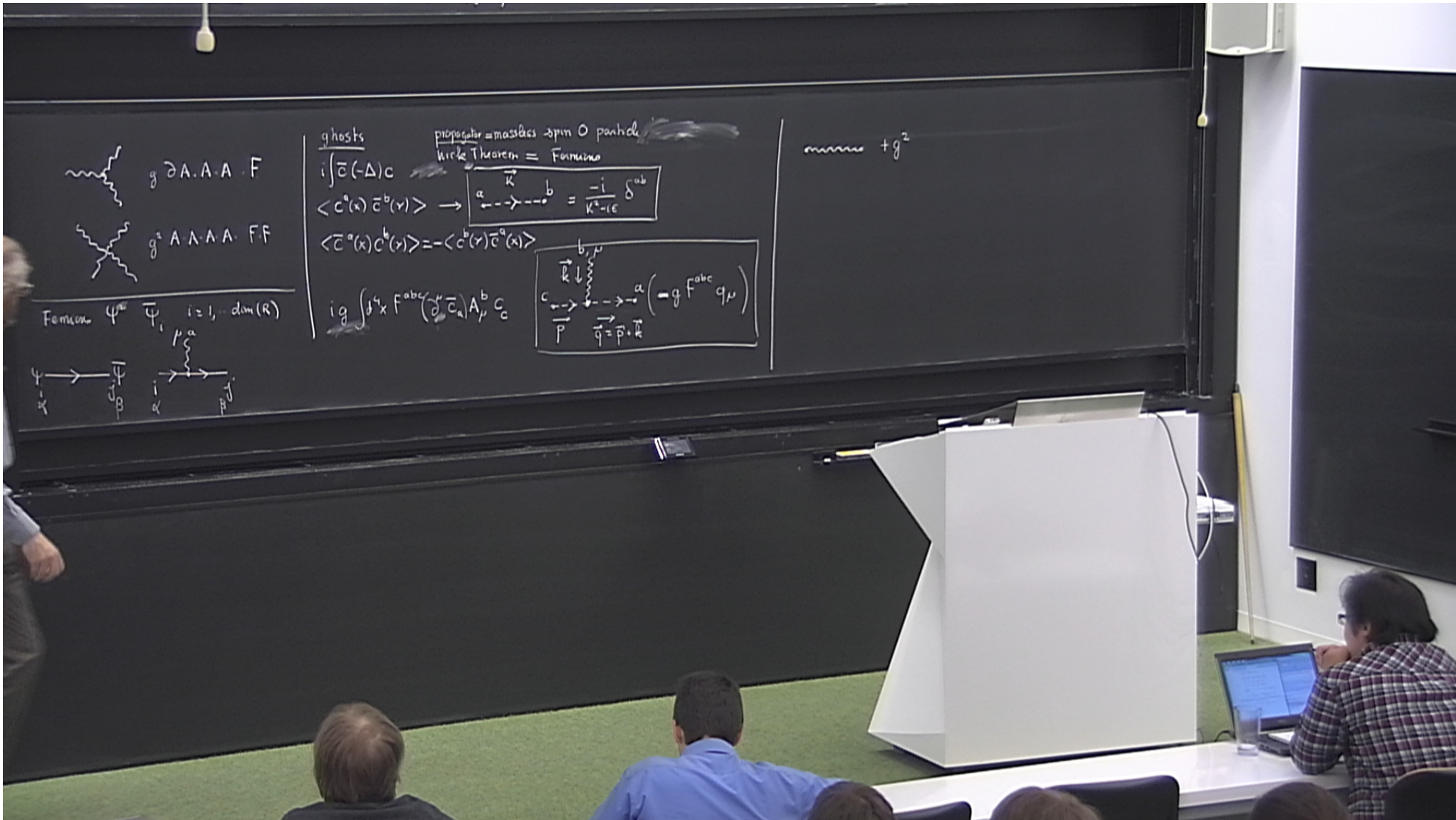
$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \begin{array}{c} \vec{k} \\ a \text{---} \text{---} \text{---} b \\ \hline = \frac{-i}{k^2 - i\epsilon} \delta^{ab} \end{array}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

