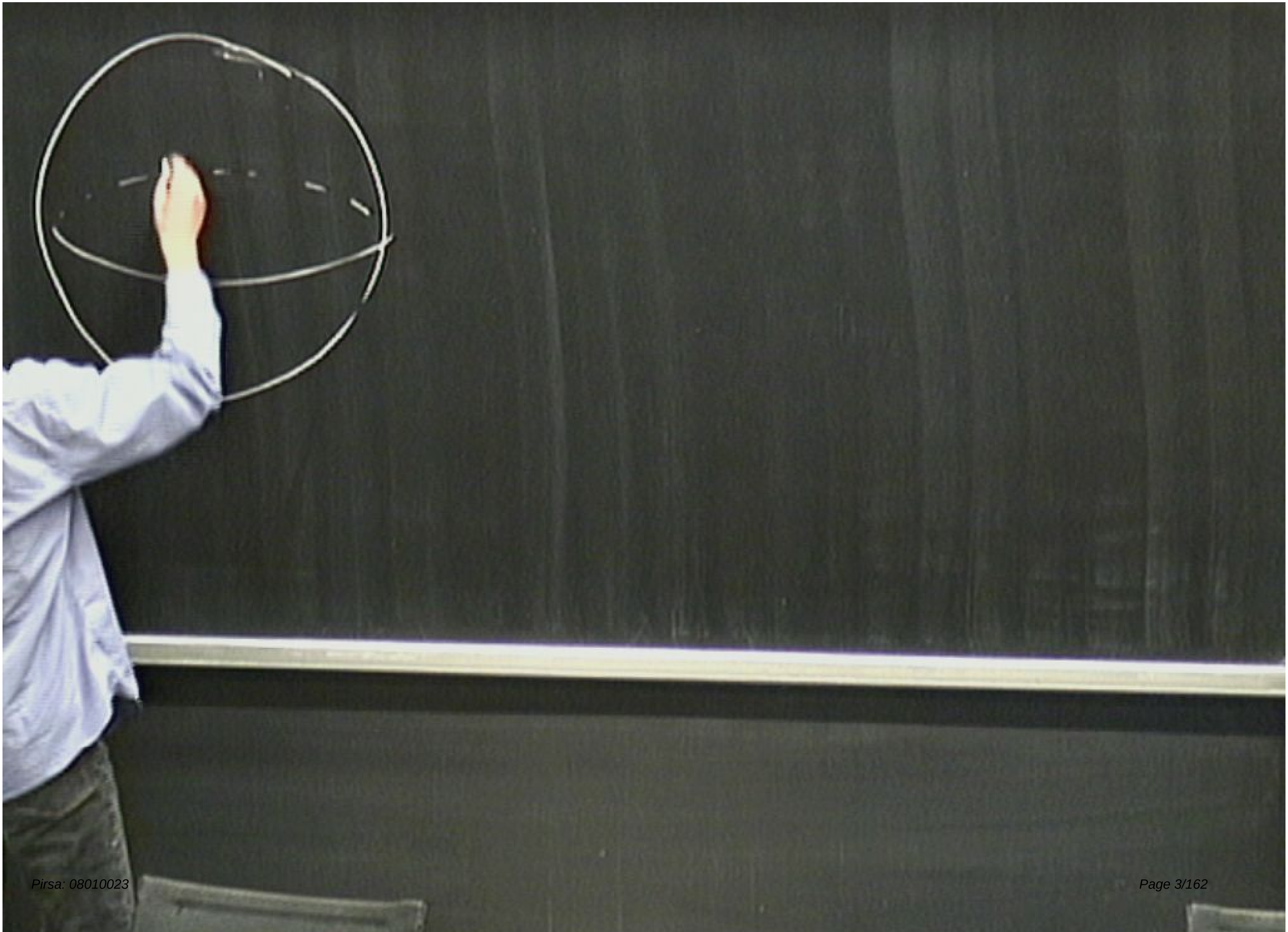
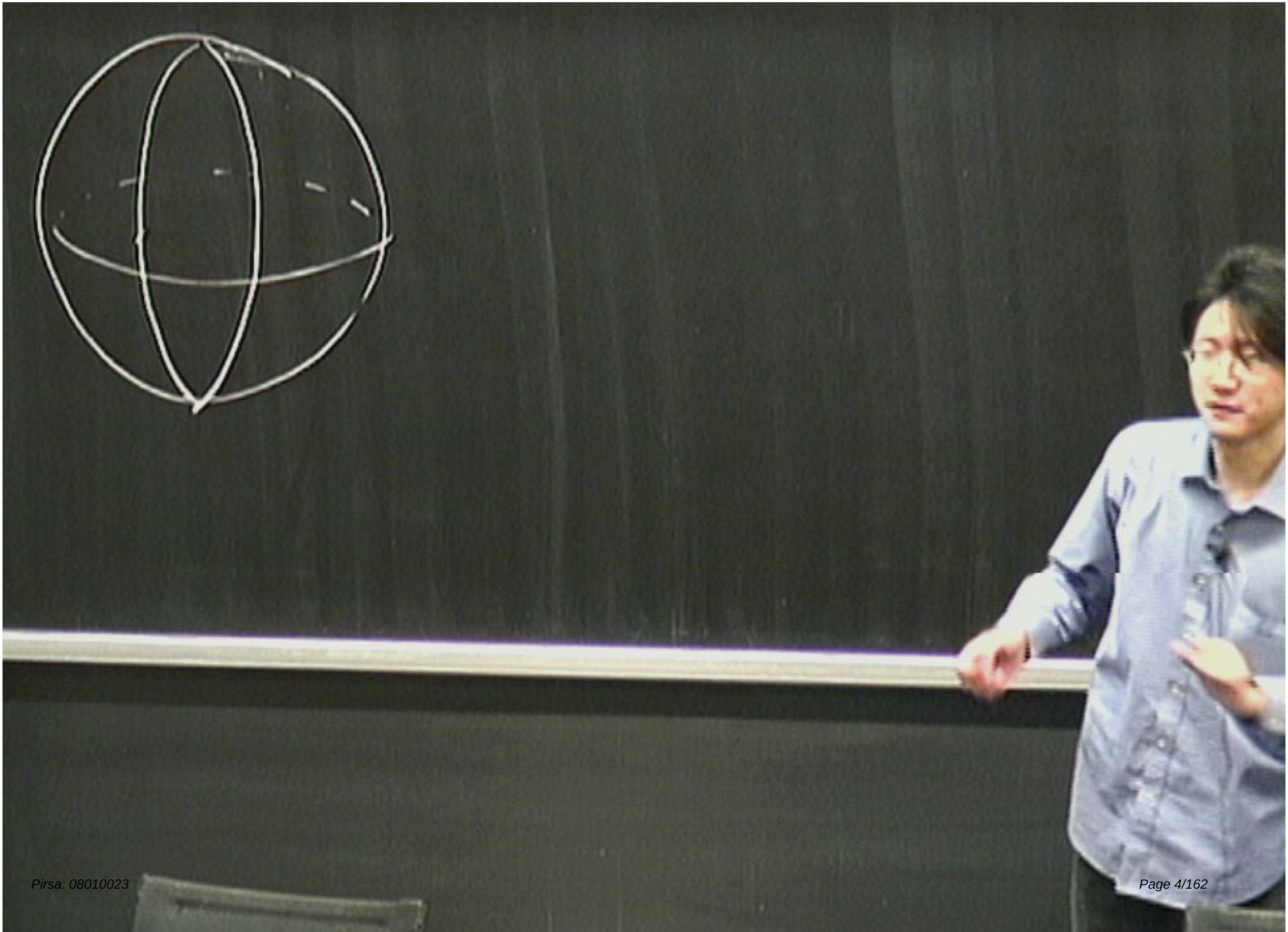
Title: String Theory #2

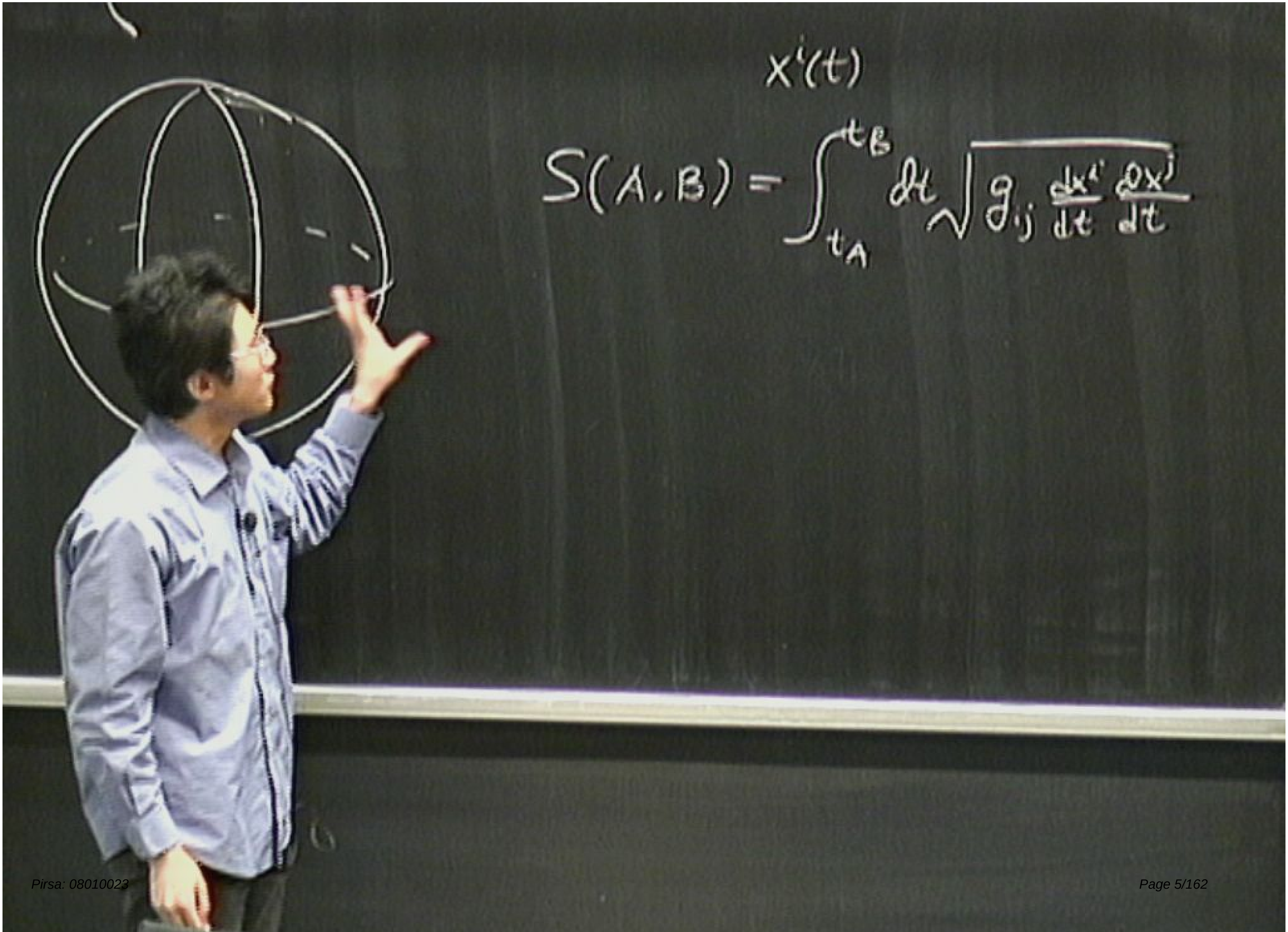
Date: Jan 24, 2008 06:30 PM

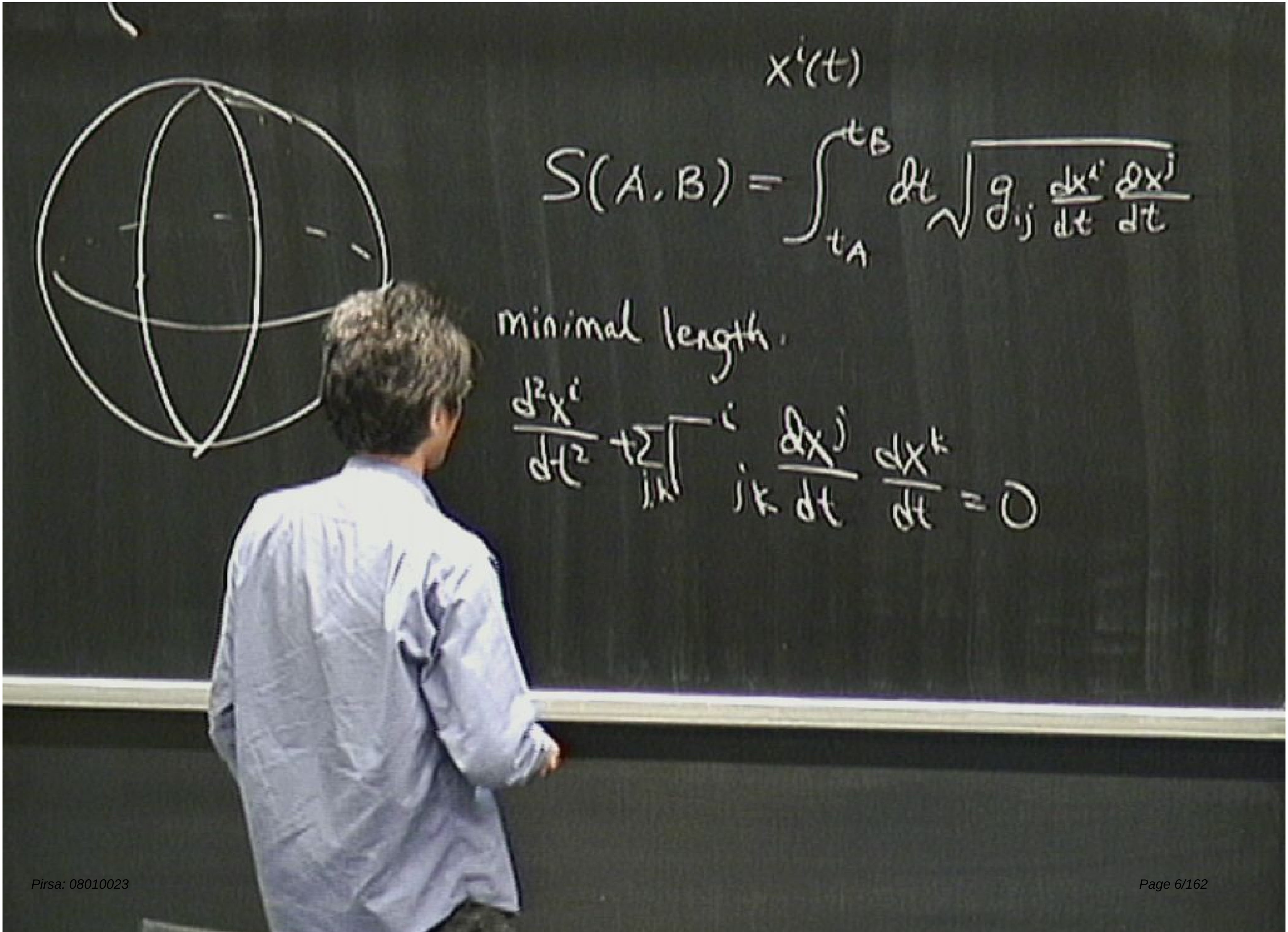
URL: http://pirsa.org/08010023

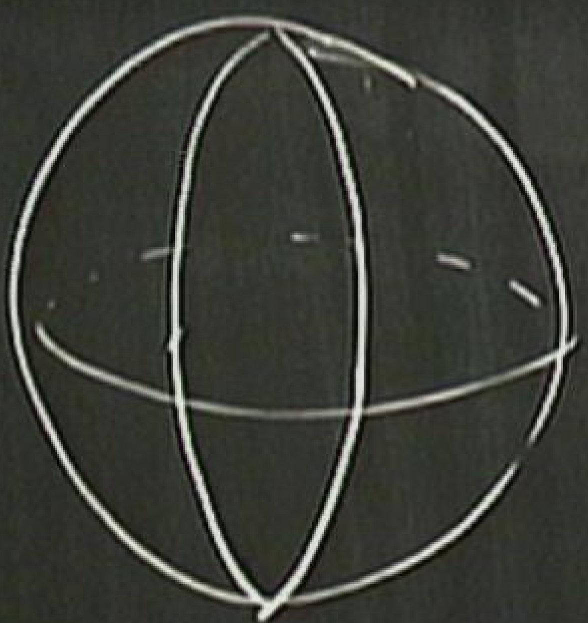
Abstract: Strings vs. particles. Branes and Holography in quantum gravity.