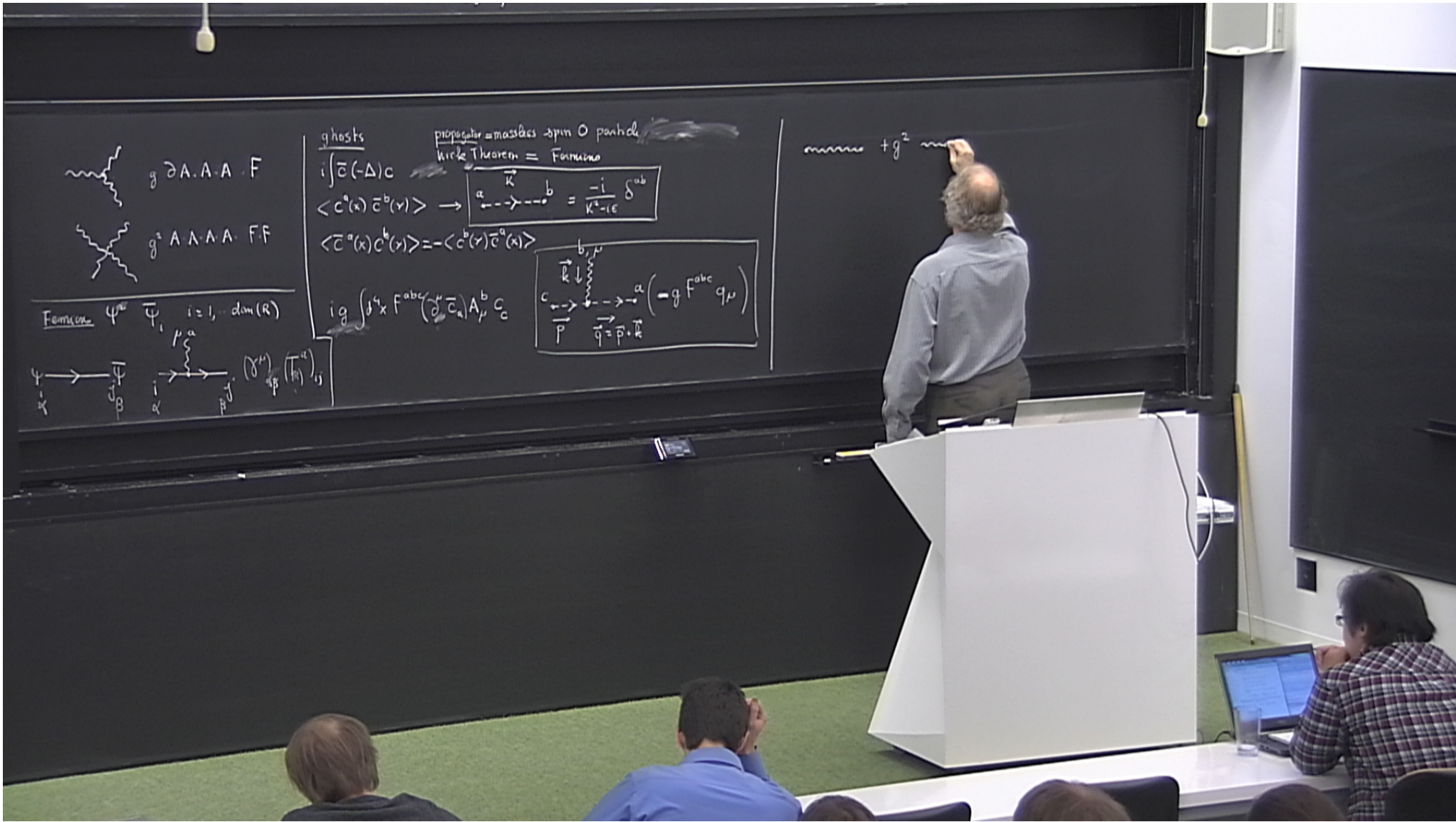
$$i g \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$

wavy  $+g^2$





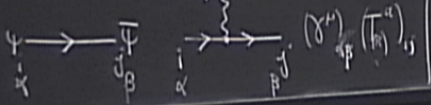




$$g \partial A \cdot A \cdot A \cdot F$$

$$g^2 A \cdot A \cdot A \cdot A \cdot F F$$

Feynman  $\psi^a \bar{\psi}_i \quad i=1, \dots, \dim(R)$



ghosts

$$i \int \bar{c}(-\Delta) c$$

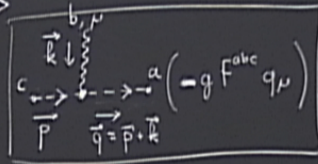
$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$i g \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$

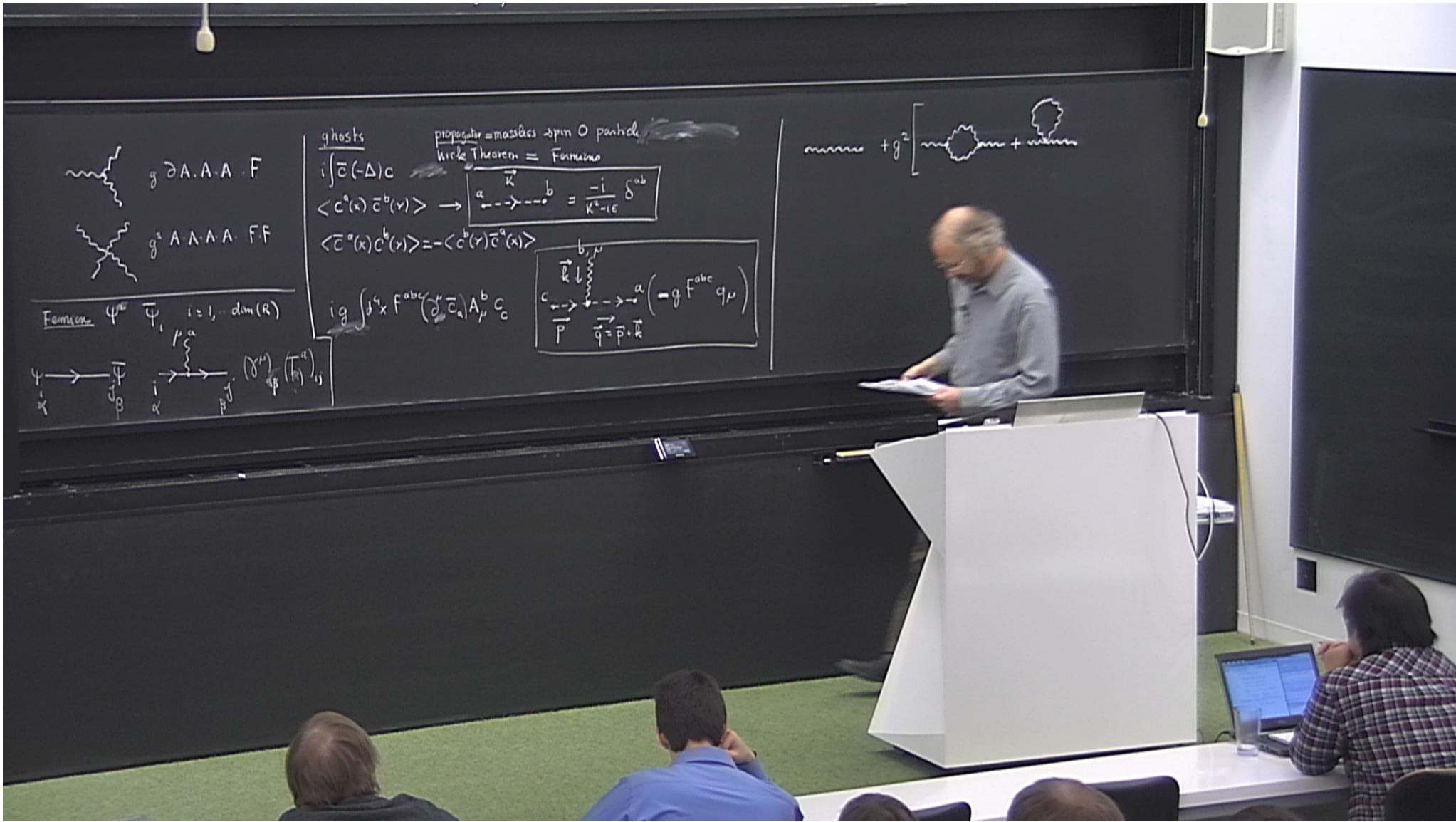
propagator = massless spin 0 particle  
Wick's Theorem = Fermions

$$\vec{k} \quad a \rightarrow \dots \rightarrow b = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$



$$+ g^2$$

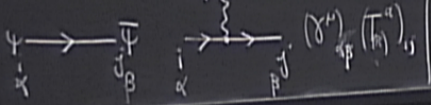




$$g \partial A \cdot A \cdot A \cdot F$$

$$g^2 A \cdot A \cdot A \cdot A \cdot F F$$

Fermions  $\psi^a, \bar{\psi}_i, i=1, \dots, \dim(R)$



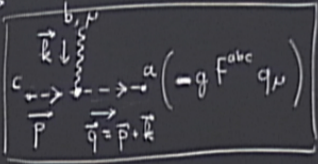
ghosts propagator = massless spin 0 particle  
Wick's Theorem = Fermions

$$i \int \bar{c}(-\Delta) c$$

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \begin{matrix} a & \xrightarrow{\vec{k}} & b \\ \text{---} & & \text{---} \end{matrix} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$i g \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$



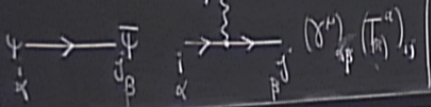
$$+ g^2 \left[ \text{diagram 1} + \text{diagram 2} \right]$$



$$g \partial A.A.A.F$$

$$g^2 A.A.A.A.FF$$

Feynman  $\psi^a \bar{\psi}_i \quad i=1, \dots, \dim(R)$



ghosts

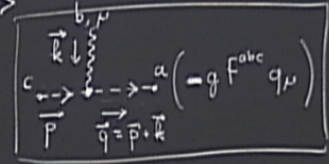
$$i \int \bar{c}(-\Delta) c$$

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow$$

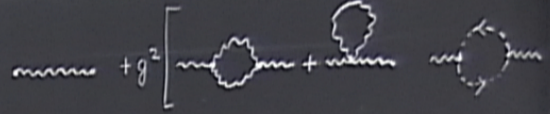
$$\frac{\vec{k}}{k^2 - i\epsilon} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