$x^i(t)$
$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$


$x^i(t)$
$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$
minimal length.
$\frac{d^2x^i}{dt^2} + \sum_{j,k} \Gamma^i_{jk} \frac{dx^j}{dt} \frac{dx^k}{dt} = 0$

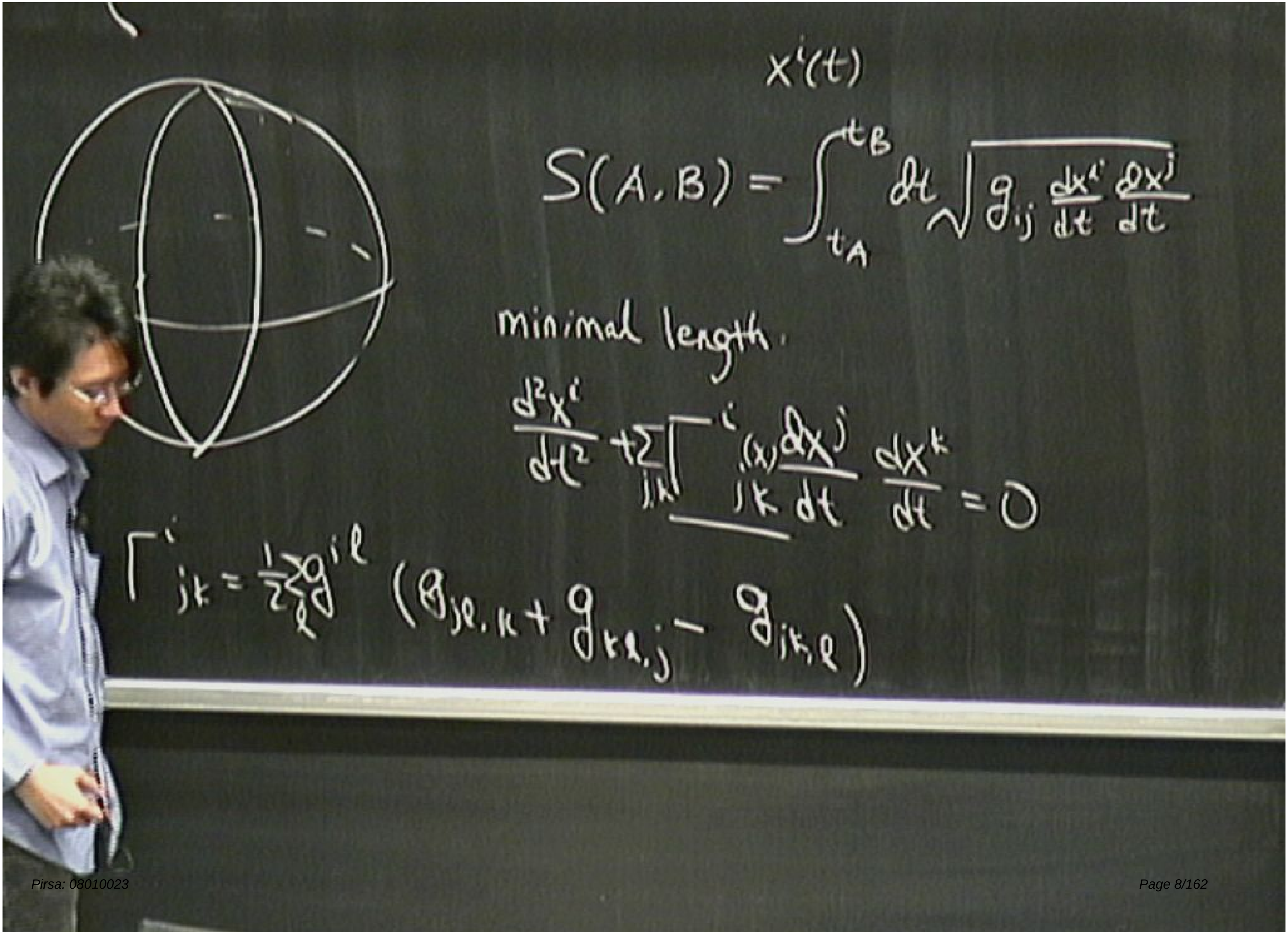


$x^i(t)$

$$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij}\frac{dx^i}{dt}\frac{dx^j}{dt}}$$

minimal length.

$$\frac{d^2x^i}{dt^2} + \sum_{j,k} \Gamma^i_{jk}(x)\frac{dx^j}{dt}\frac{dx^k}{dt} = 0$$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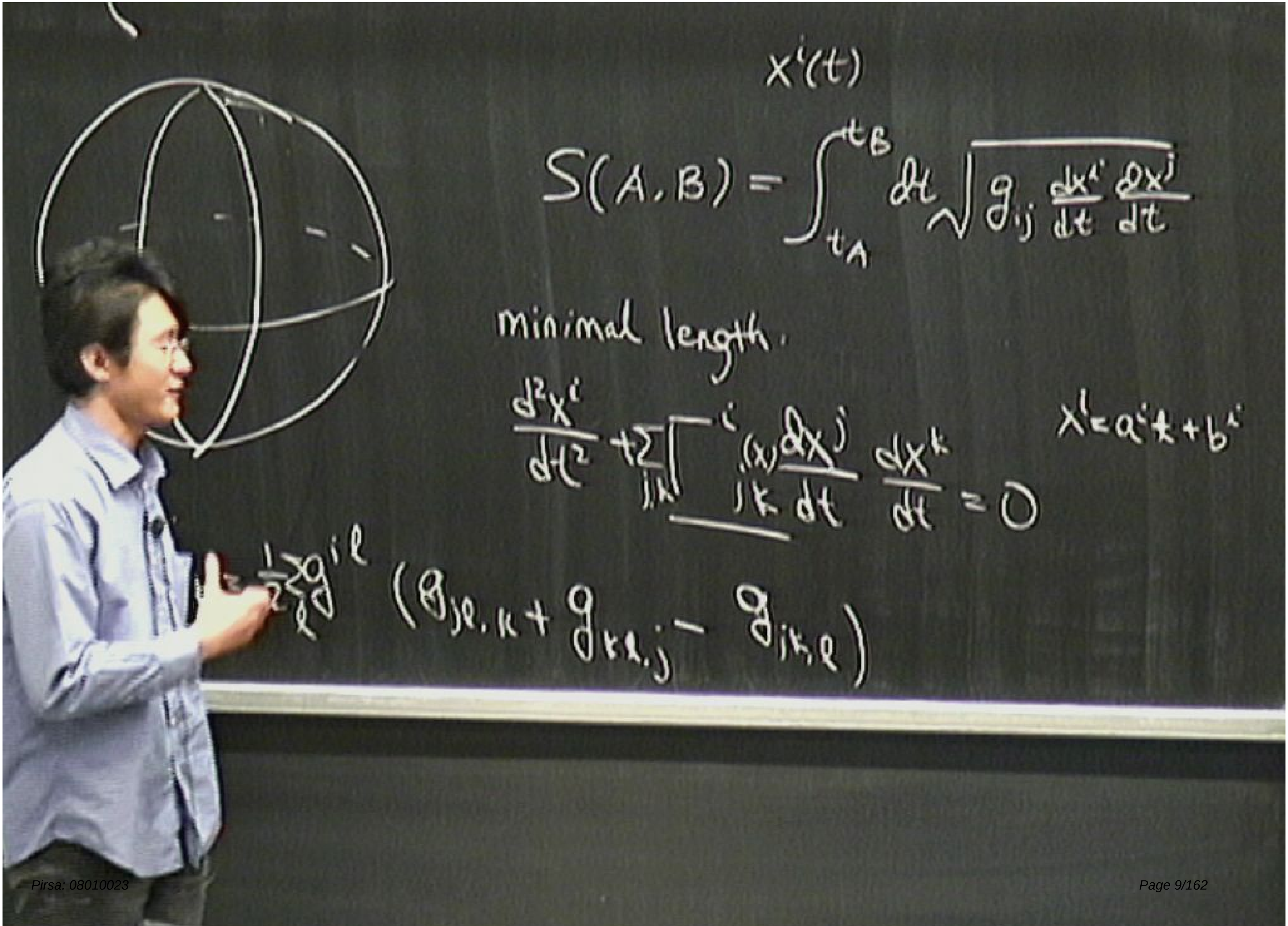
$\frac{d^2x^i}{dt^2} + \sum_{j,k} \Gamma^i_{jk}(x) \frac{dx^j}{dt} \frac{dx^k}{dt} = 0$
$\Gamma^i_{jk} = \frac{1}{2} \sum_{l} g^{il} (g_{jl,k} + g_{kl,j} - g_{jk,l})$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$x^i = a^i t + b^i$
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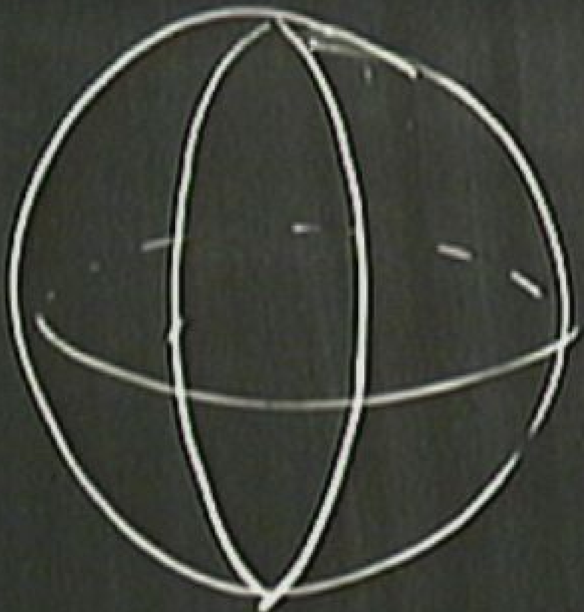


$x^i(t)$

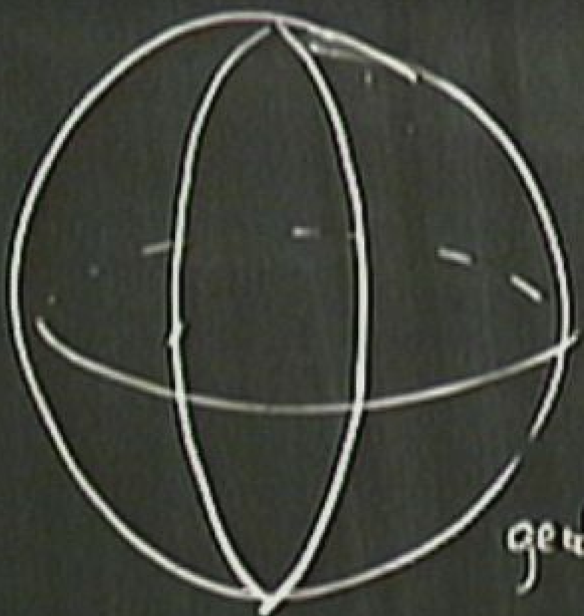
$$S(A,B)=\int_{t_A}^{t_B} dt \sqrt{g_{ij}\frac{dx^i}{dt}\frac{dx^j}{dt}}$$

minimal length.

$$\frac{d^2x^i}{dt^2}+\sum_{j,k}\Gamma^i_{jk}(x)\frac{dx^j}{dt}\frac{dx^k}{dt}=0$$

$x^i=a^it+b^i$

$$\Gamma^i_{jk}=\frac{1}{2}\sum_{l} g^{il}\left(g_{jl,k}+g_{kl,j}-g_{jk,l}\right)$$



$x^i(t)$

$$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij}\frac{dx^i}{dt}\frac{dx^j}{dt}}$$

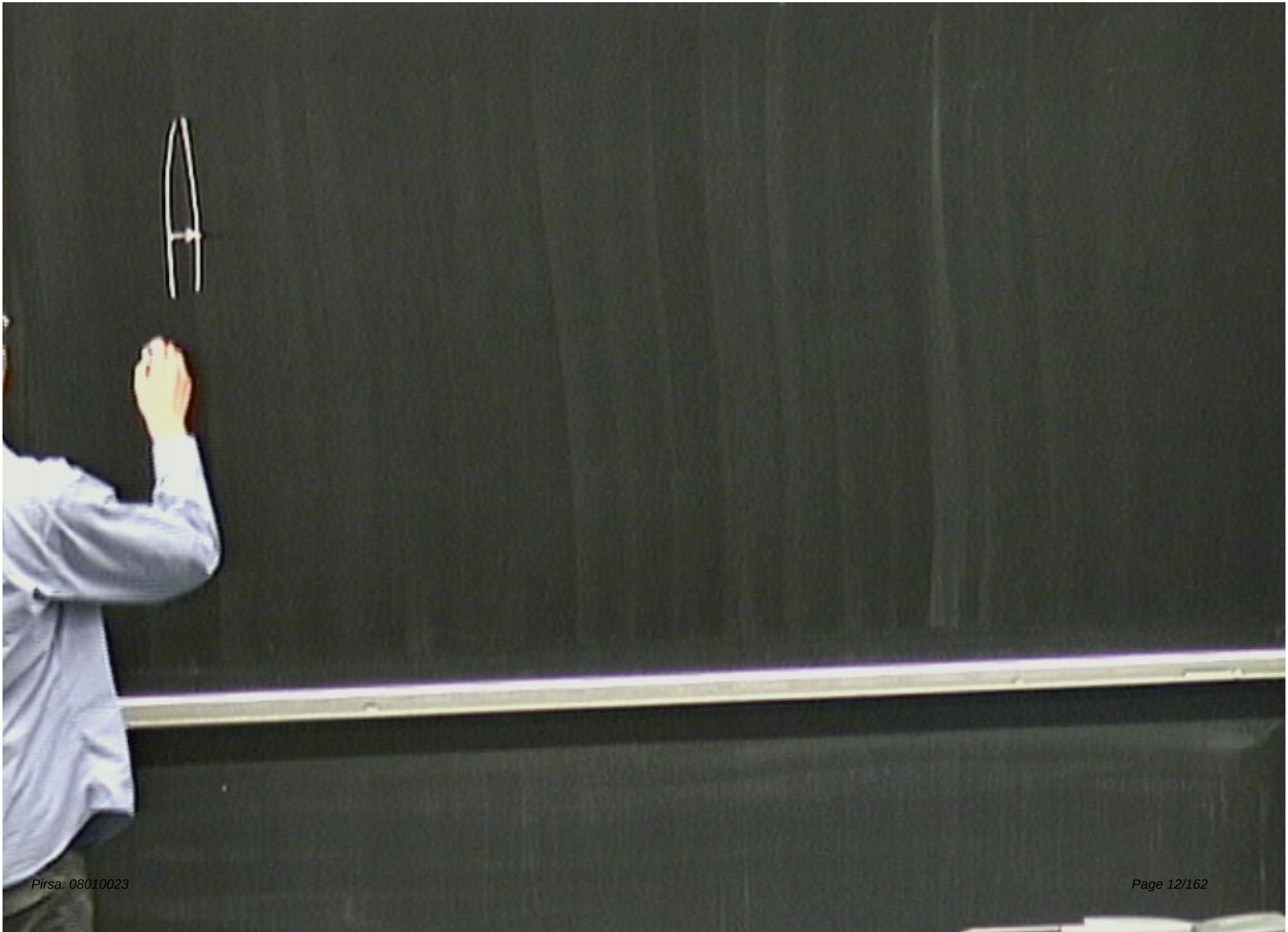
minimal length.

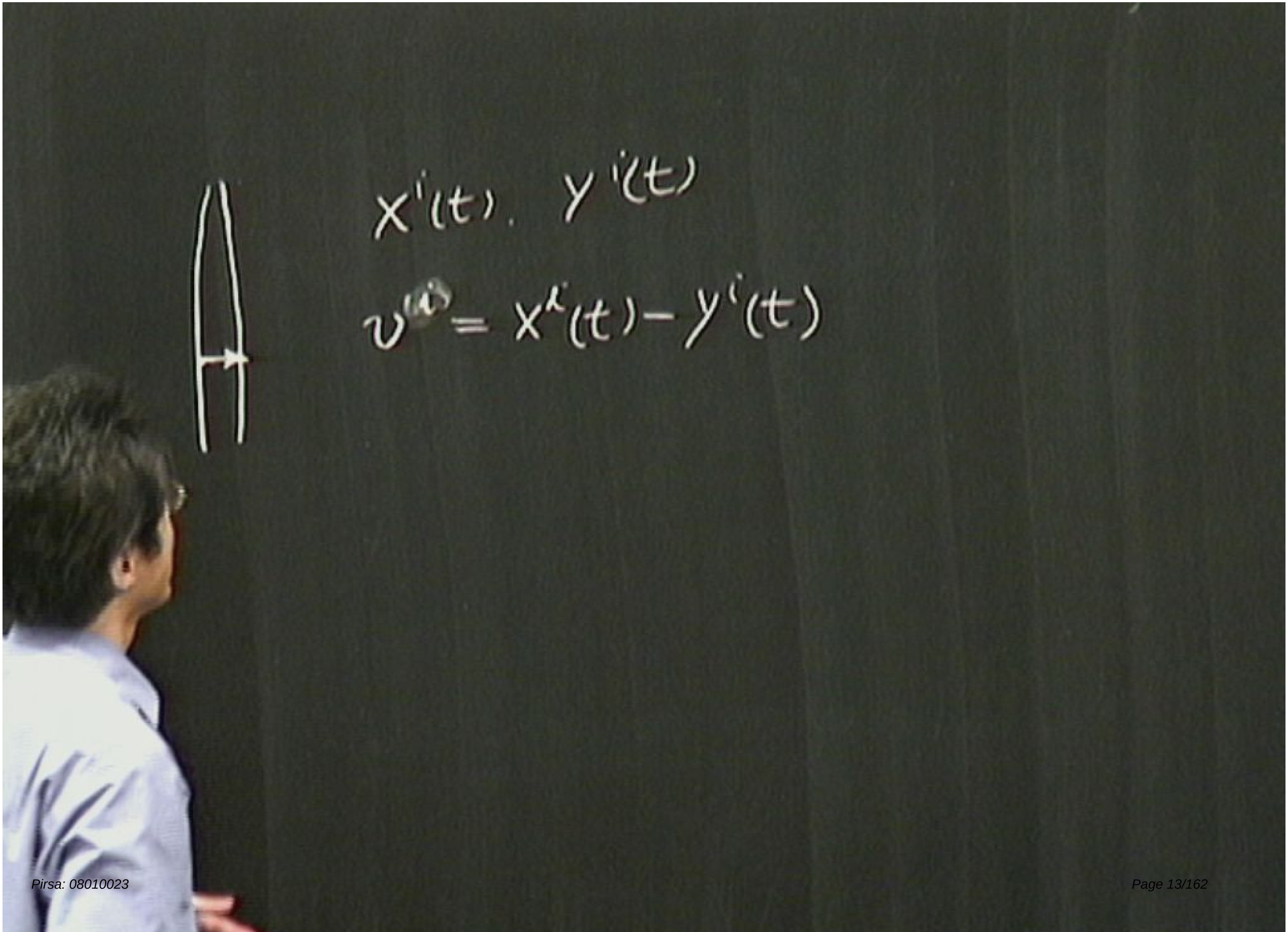
geodesic

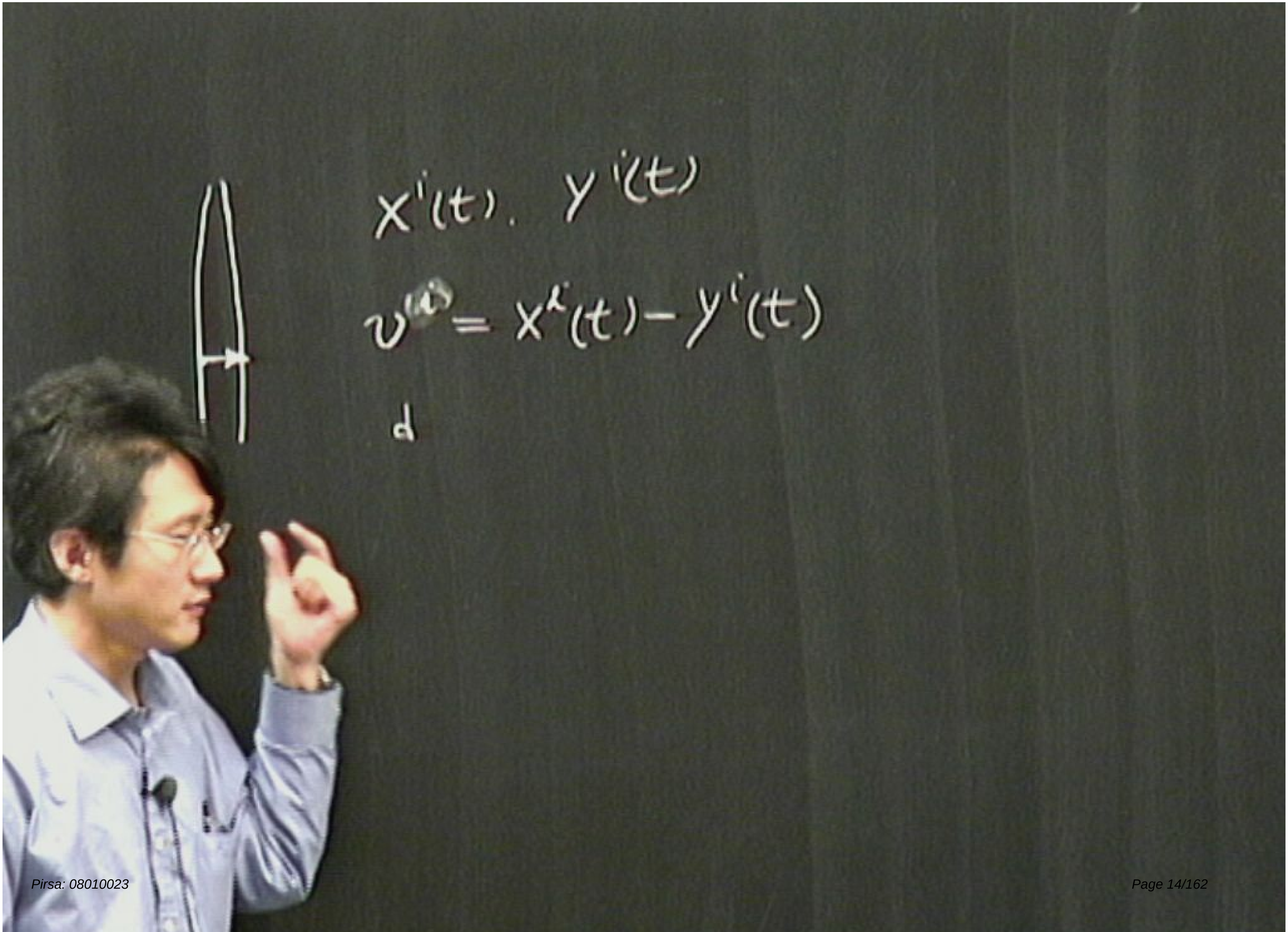
$$\frac{d^2x^i}{dt^2} + \sum_{jk} \underline{\Gamma^i_{jk}(x)}\frac{dx^j}{dt}\frac{dx^k}{dt} = 0$$

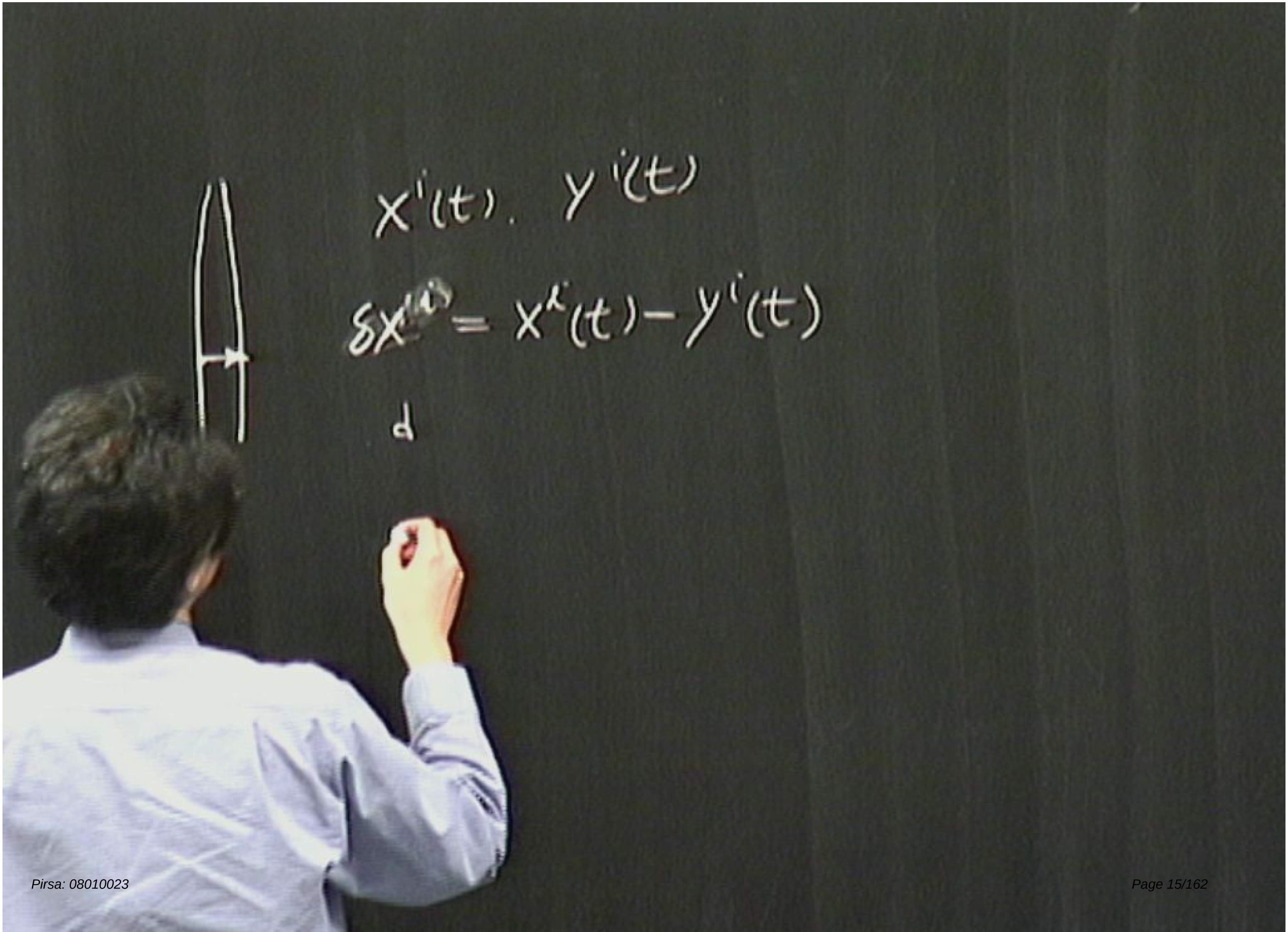
$x^i = a^i t + b^i$

$$\Gamma^i_{jk} = \frac{1}{2}\sum_{l} g^{il}\left(g_{jl,k} + g_{kl,j} - g_{jk,l}\right)$$




$x^i(t)$, $y^i(t)$
$v^{(i)} = x^i(t) - y^i(t)$

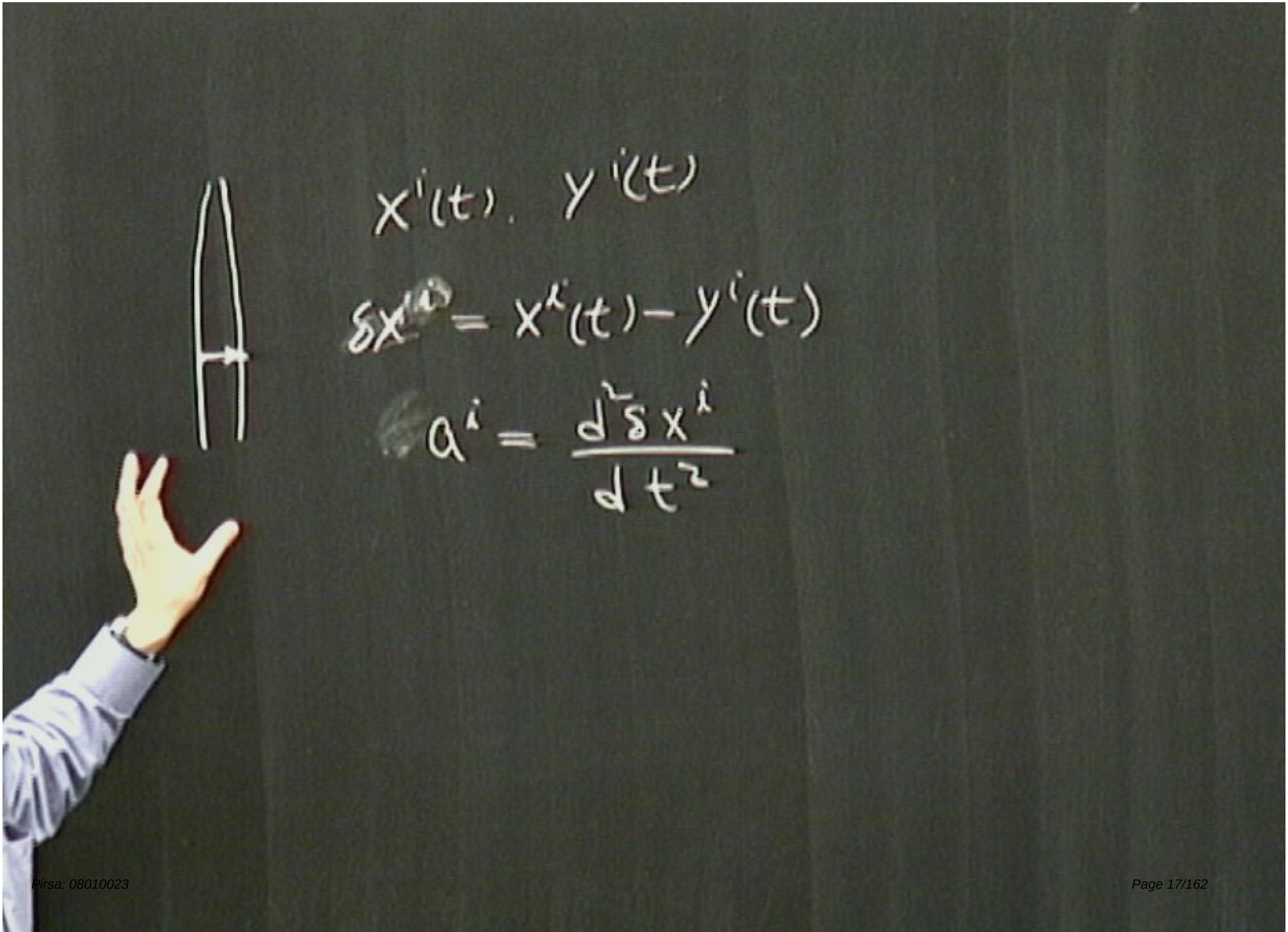

x^i(t), y^i(t)
v^(i) = x^i(t) - y^i(t)
d


$x^i(t)$, $y^i(t)$
$\delta x^i = x^i(t) - y^i(t)$
d

$x^i(t)$, $y^i(t)$

$\delta x^i = x^i(t) - y^i(t)$

$a^i =$


$x^i(t)$, $y^i(t)$
$\delta x^i = x^i(t) - y^i(t)$
$a^i = \frac{d^2 \delta x^i}{dt^2}$

$x^i(t), \quad y^i(t)$

$\delta x^i = x^i(t) - y^i(t)$

$a^i = \dfrac{d^2 \delta x^i}{dt^2} =$

$x^i(t)$, $y^i(t)$

$$\delta x^i = x^i(t) - y^i(t)$$

$$a^i = \frac{d^2 \delta x^i}{d t^2} =$$

$x^i(t)$, $y^i(t)$

$$\delta x^i = x^i(t) - y^i(t)$$

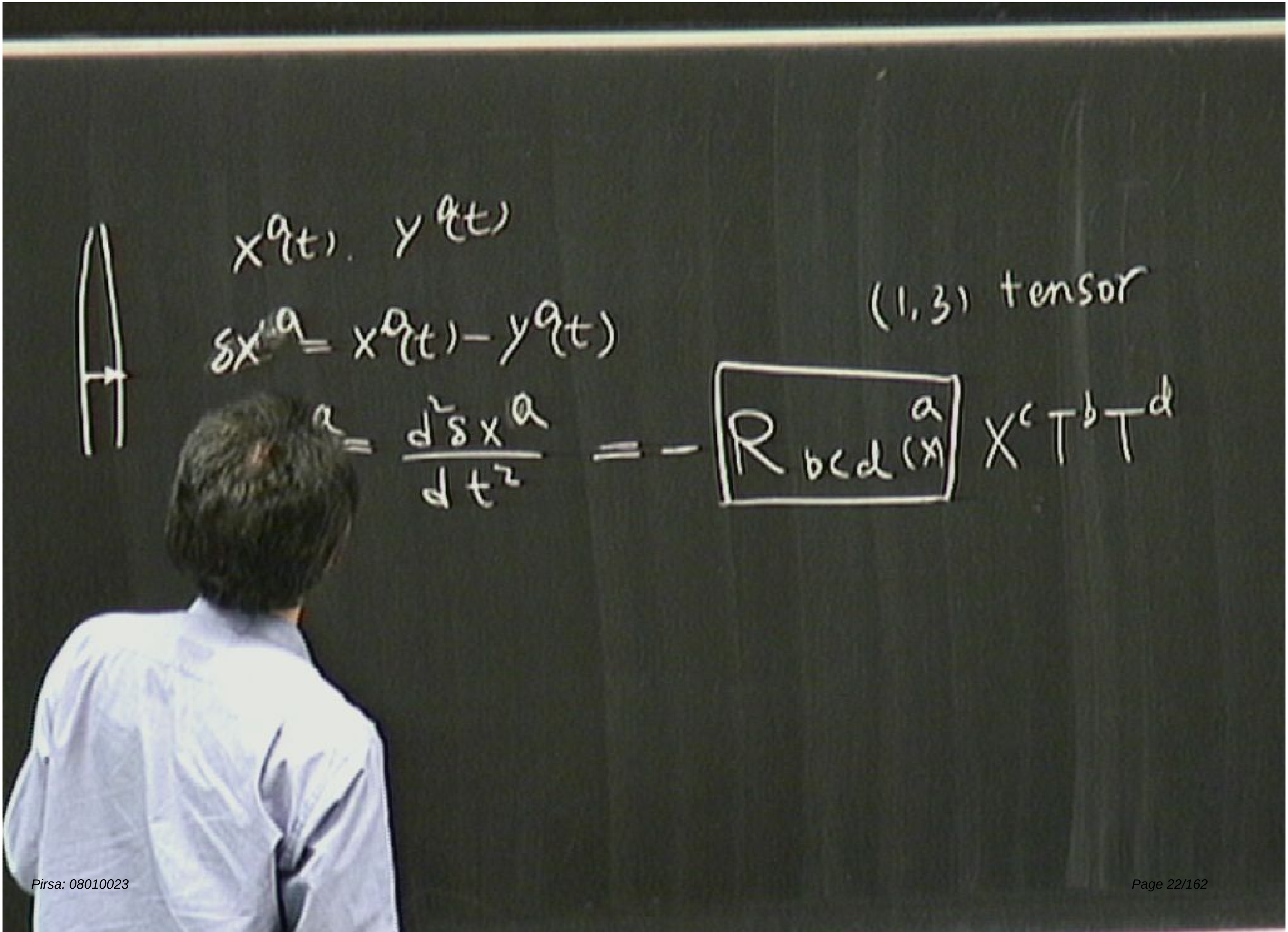
$$a^i = \frac{d^2 \delta x^i}{dt^2} = - R_{bcd}{}^{a} X^c T^b T^d$$

$x^i(t), \quad y^i(t)$

(1,3) tensor

$$\delta x^i = x^i(t) - y^i(t)$$

$$a^i = \frac{d^2 \delta x^i}{dt^2} = -\boxed{R_{bcd}{}^{a}(x)}\, X^c T^b T^d$$


$x^a(t),\ y^a(t)$
$\delta x^a = x^a(t) - y^a(t)$
(1,3) tensor
$= \frac{d^2 \delta x^a}{dt^2} = - \boxed{R_{bcd}{}^a(x)}\, X^c T^b T^d$

$x^a(t)$, $y^a(t)$

(1, 3) tensor

$$\delta x^a = x^a(t) - y^a(t)$$

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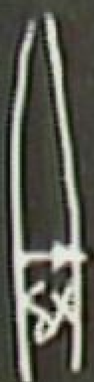

$x^a(t)$, $y^a(t)$

(1,3) tensor

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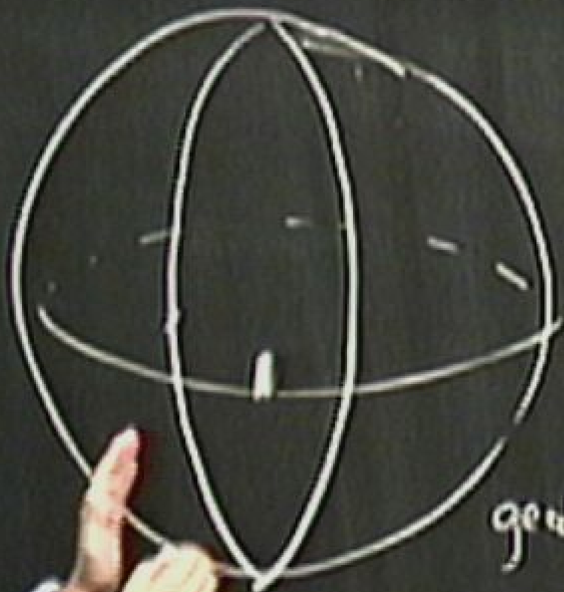

$x^i(t)$

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geodesic $\frac{d^2x^i}{dt^2} + \sum_{j,k} \Gamma^i_{jk}(x)\frac{dx^j}{dt}\frac{dx^k}{dt} = 0$

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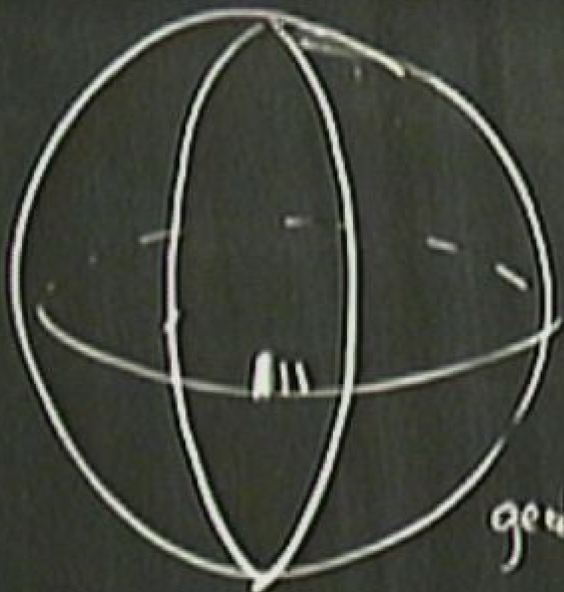