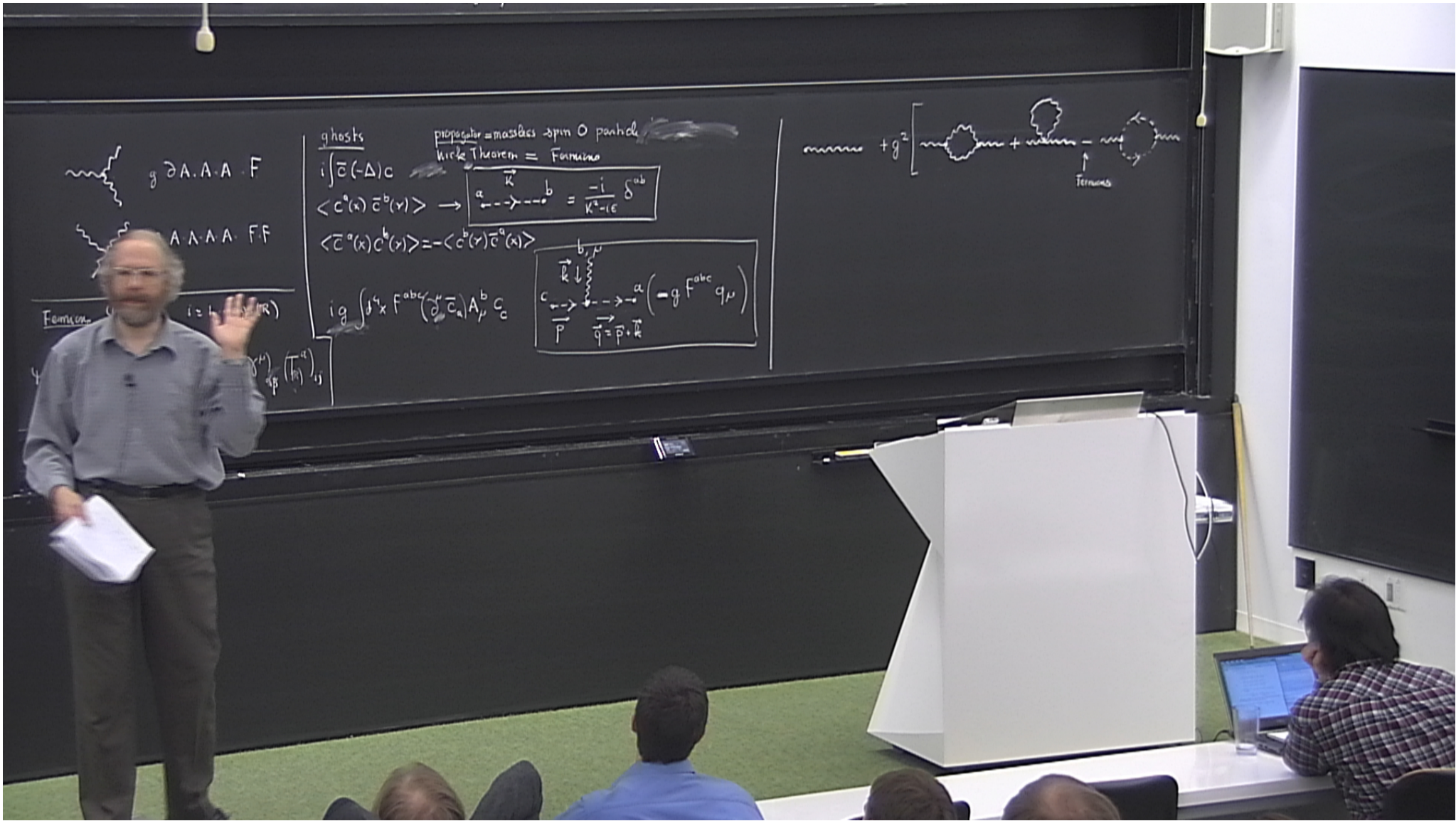
$$ig \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$



propagator = massless spin 0 particle  
Wick's Theorem = Feynman







$$g \partial A.A.A.F$$

$$A.A.A.FF$$

Feynman  $(i = 1, \dots, 4)$

ghosts propagator = massless spin 0 particle  
Keldysh Theorem = Fermions

$$i \int \bar{c}(-\Delta)c$$

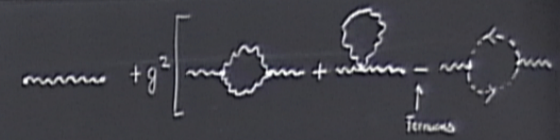
$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \begin{matrix} \vec{k} \\ a \dashrightarrow \quad \dashrightarrow b \end{matrix} = \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = - \langle c^b(y) \bar{c}^a(x) \rangle$$