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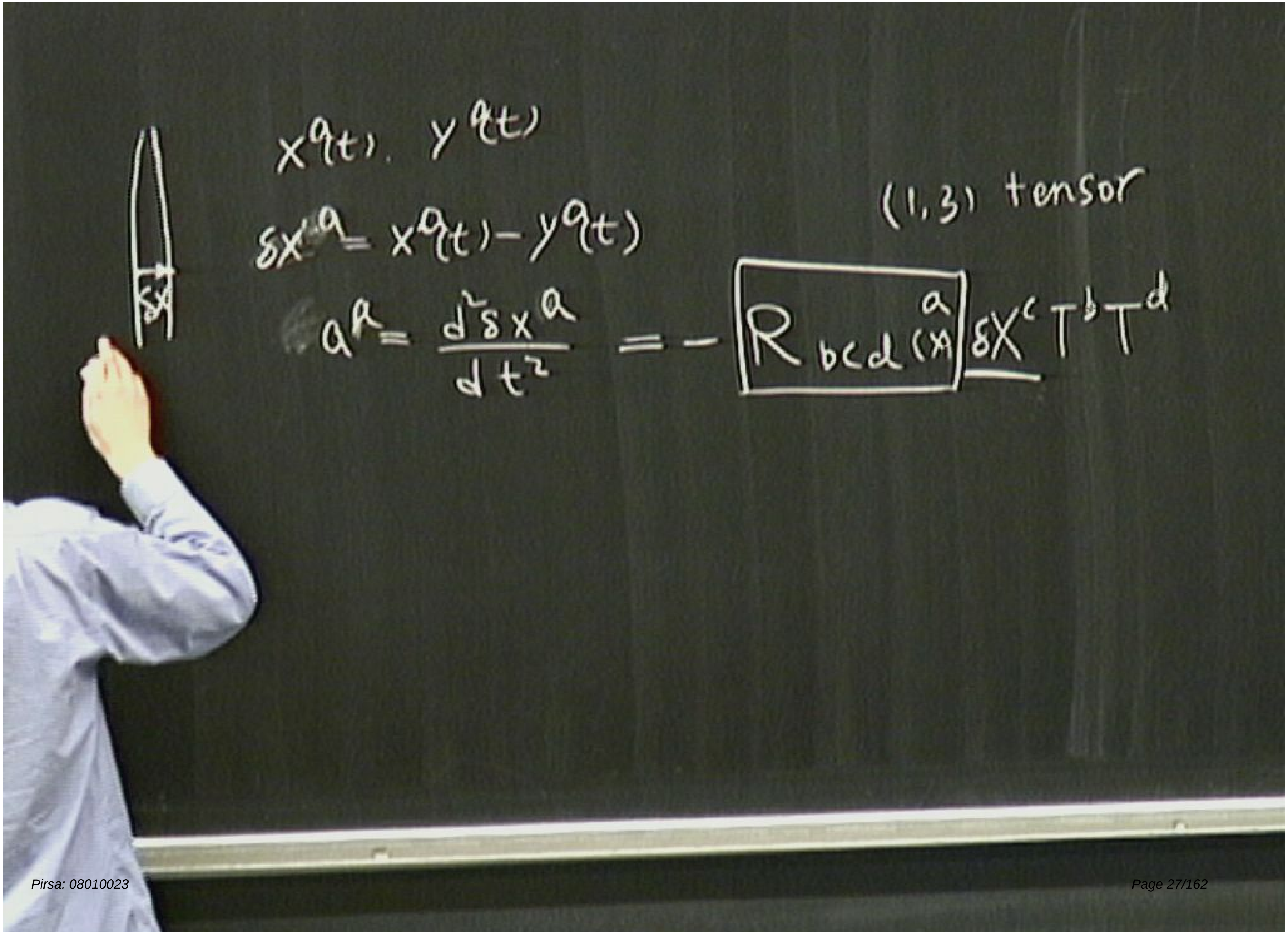
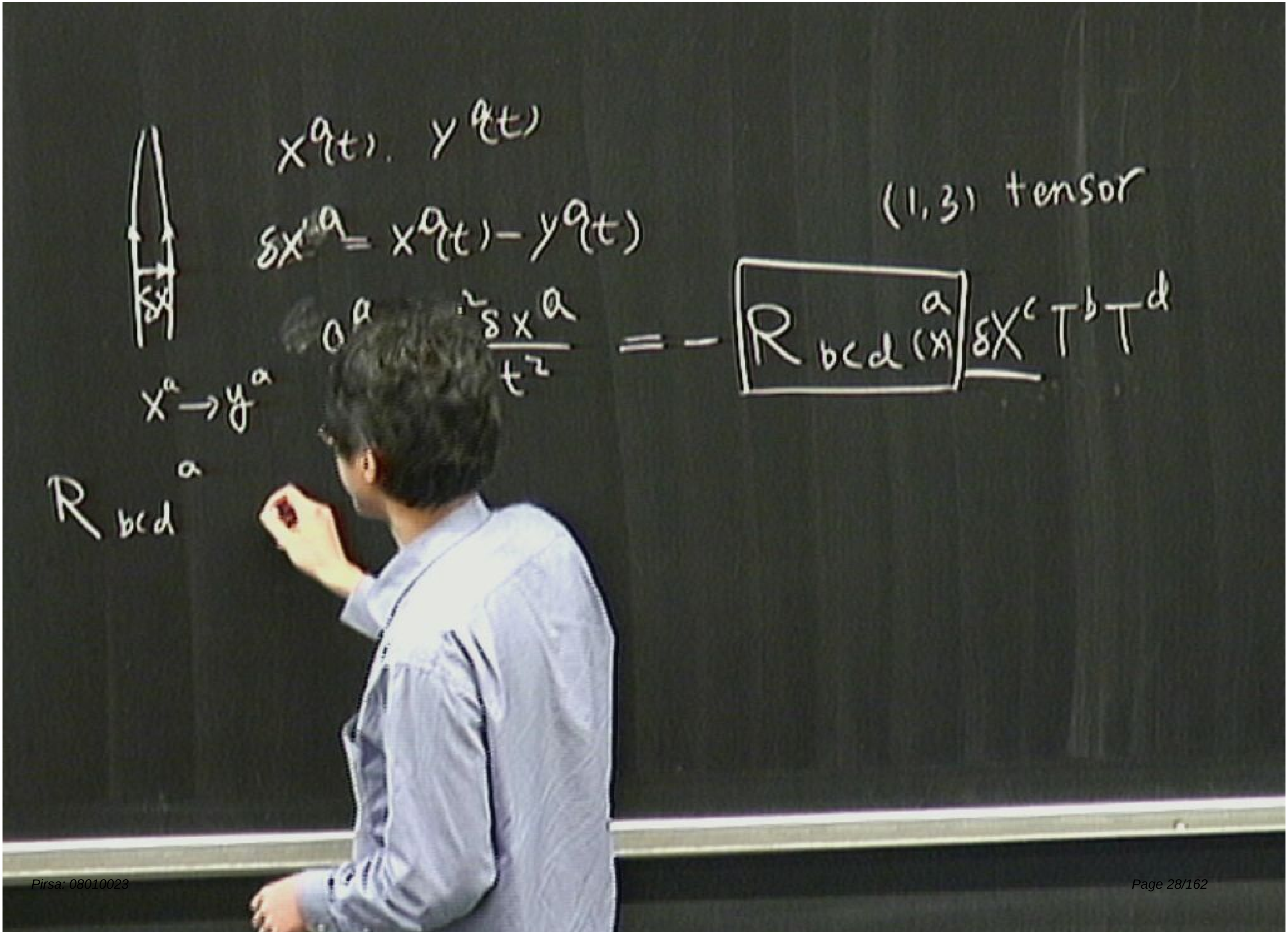
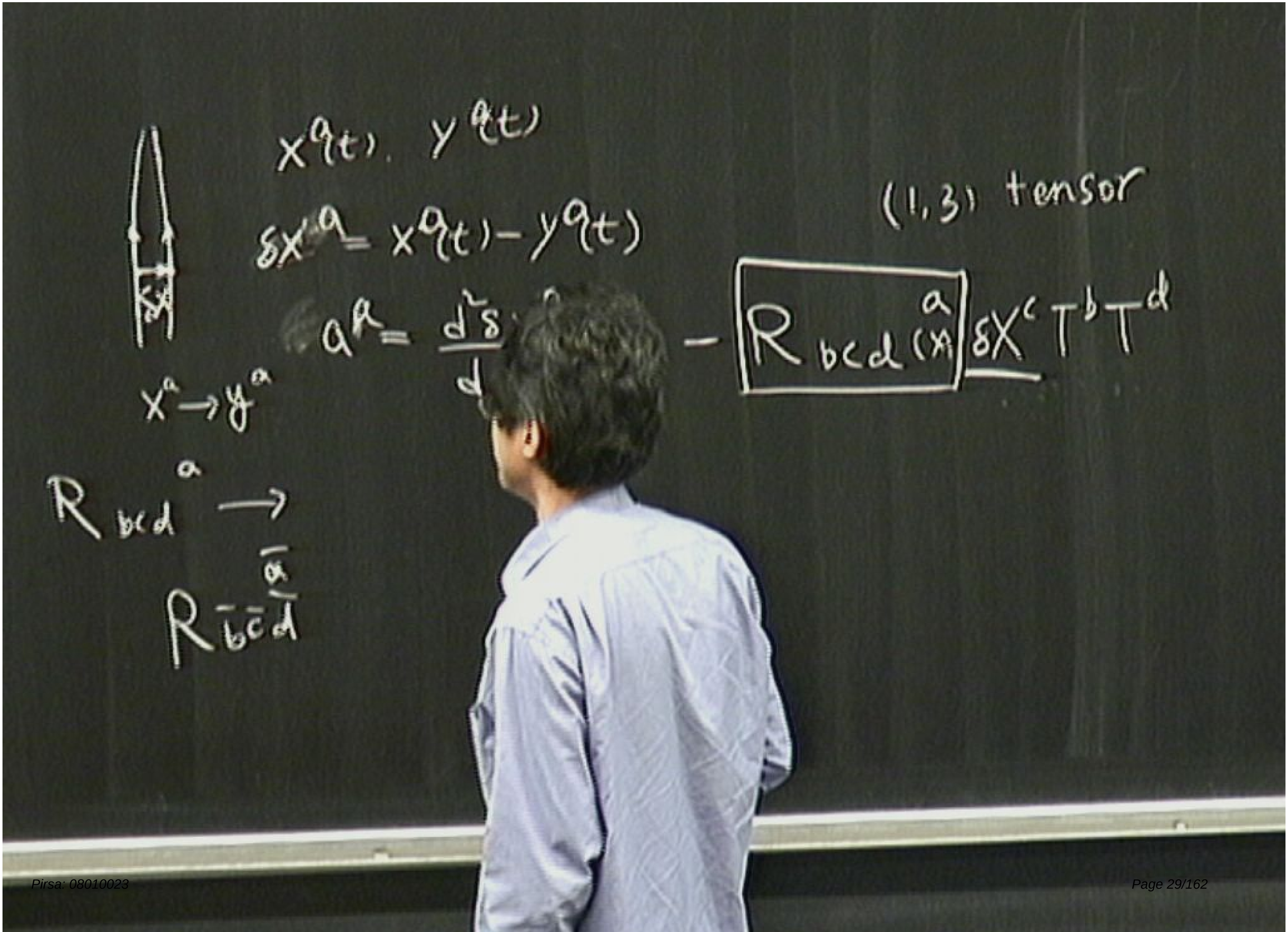

$x^a(t)$, $y^a(t)$
$\delta x^a = x^a(t) - y^a(t)$
(1,3) tensor
$a^a = \frac{d^2 \delta x^a}{dt^2} = -\boxed{R_{bcd}{}^a(x)}\,\underline{\delta X^c}\,T^b T^d$
δx



$x^a(t)$, $y^a(t)$
$\delta x^a = x^a(t) - y^a(t)$
(1,3) tensor
δx
$= -\boxed{R_{bcd}{}^{a}(x)}\,\delta X^c T^b T^d$
$x^a \to y^a$
$R_{bcd}{}^{a}$



x^a(t) y^a(t)
(1,3) tensor
δx^a = x^a(t) − y^a(t)
a^a = d²s / d
R_bcd^a (x) δx^c T^b T^d
x^a → y^a
R_bcd^a →
R_b̄c̄d̄^ā

$x^a(t)$, $y^a(t)$

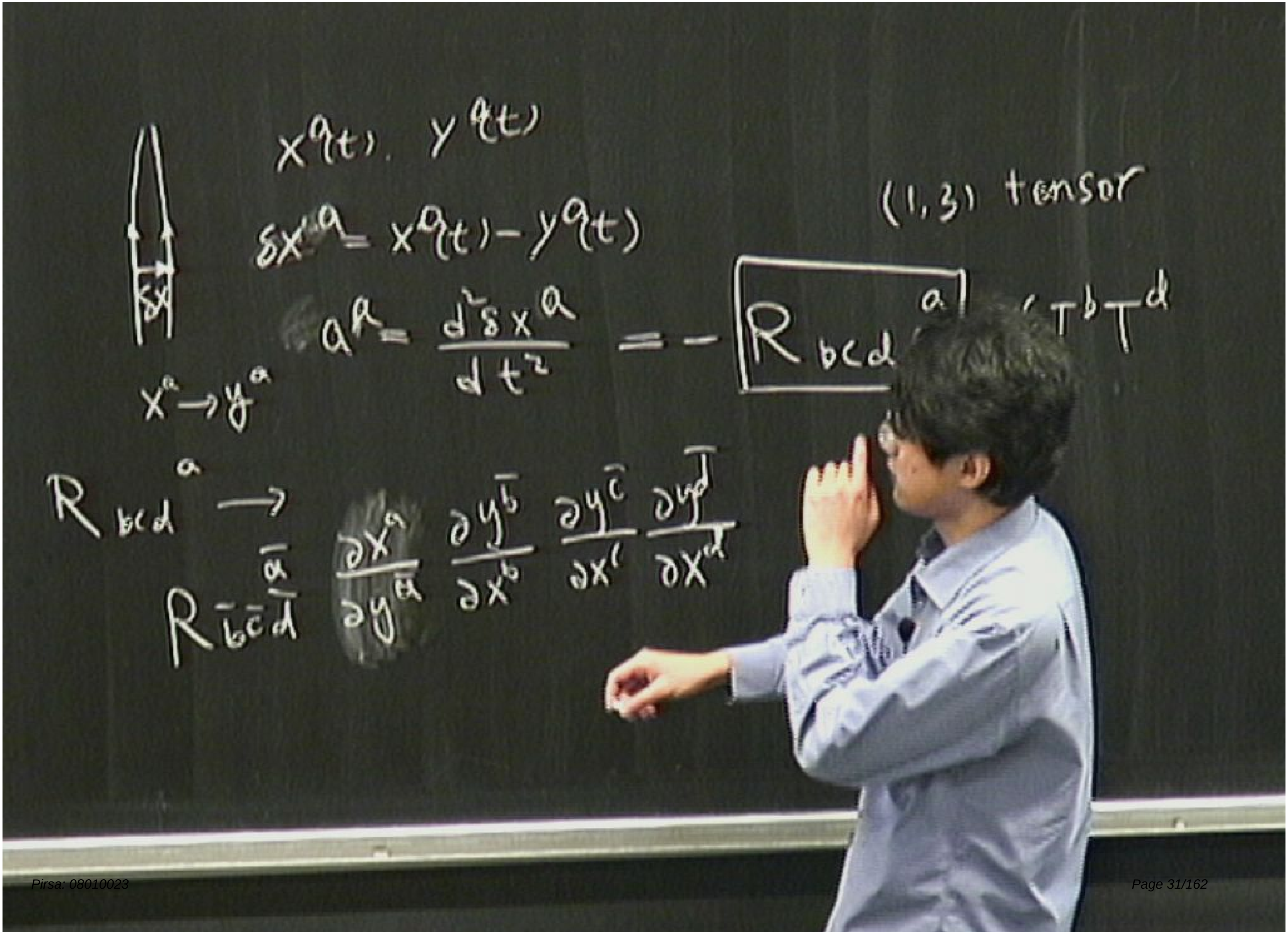
(1,3) tensor

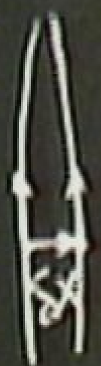
$$\delta x^a = x^a(t) - y^a(t)$$

$$a^a = \frac{d^2 \delta x^a}{dt^2} = -\boxed{R_{bcd}{}^{a}(x)}\,\underline{\delta x^c}\, T^b T^d$$

$x^a \to y^a$

$$R_{bcd}{}^{a} \longrightarrow R_{\bar b \bar c \bar d}{}^{\bar a} \frac{\partial x^a}{\partial y^{\bar a}} \frac{\partial y^{\bar b}}{\partial x^b} \frac{\partial y^{\bar c}}{\partial x^c} \frac{\partial y^{\bar d}}{\partial x^d}$$


$x^a(t),\ y^a(t)$
$(1,3)$ tensor
δx
$\delta x^a = x^a(t) - y^a(t)$
$a^a = \frac{d^2 \delta x^a}{dt^2} = - \boxed{R_{bcd}{}^{a}}\ T^b T^d$
$x^a \to y^a$
$R_{bcd}{}^{a} \longrightarrow$
$R_{\bar b \bar c \bar d}{}^{\bar a} \frac{\partial x^a}{\partial y^{\bar a}} \frac{\partial y^{\bar b}}{\partial x^b} \frac{\partial y^{\bar c}}{\partial x^c} \frac{\partial y^{\bar d}}{\partial x^d}$



$x^a(t)$, $y^a(t)$

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$x^a \to y^a$

$$R_{bcd}{}^{a} \to R_{\bar b \bar c \bar d}{}^{\bar a} \frac{\partial x^a}{\partial y^{\bar a}} \frac{\partial y^{\bar b}}{\partial x^b} \frac{\partial y^{\bar c}}{\partial x^c} \frac{\partial y^{\bar d}}{\partial x^d}$$

$x^a(t)$, $y^a(t)$

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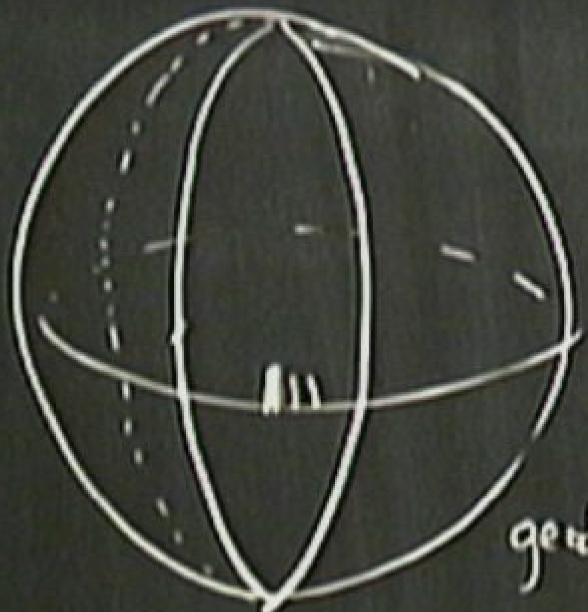
$x^a \to y^a$

$$R_{bcd}{}^{a} \longrightarrow R_{\bar b \bar c \bar d}{}^{\bar a} \frac{\partial x^a}{\partial y^{\bar a}} \frac{\partial y^{\bar b}}{\partial x^b} \frac{\partial y^{\bar c}}{\partial x^c} \frac{\partial y^{\bar d}}{\partial x^d}$$