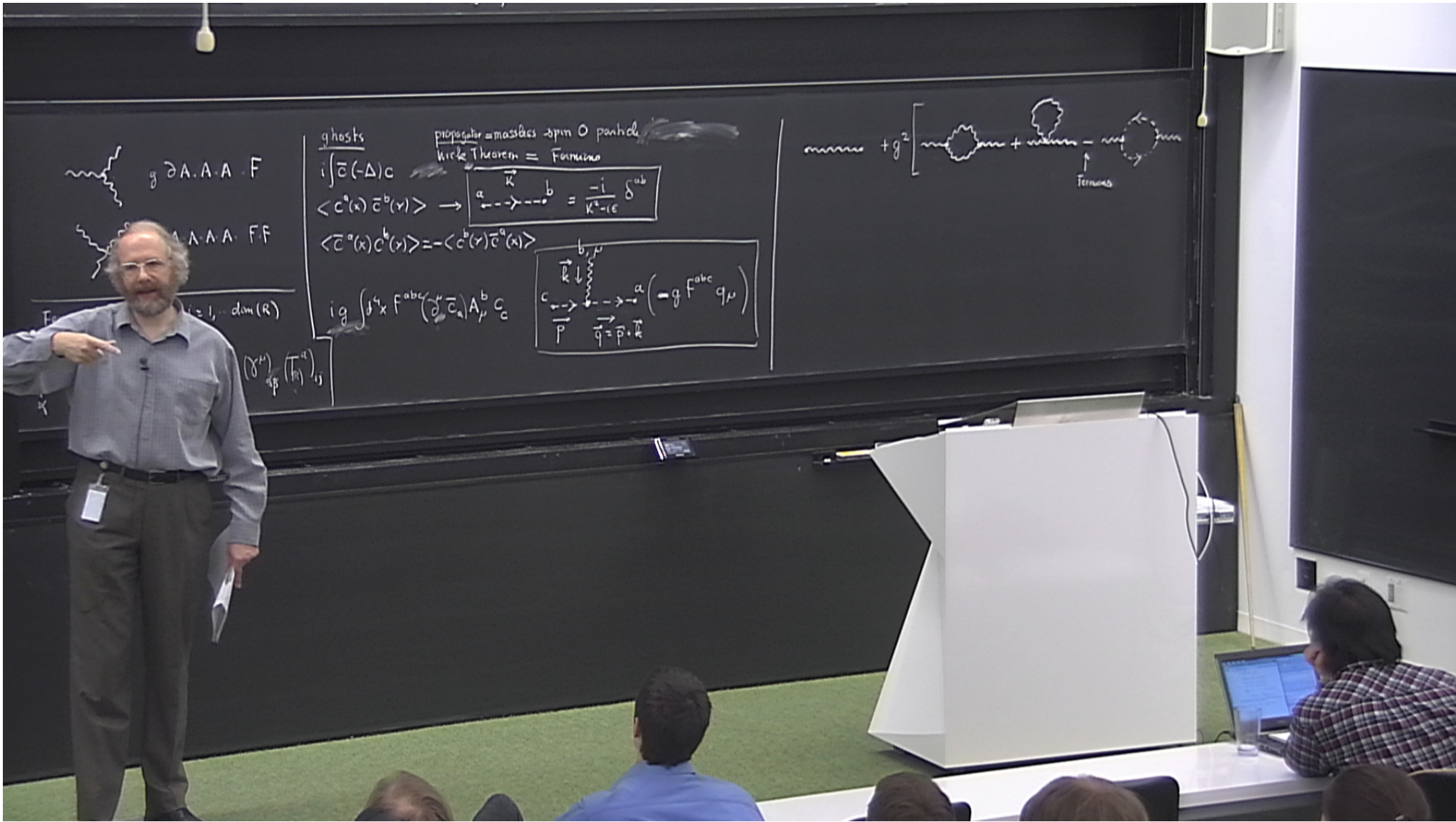
$$ig \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$

$$\begin{matrix} b, \mu \\ \vec{k} \downarrow \\ c \dashrightarrow \quad \dashrightarrow a \end{matrix} \left( -g F^{abc} q_\mu \right)$$

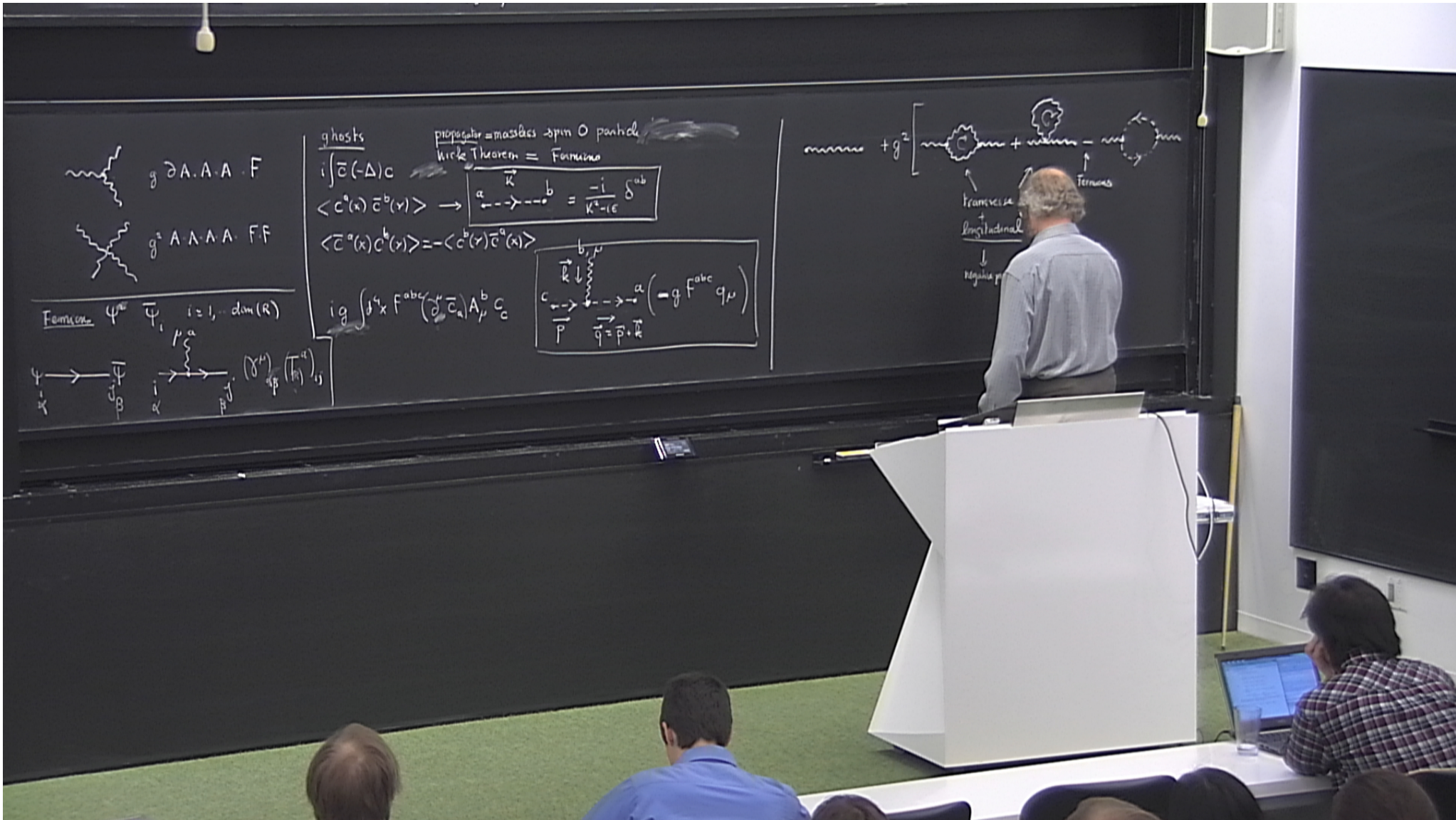
$$\vec{p} \quad \vec{q} = \vec{p} + \vec{k}$$











$$g \partial A.A.A.F$$

$$g^2 A.A.A.A.FF$$

Fermions  $\psi^a, \bar{\psi}_i, i=1, \dots, \dim(R)$

ghosts  $i(\bar{c}(-\Delta)c$

propagator = massless spin 0 particle  
Wick's Theorem = Fermions

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

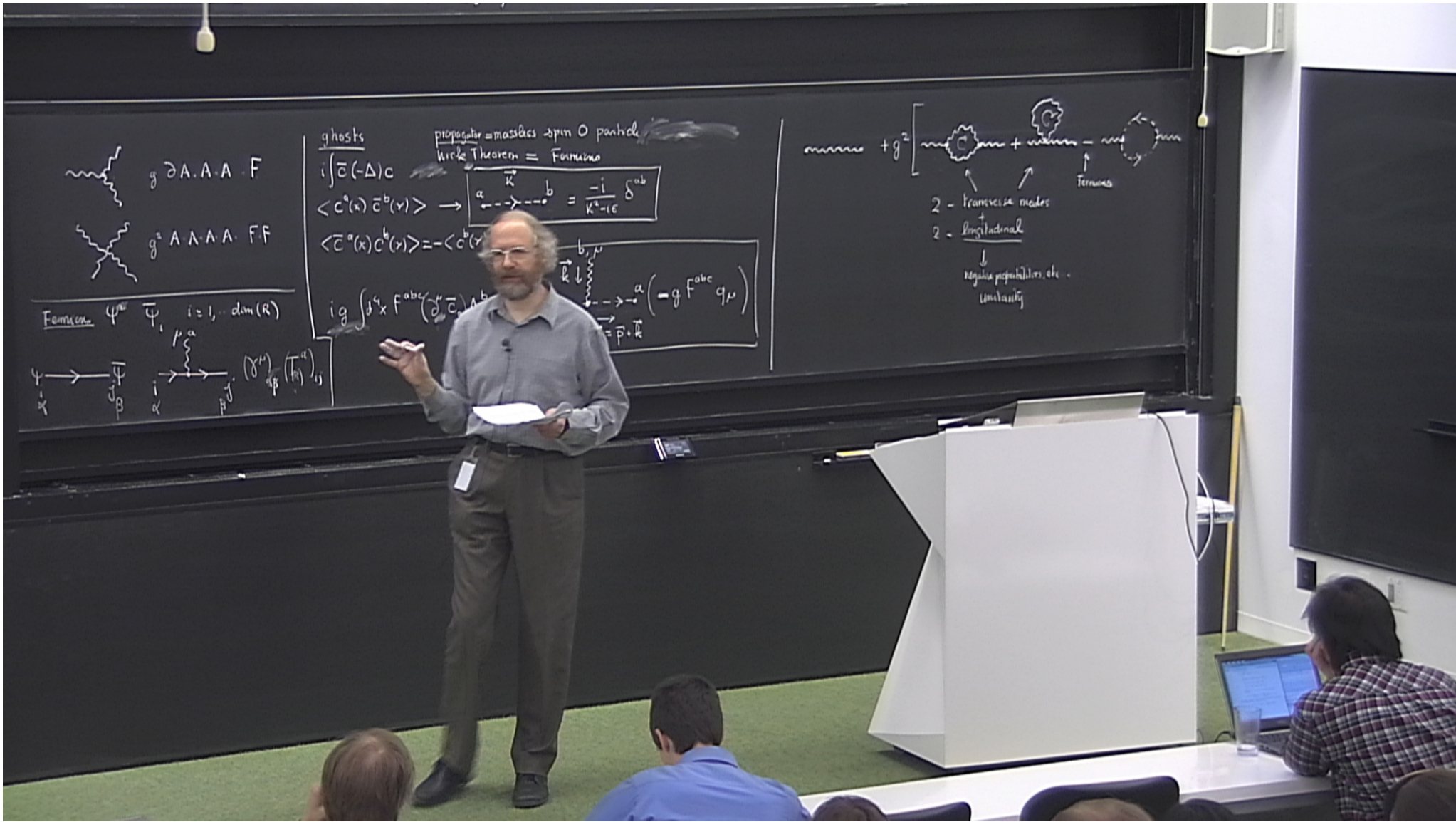
$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$ig \int d^4x F^{abc} (\partial_\mu \bar{c}_a) A_\mu^b c_c$$