$x^i(t)$



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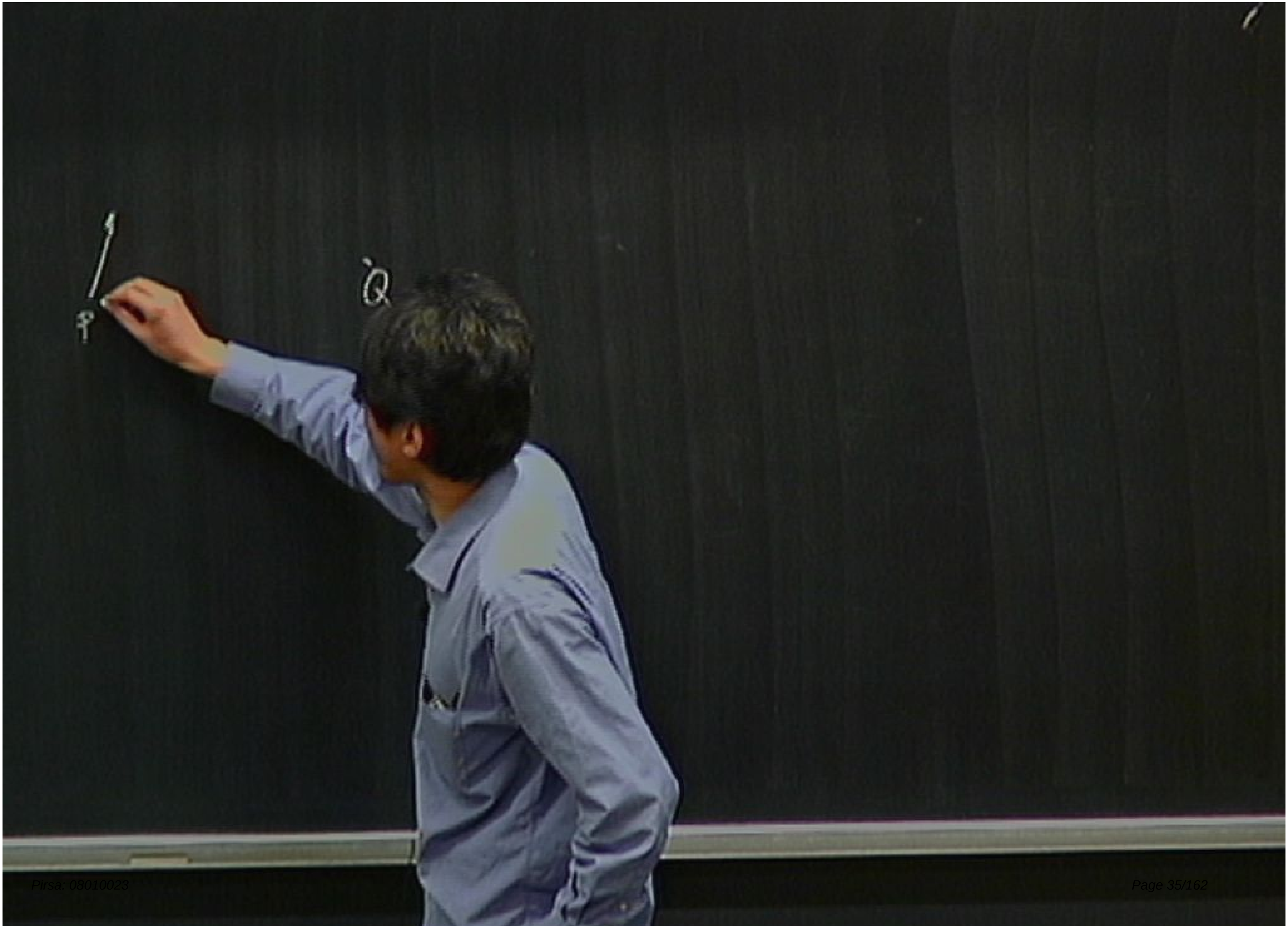
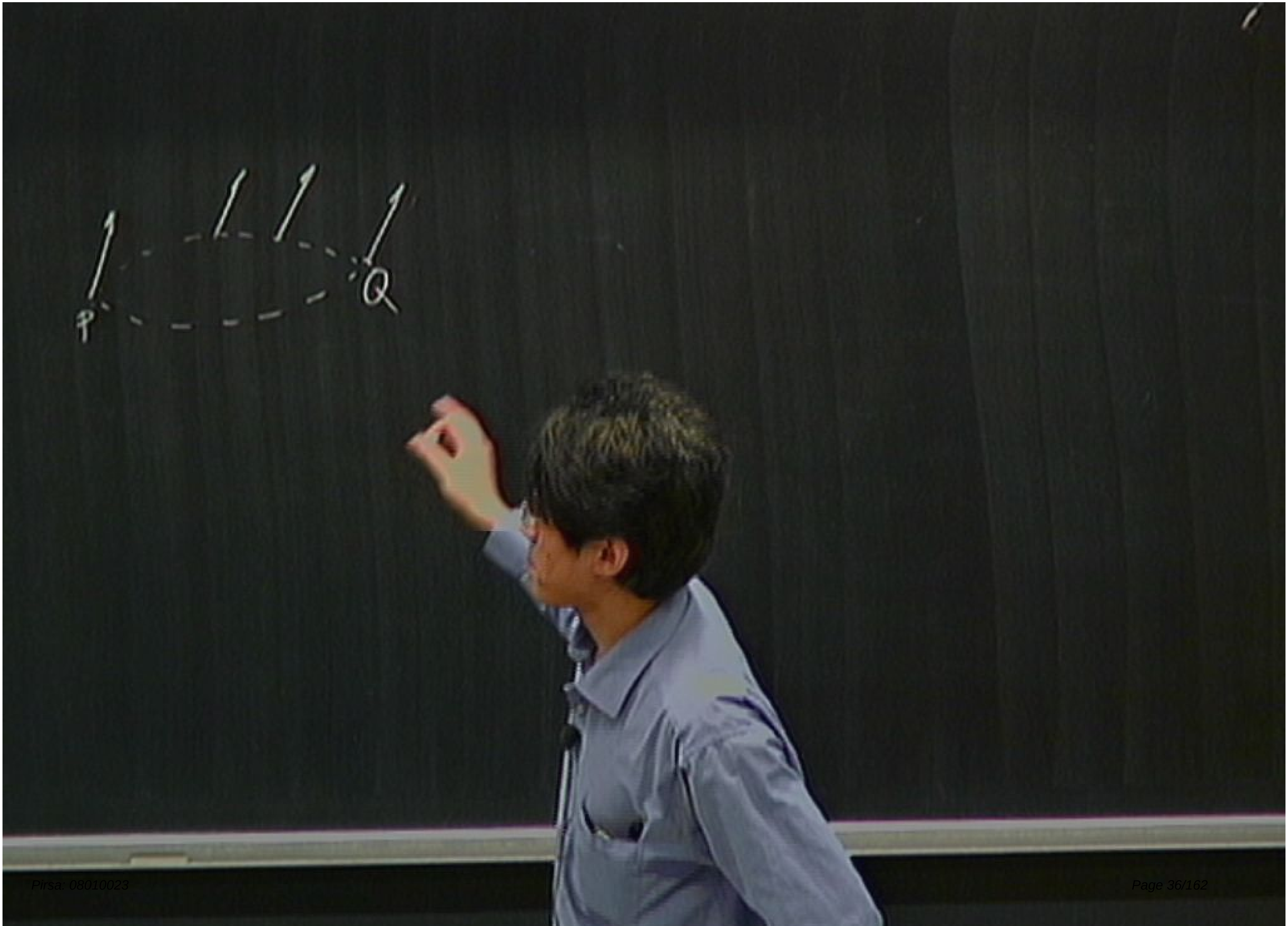
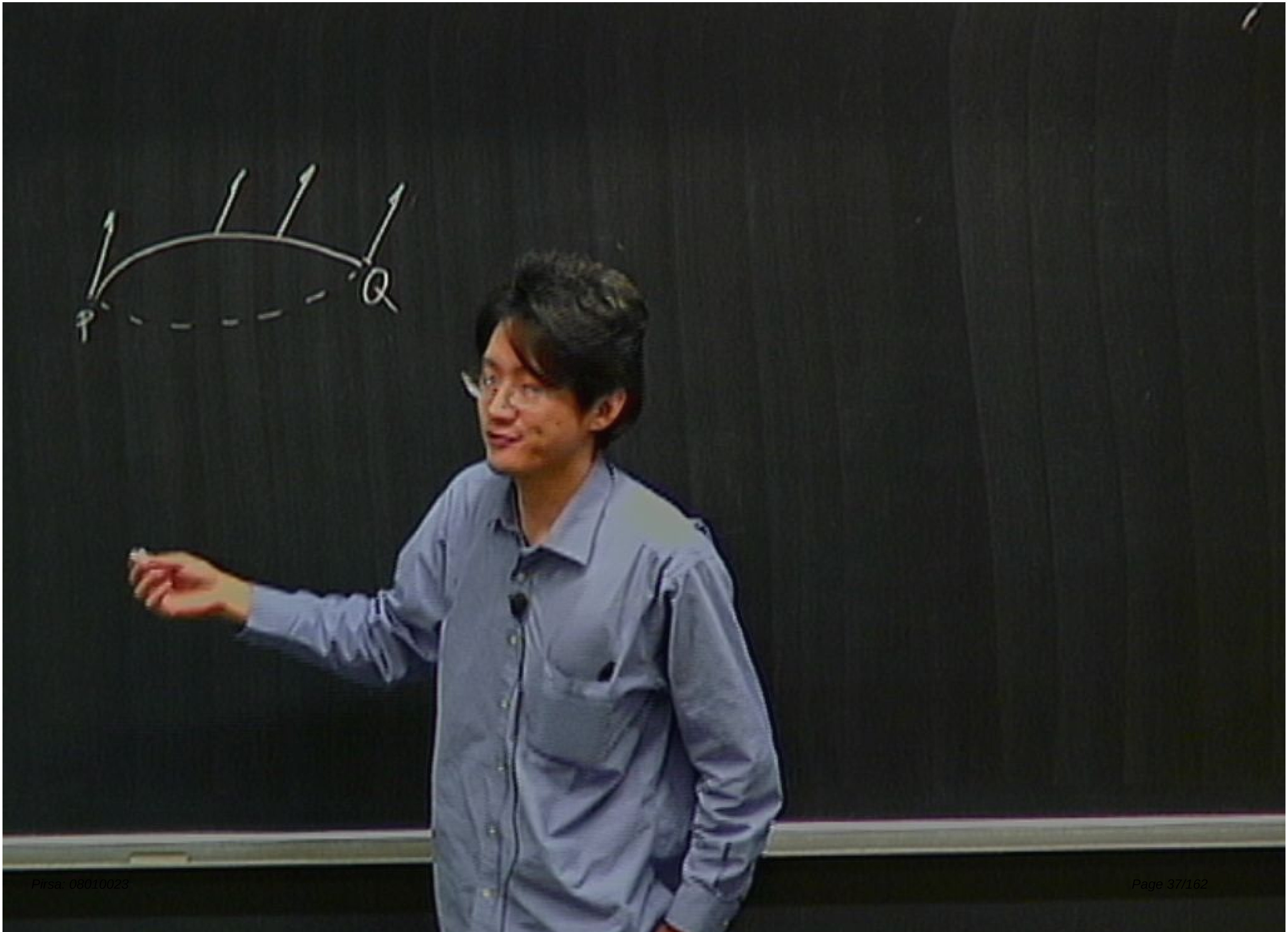
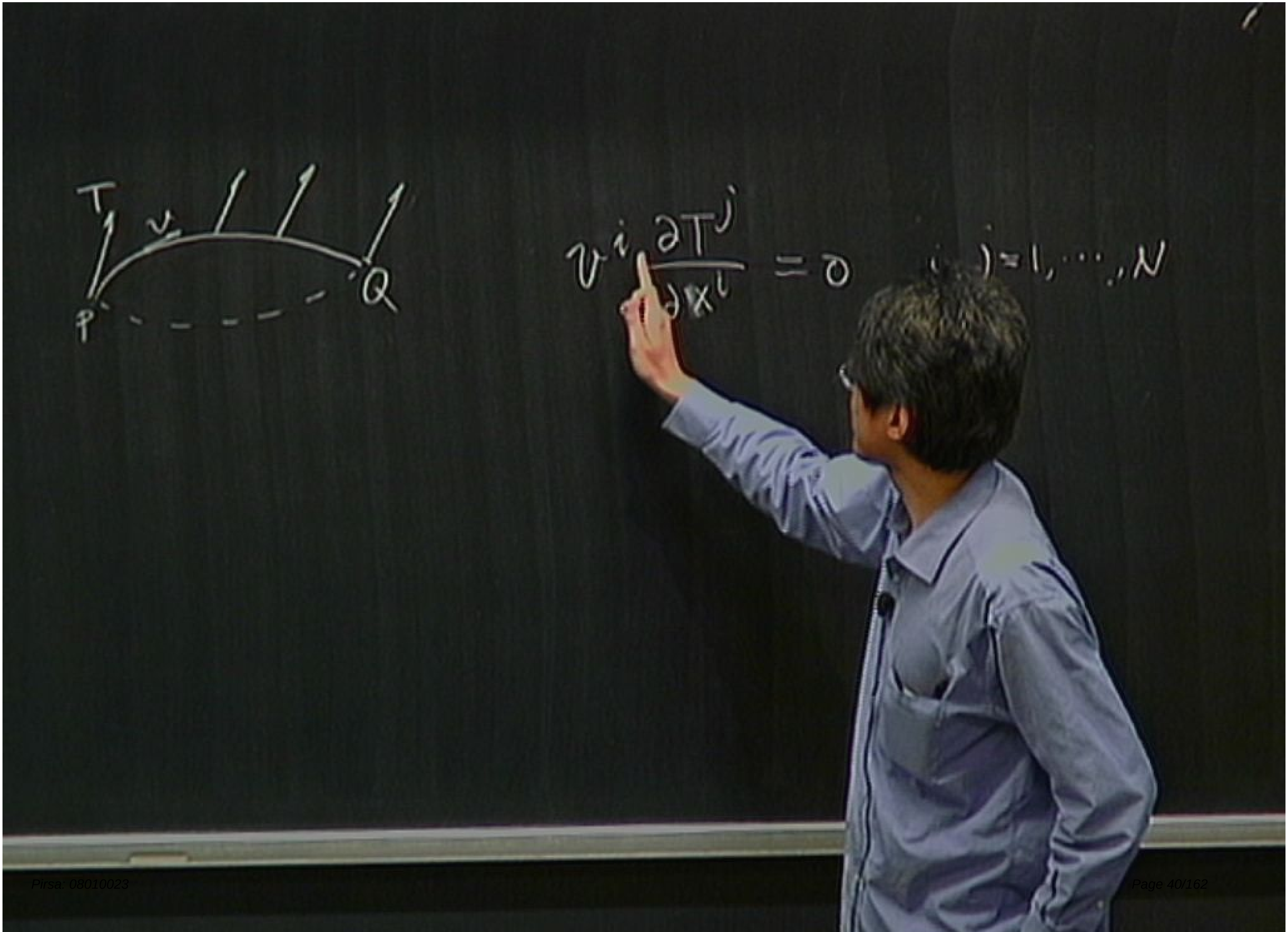