$$+ g^2 \left[ \text{diagram 1} + \text{diagram 2} + \text{diagram 3} \right]$$

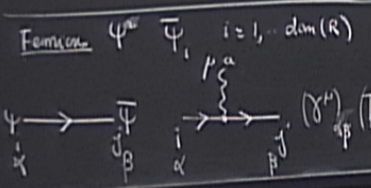
transverse + longitudinal  
↓  
negative p





$$g \partial A \cdot A \cdot A \cdot F$$

$$g^2 A \cdot A \cdot A \cdot A \cdot F F$$



ghosts propagator = massless spin 0 particle  
 Wick's Theorem = Formula

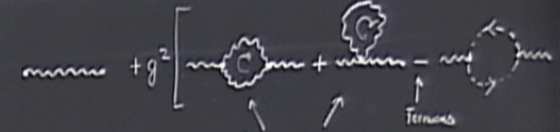
$$i \int \bar{c}(-\Delta) c$$

$$\langle c^a(x) \bar{c}^b(y) \rangle \rightarrow \frac{-i}{k^2 - \epsilon} \delta^{ab}$$

$$\langle \bar{c}^a(x) c^b(y) \rangle = -\langle c^b(y) \bar{c}^a(x) \rangle$$

$$i g \int d^4x F^{abc} (\partial_\mu \bar{c})^a \Lambda^b$$

$$= \frac{-i}{\vec{p} \cdot \vec{k}} \left( -g F^{abc} q_\mu \right)$$



2 - transverse modes  
 2 - longitudinal  
 ↓  
 negative probabilities, etc.  
 Unitarity

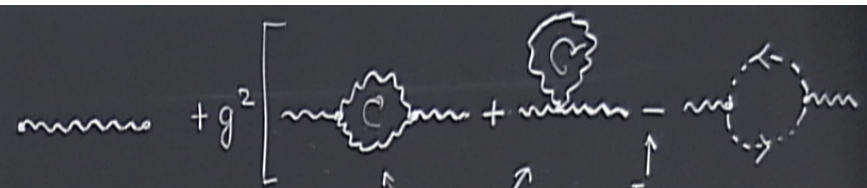


0 particle  
zero

$$\frac{-i}{k^2 - i\epsilon} \delta^{ab}$$

$b_\mu$   
 $a_\mu$   
 $q^\mu = p^\mu + k^\mu$

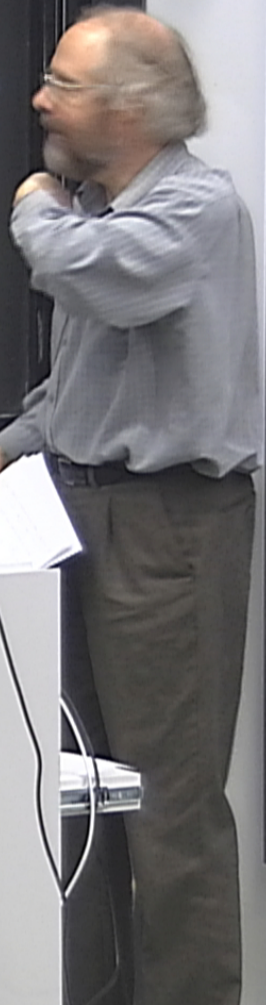
$$a \left( -g F^{abc} q_\mu \right)$$



2 - transverse modes  
+  
2 - longitudinal

↓  
negative probabilities, etc.  
Unitarity

Fermions  
cancelled  
by the  
ghost





$c = c^a(x)$  Ghost charge  
 $\bar{c} = \bar{c}_a(x)$  Ghost but no spin  
 $\text{Spin-Statistics theorem}$   
 $\text{Lorentz invariance}$