P
Q

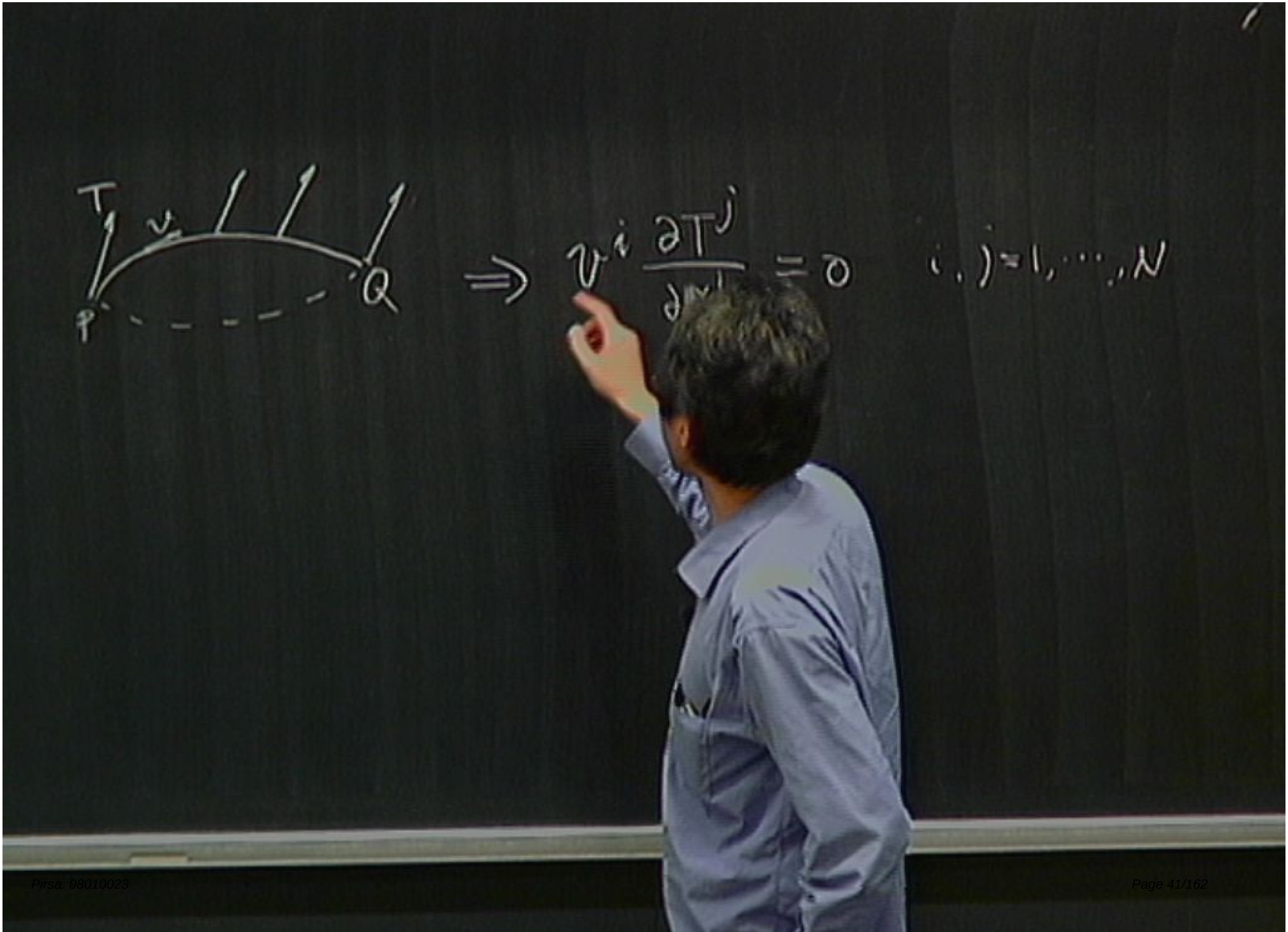

P
Q

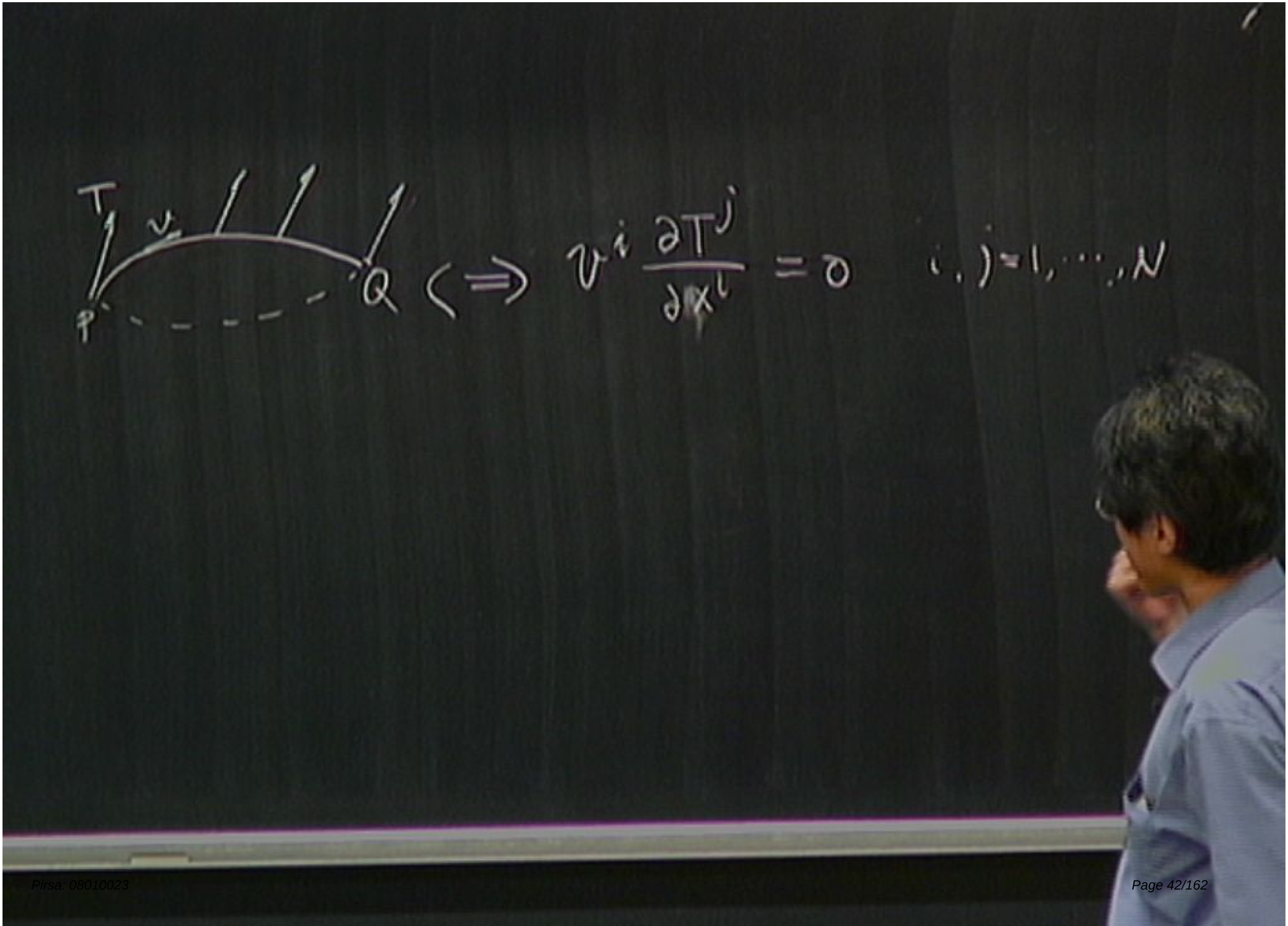

P
Q

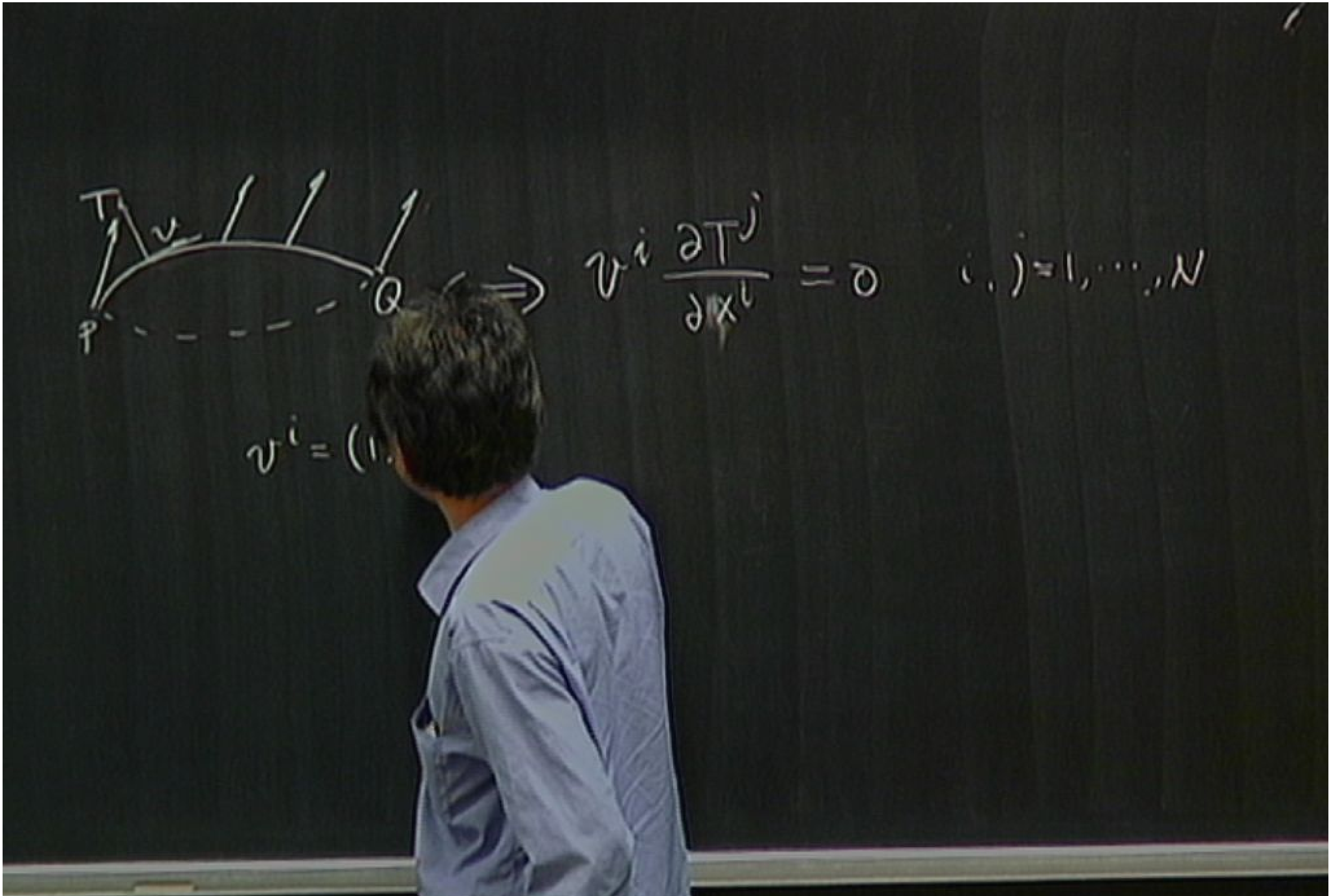
$$v^i \frac{\partial T^j}{\partial x^i} = 0$$

$$v^i \frac{\partial T^j}{\partial x^i} = 0 \qquad i, j = 1, \cdots, N$$


T
v
P
Q
$v^i \frac{\partial T^j}{\partial x^i} = 0 \quad i, j = 1, \cdots, N$


T
v
P
Q
$\Rightarrow v^i \frac{\partial T^j}{\partial x^i} = 0 \quad i, j = 1, \cdots, N$


T
v
P
Q
$\Longleftrightarrow v^i \frac{\partial T^j}{\partial x^i} = 0 \quad i, j = 1, \cdots, N$


T
v
P
Q
$\Longleftrightarrow v^i \frac{\partial T^j}{\partial x^i} = 0 \quad i, j = 1, \cdots, N$

$$\iff \quad v^i \frac{\partial T^j}{\partial x^i} = 0 \qquad i, j = 1, \cdots, N$$

$$v^i = (1, 0, 0, \cdots 0)$$

$$\frac{\partial T^j}{\partial x^1} = 0$$

$$v^i \frac{\partial}{\partial x^i}$$

$$\Longleftrightarrow \quad v^i \frac{\partial T^j}{\partial x^i} = 0 \qquad i, j = 1, \cdots, N$$

$$v^i = (1, 0, 0, \cdots 0) \qquad \frac{\partial T^j}{\partial x^1} = 0$$

$$v^i \frac{\partial}{\partial x^i}$$

$$\Longleftrightarrow \quad v^i \frac{\partial T^j}{\partial x^i} = 0 \qquad i, j = 1, \cdots, N$$

$$v^i = (1, 0, 0, \cdots 0)$$

$$\frac{\partial T^j}{\partial x^1} = 0$$

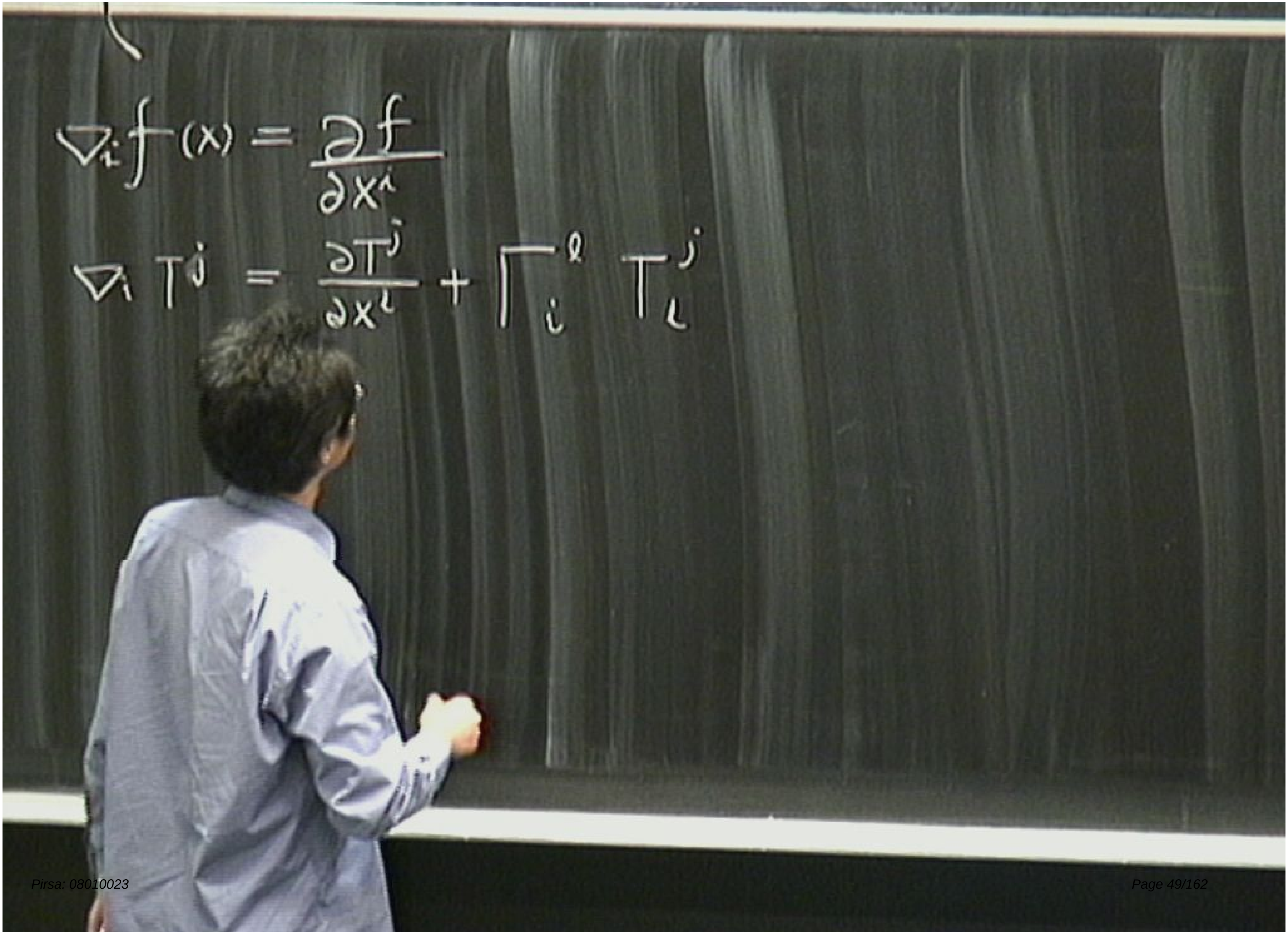
$$v^i \frac{\partial}{\partial x^i} \longrightarrow v^i \nabla_i$$

$$\Longleftrightarrow \quad v^i \frac{\partial T^j}{\partial x^i} = 0 \qquad i, j = 1, \cdots, N$$

$$v^i = (1, 0, 0, \cdots 0) \qquad \frac{\partial T^j}{\partial x^1} = 0$$

$$v^i \frac{\partial}{\partial x^i} \longrightarrow v^i \nabla_i$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$


$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$
$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma_i^{\,l} \, T_l^{\,j}$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma_i^{\,l} \; T_l^{\,j}$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^{j}_{i\ell}\, T^{\ell}_{k}$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{i\ell} T^\ell_k$$

$$\nabla_i T_j$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{i\ell} T^\ell$$

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij} T_k$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{ik} T^k$$

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij} T_k$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

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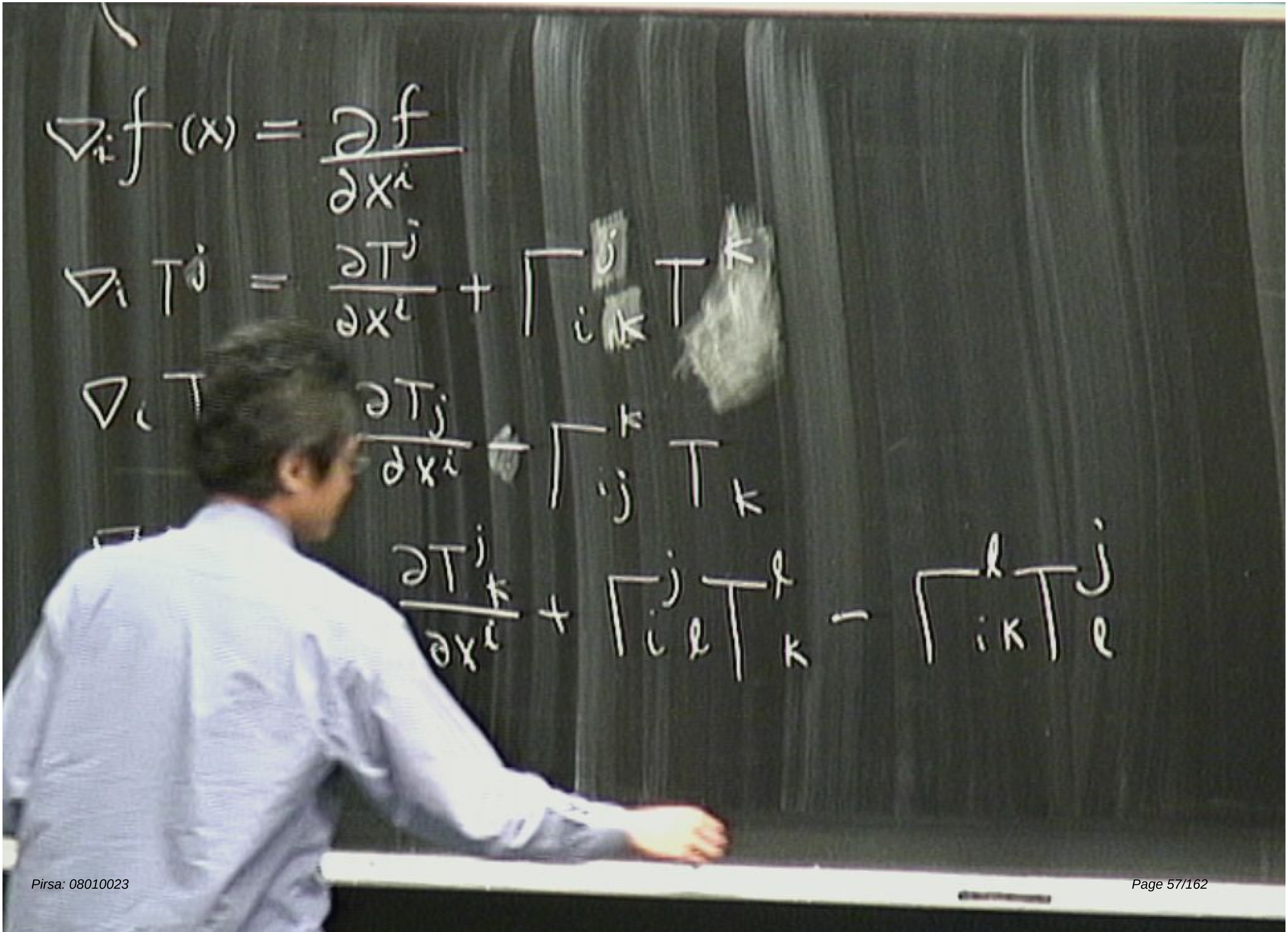
$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij} T_k$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{ik} T^k$$

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij} T_k$$

$$\nabla_i T^j{}_k = \frac{\partial T^j{}_k}{\partial x^i} + \Gamma^j_{il} T^l$$



$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$
$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{ik} T^k$
$\nabla_i T$
$\frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij} T_k$
$\frac{\partial T^j_k}{\partial x^i} + \Gamma^j_{il} T^l_k - \Gamma^l_{ik} T^j_l$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{ik} T^k$$

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij} T_k$$

$$\nabla_i T^j{}_k = \frac{\partial T^j{}_k}{\partial x^i} + \Gamma^j_{il} T^l{}_k - \Gamma^l_{ik} T^j{}_l$$

$$\vdots$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{ik} T^k$$

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij} T_k$$

$$\nabla_i T^j{}_k = \frac{\partial T^j{}_k}{\partial x^i} + \Gamma^j_{i\ell} T^\ell{}_k - \Gamma^\ell_{ik} T^j{}_\ell$$

$$\vdots$$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

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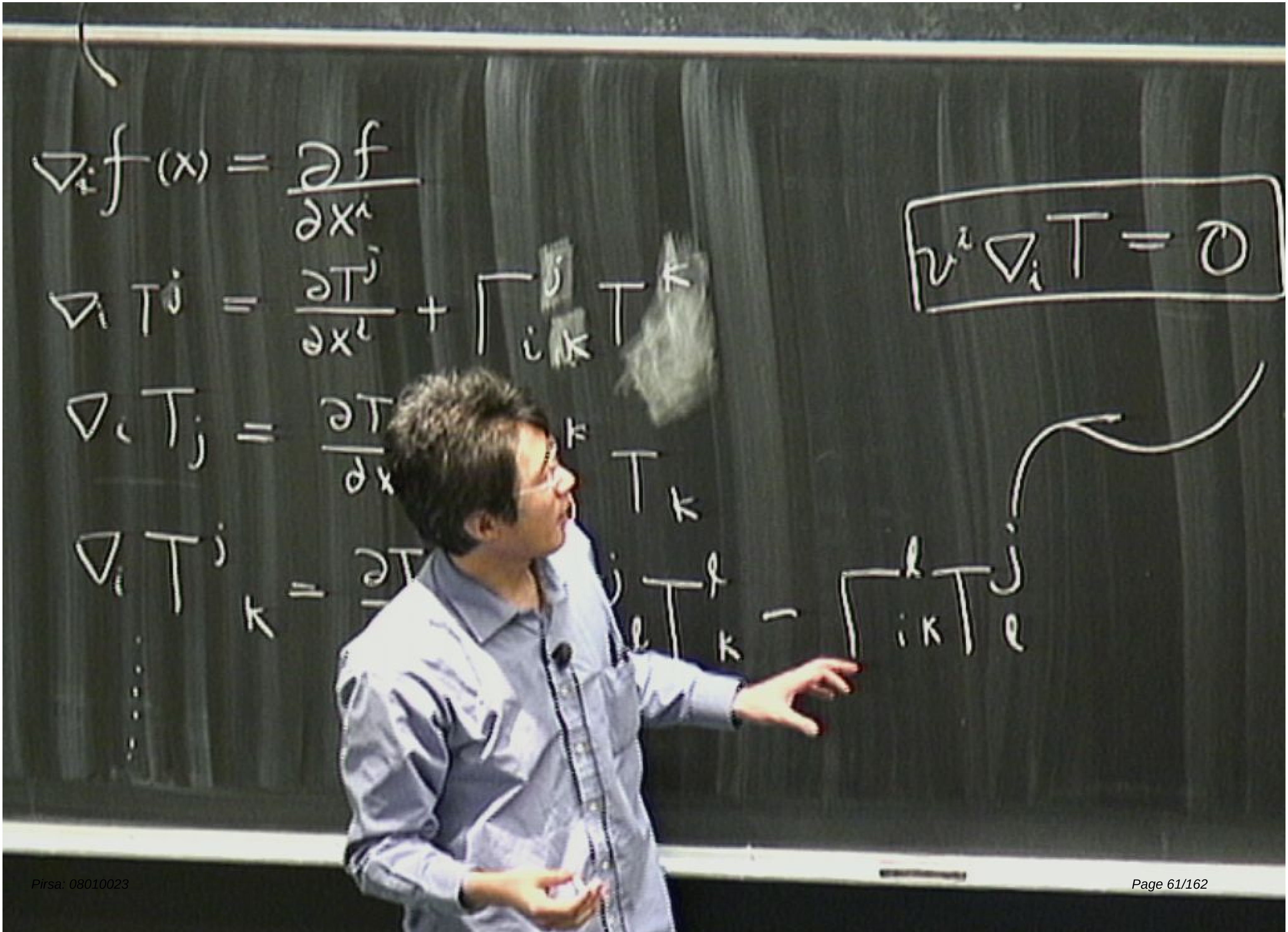
$$\nabla_i T^j{}_k = \frac{\partial T^j{}_k}{\partial x^i} + \Gamma^j_{i\ell} T^\ell{}_k - \Gamma^\ell_{ik} T^j{}_\ell$$

$$\vdots$$


$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$
$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{ik} T^k$
$\boxed{v^i \nabla_i T = 0}$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