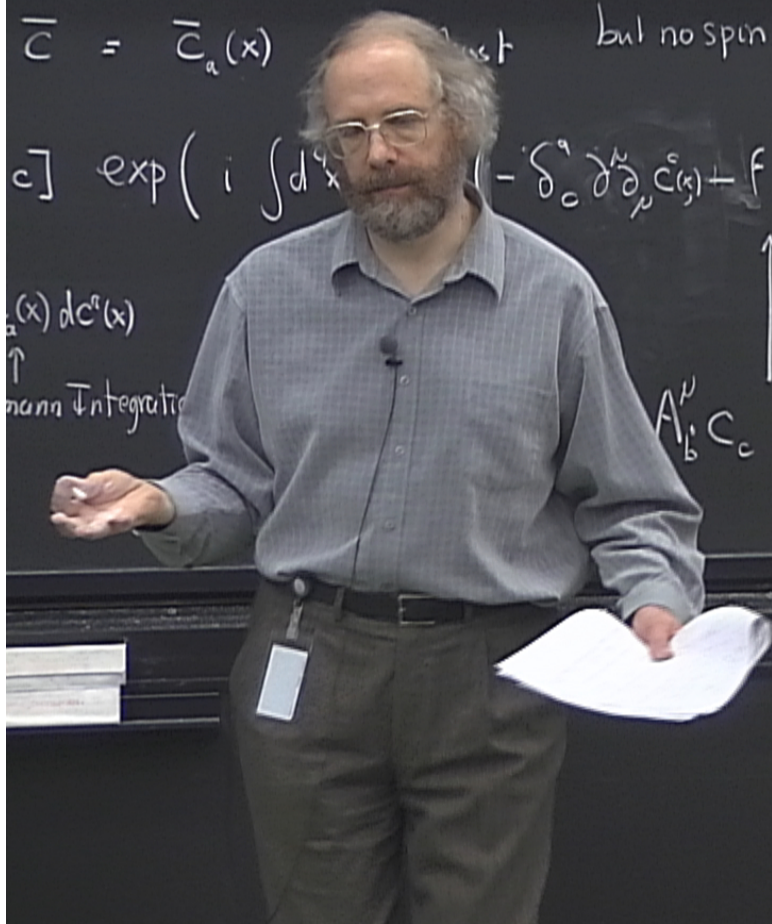
$\int D[A] D[\bar{c}, c] \delta[\text{gauge fixing}] \exp(i S[A, \bar{c}, c])$

$\int_{\mathbb{R}^{25}} Z(\omega)$  independent of  $\omega$

$\int d\omega dA = \int dA d\omega$

$\int d^4x \left( -\delta_c^a \partial^\mu \partial_\mu \bar{c}^c(x) + f_{bc}^a \partial^\mu (A_\mu^b(x) \bar{c}^c(x)) \right)$

$A_\mu^b \bar{c}^c$  coupling between gauge field & ghost if  $f^{abc} \neq 0$  if  $G$  nonabelian





$c = c^a(x)$  Ghost charge  
 $\bar{c} = \bar{c}_a(x)$  Antighost but no

☹ Spin-Statistics theorem  
 Invariance + Unitarity

$\int D[A] D[\bar{c}, c] \cancel{S[A]} \exp(i S)$   
 gauge fixing

$\int d^4x \left[ \bar{c}_a(x) \left( -\delta_c^a \partial_\mu \partial_\nu c^c(x) + A_\mu^b(x) c^c(x) \right) \right]$

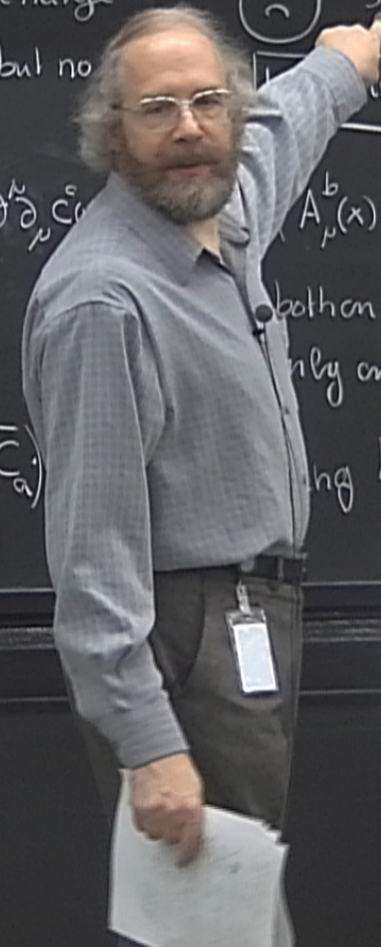
$\int e^{\frac{i\epsilon^2}{25}} Z(w)$  independent of  $w$   
 $\int dw dA = \int dA dw$

$\int d^4x d^a c^a(x)$   
 ↑  
 main Integration

$f^{abc} (\partial_\mu \bar{c}_a)$

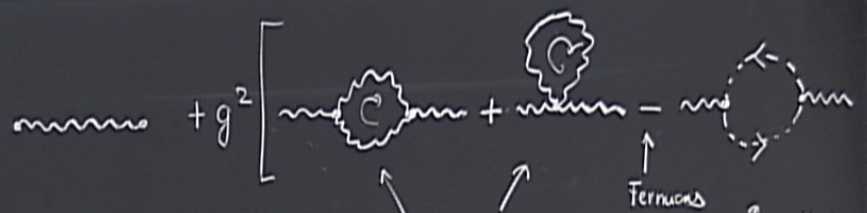
both A and c  
 only on  $\bar{c}$

coupling between gauge field & ghost if  $f^{abc} \neq 0$  if  $G$  nonabelian





Transverse polarisation states



2 - transverse modes  
+  
2 - longitudinal  
↓  
negative probabilities, etc.  
non Unitarity

↑  
Fermions

↑  
cancelled by the ghost (not unitary)

$$= g F^{abc} q_\mu$$