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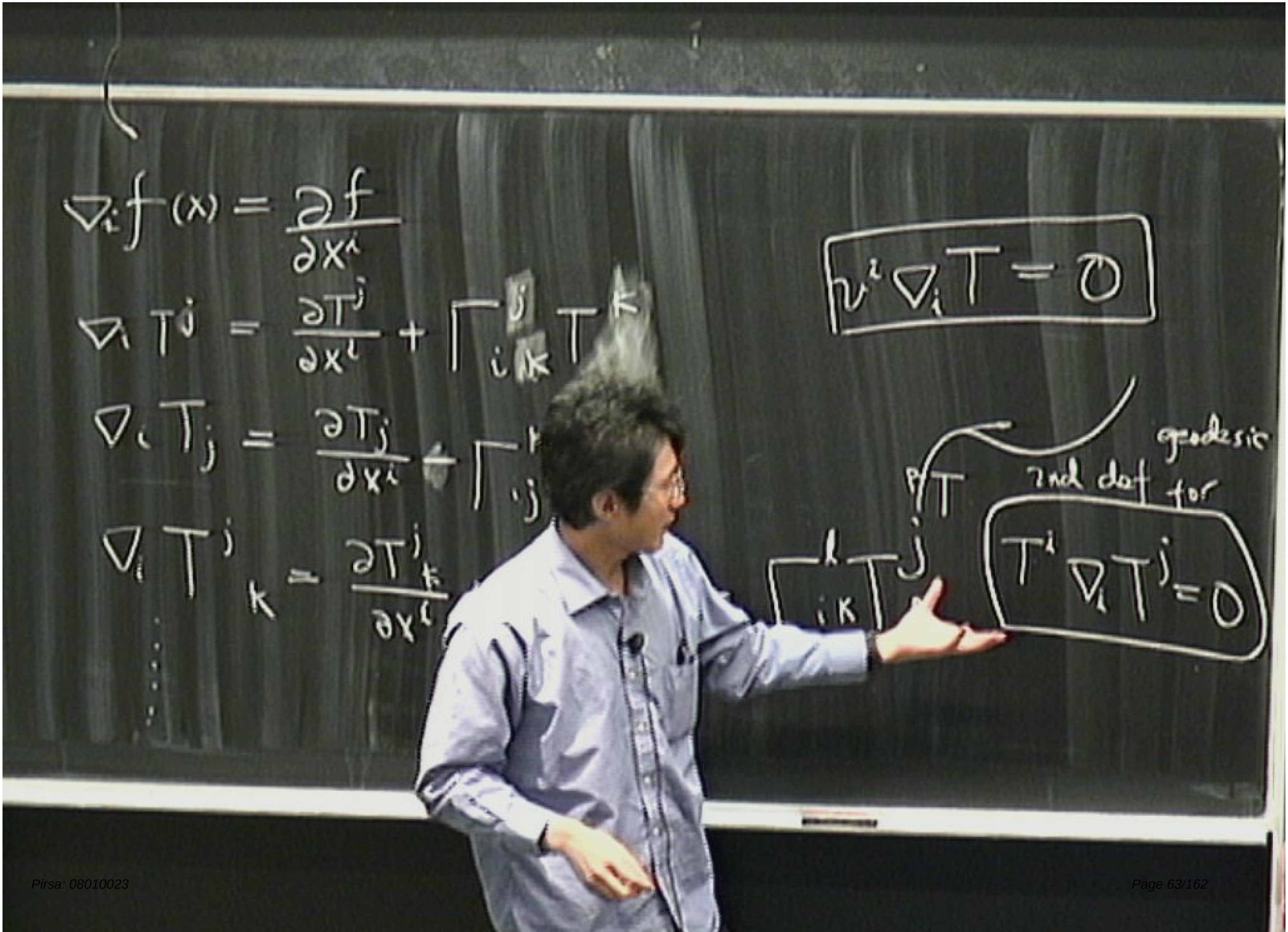


$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$
$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{ik} T^k$
$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij}$
$\nabla_i T^j{}_k = \frac{\partial T^j{}_k}{\partial x^i}$
$\boxed{v^i \nabla_i T = 0}$
geodesic
2nd def for
$\boxed{T^i \nabla_i T^j = 0}$

$$\nabla_i f(x) = \frac{\partial f}{\partial x^i}$$

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma^j_{ik} T^k$$

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma^k_{ij} T_k$$

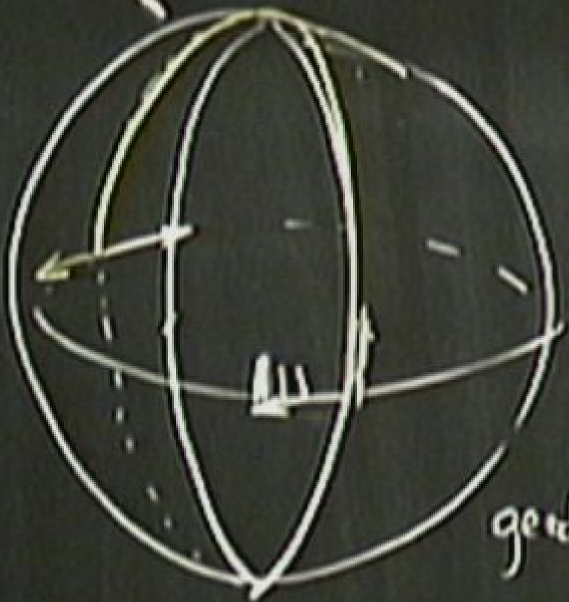
$$\nabla_i T^j{}_k = \frac{\partial T^j{}_k}{\partial x^i} + \Gamma^j_{il} T^l{}_k - \Gamma^l_{ik} T^j{}_l$$

$$\boxed{v^i \nabla_i T = 0}$$

∇T

2nd def for geodesic

$$\boxed{T^i \nabla_i T^j = 0}$$



$$x^i(t)$$

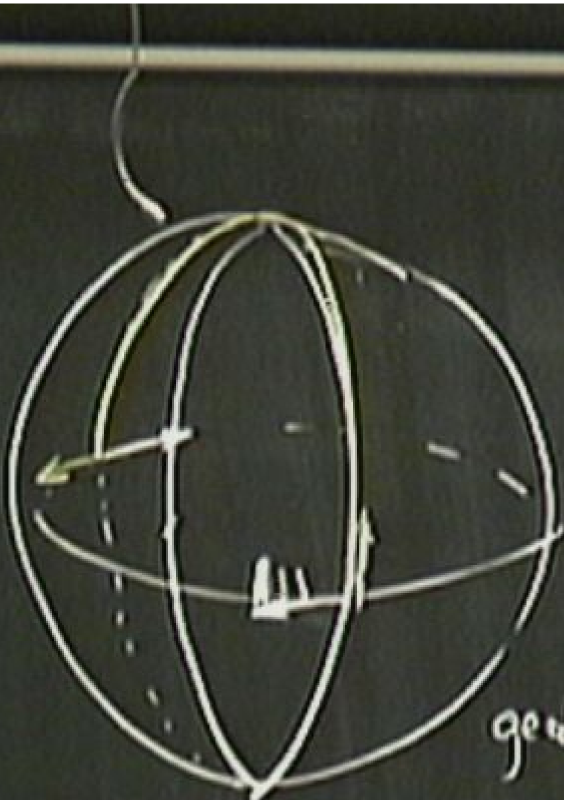
$$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij}\frac{dx^i}{dt}\frac{dx^j}{dt}}$$

minimal length.

geodesic $\frac{d^2x^i}{dt^2} + \sum_{jk} \Gamma^i_{jk}(x) \frac{dx^j}{dt}\frac{dx^k}{dt} = 0$

$x^i = a^i t + b^i$

$$\Gamma^i_{jk} = \frac{1}{2}\sum_\ell g^{i\ell}\left(g_{j\ell,k} + g_{k\ell,j} - g_{jk,\ell}\right)$$



$x^i(t)$

$$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij}\frac{dx^i}{dt}\frac{dx^j}{dt}}$$

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$$\frac{d^2x^i}{dt^2} + \sum_{jk}\Gamma^i_{jk}(x)\frac{dx^j}{dt}\frac{dx^k}{dt} = 0$$

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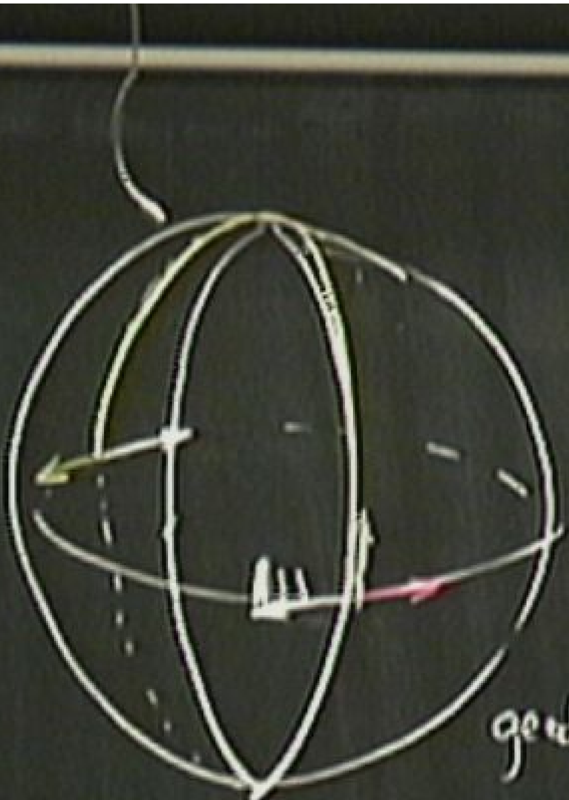

$x^i(t)$

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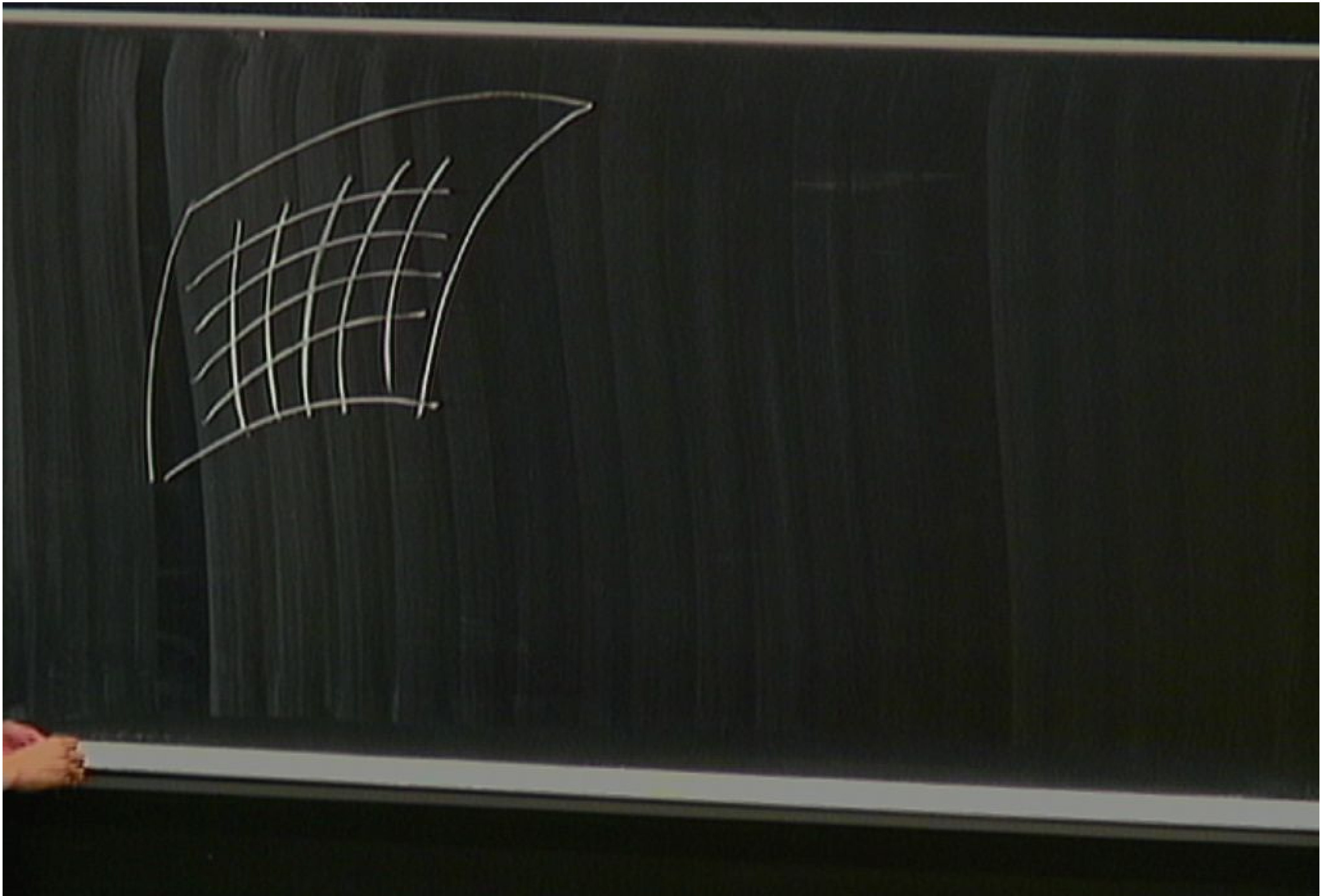
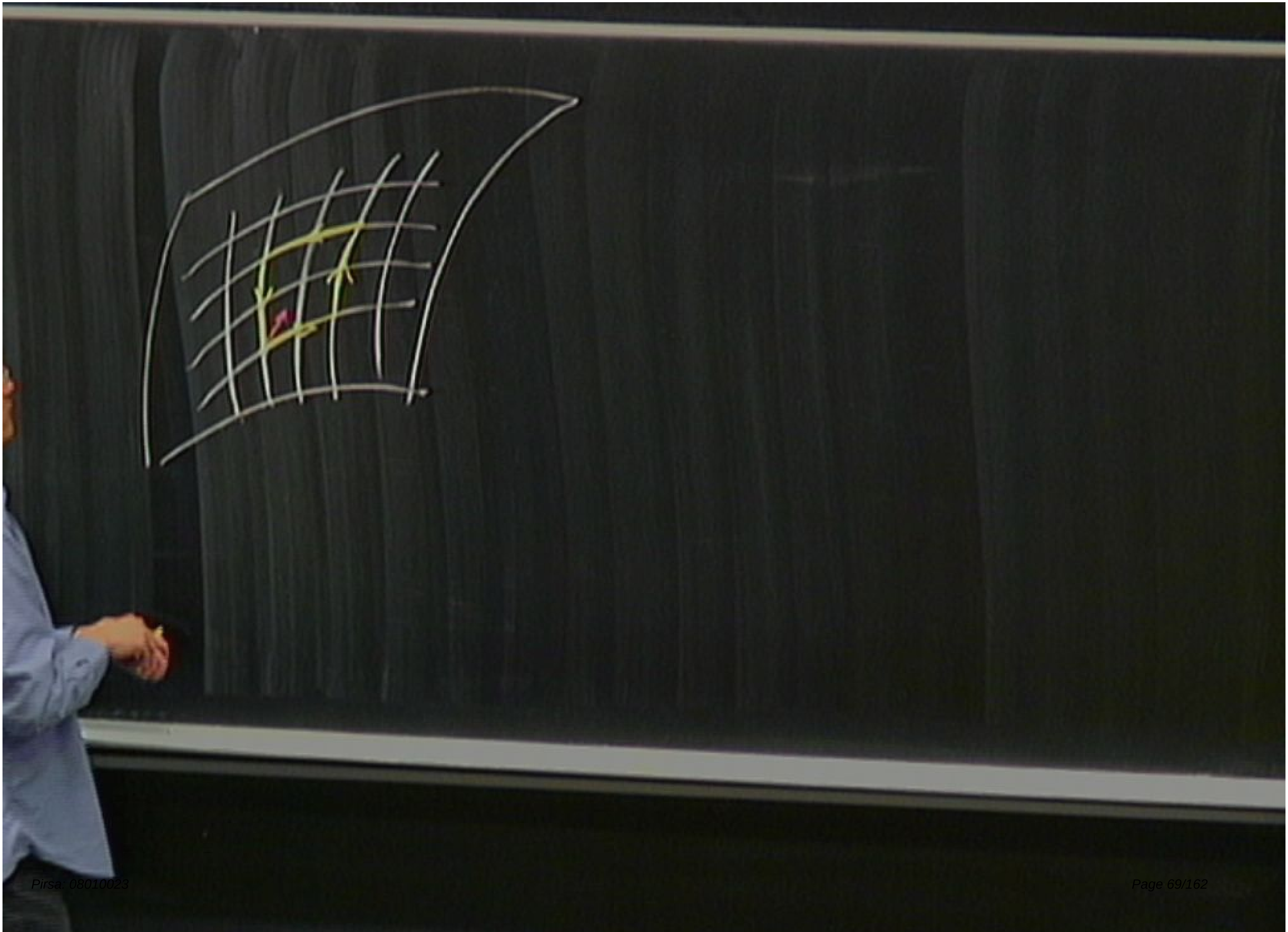
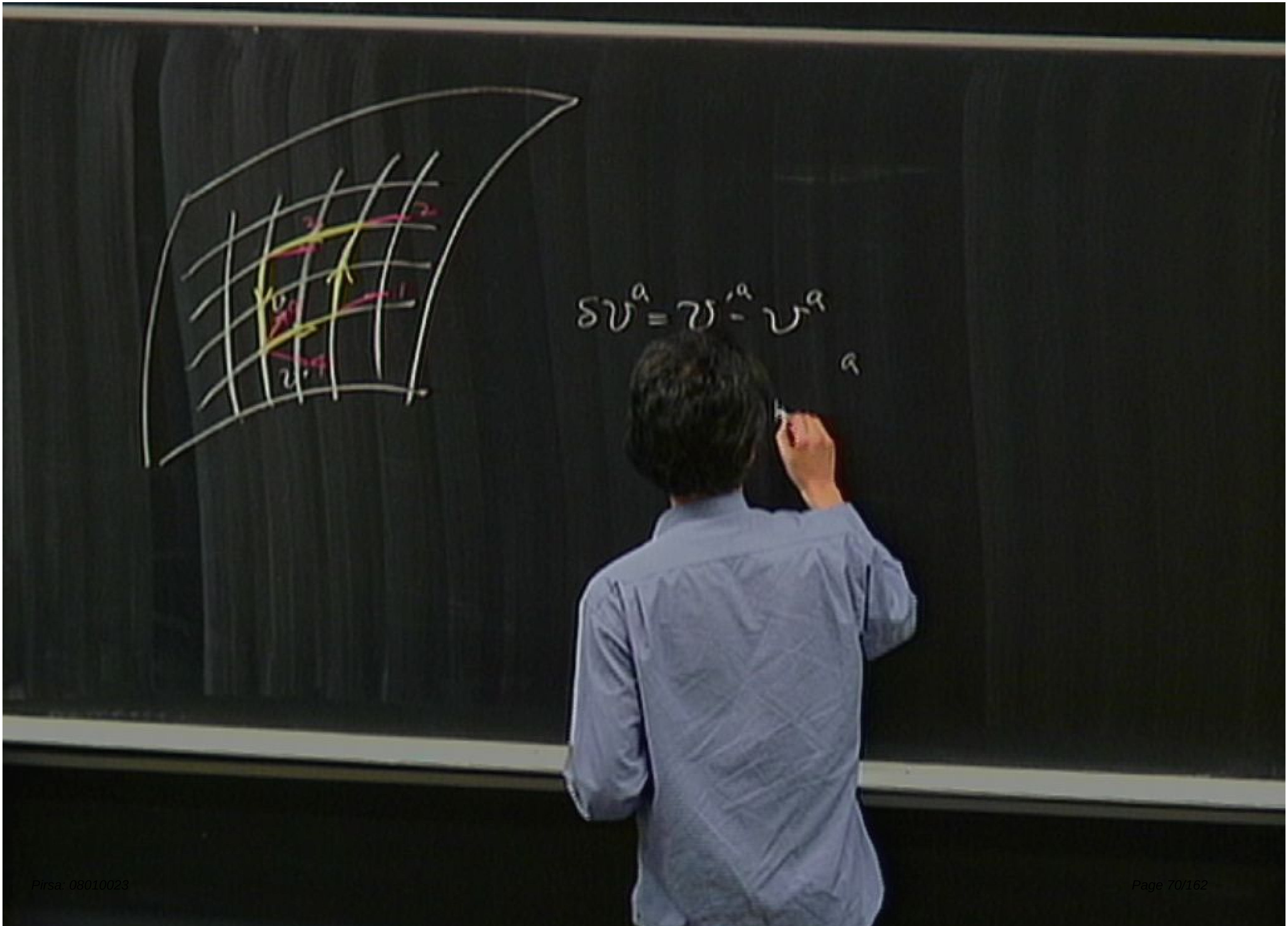
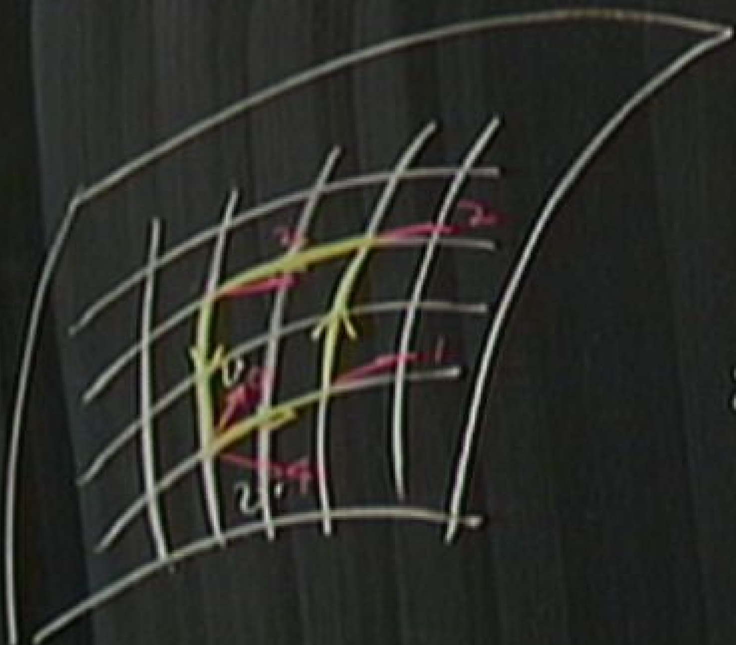




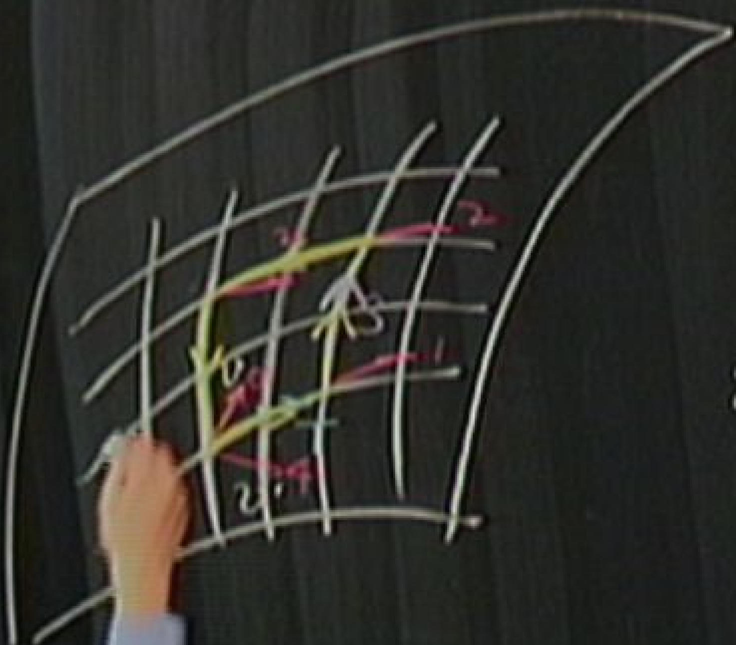

δv^a = v'^a - v^a



$$\delta v^a = v'^a - v^a$$

$$= R_{bcd}{}^a T^b S^c v^d \Delta s \Delta t$$

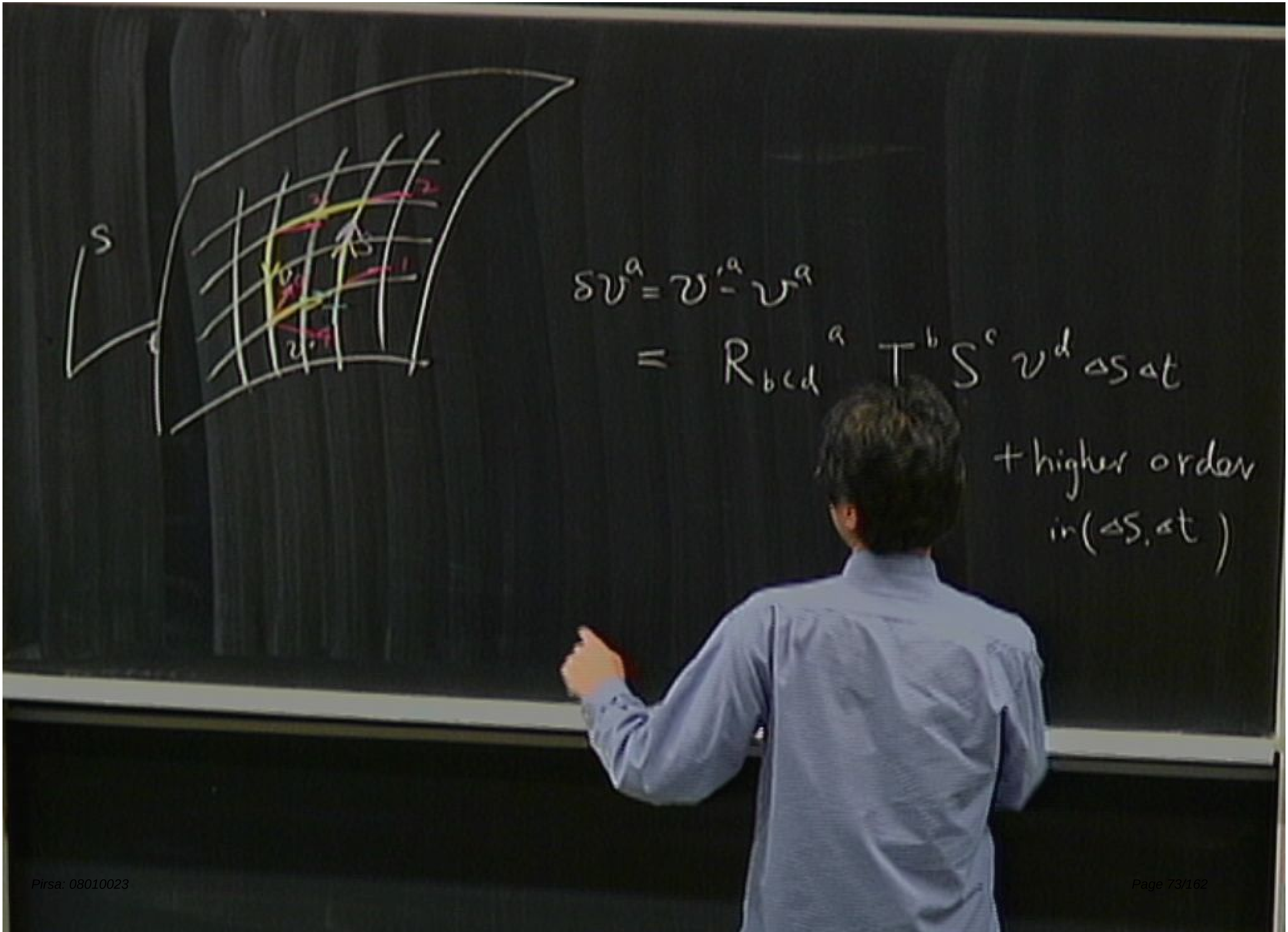
+ higher order in ($\Delta s, \Delta t$)

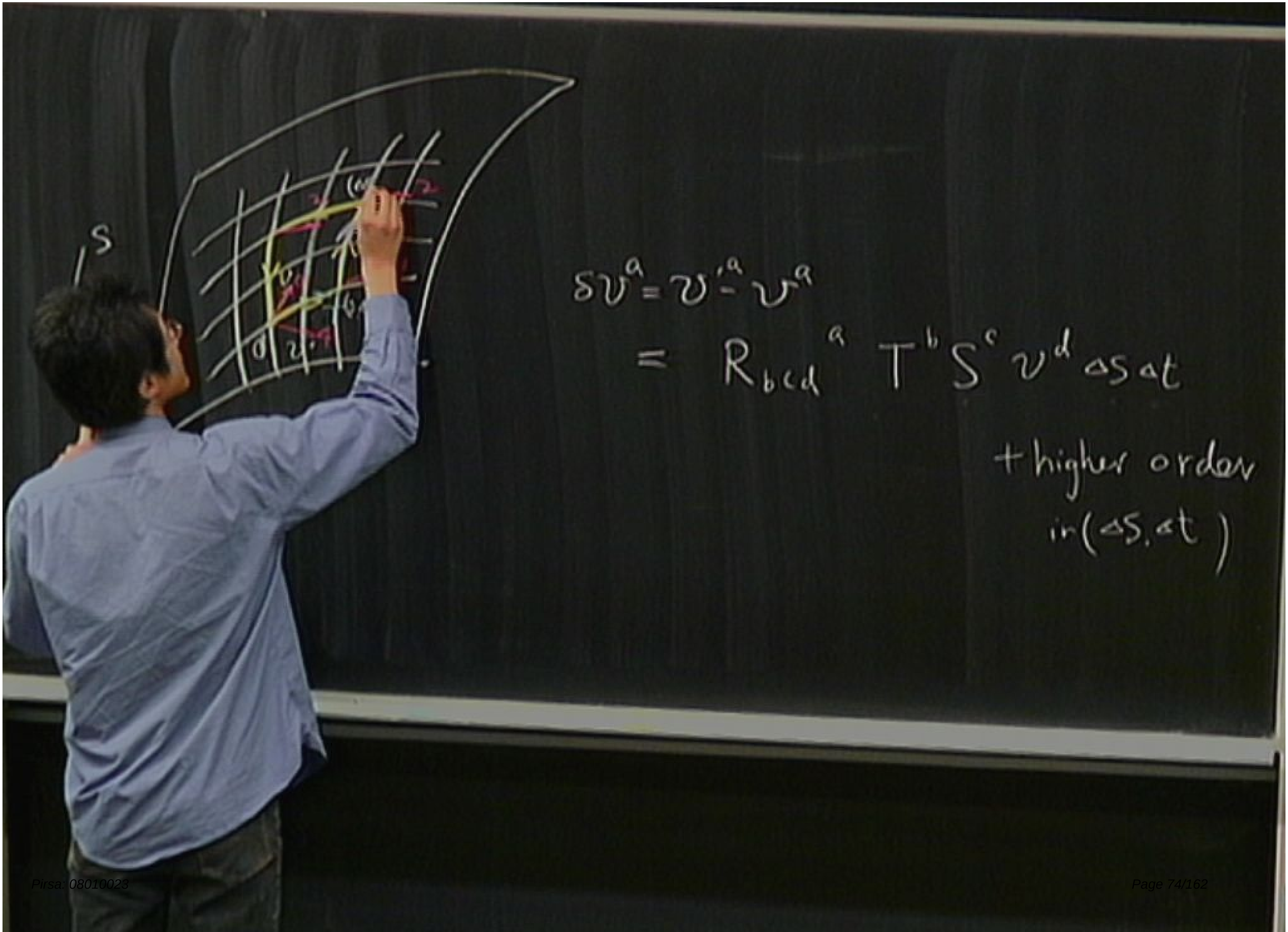


$$\delta v^a = v'^a - v^a$$

$$= R_{bcd}{}^{a}\, T^b S^c v^d \,\Delta s\, \Delta t$$

$$+ \text{higher order in } (\Delta s, \Delta t)$$


S
$\delta v^a = v'^a - v^a$
$= R_{bcd}{}^a T^b S^c v^d \Delta s \Delta t$
+ higher order
in $(\Delta s, \Delta t)$


S
$\delta v^a = v'^a - v^a$
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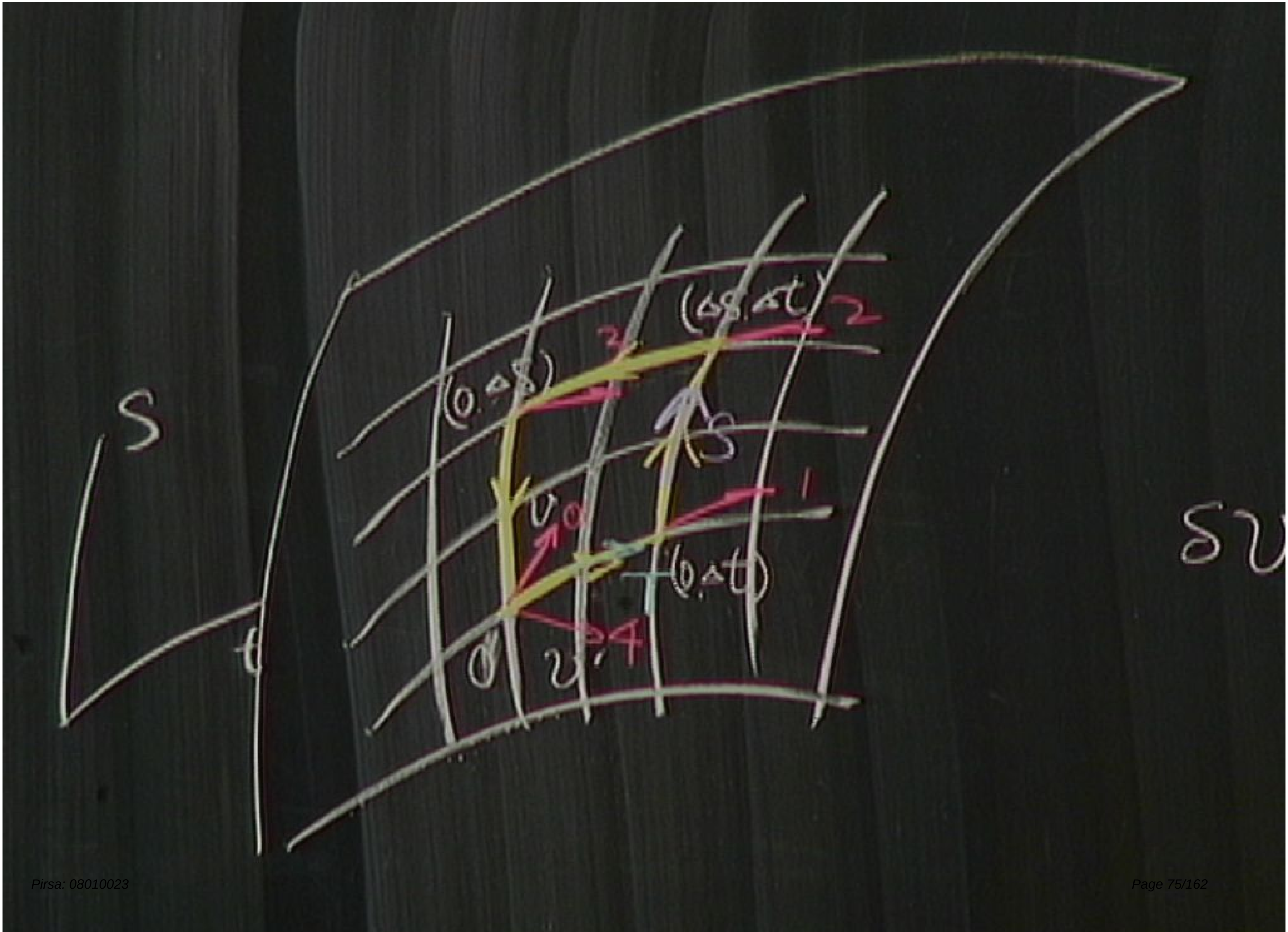
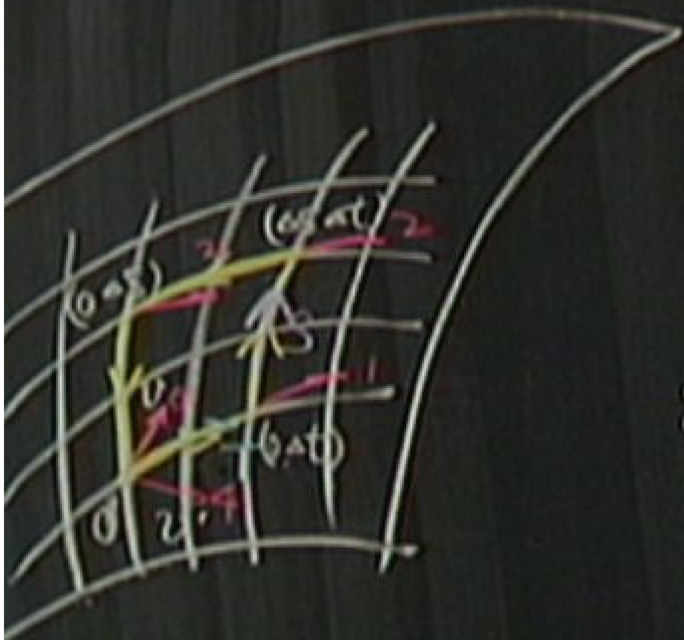

S
(0,Δs)
(Δs,Δt)
(0,Δt)



$$\delta v^a = v'^a - v^a$$

$$= R_{bcd}{}^{a}\, T^b S^c v^d \,\Delta s\, \Delta t$$

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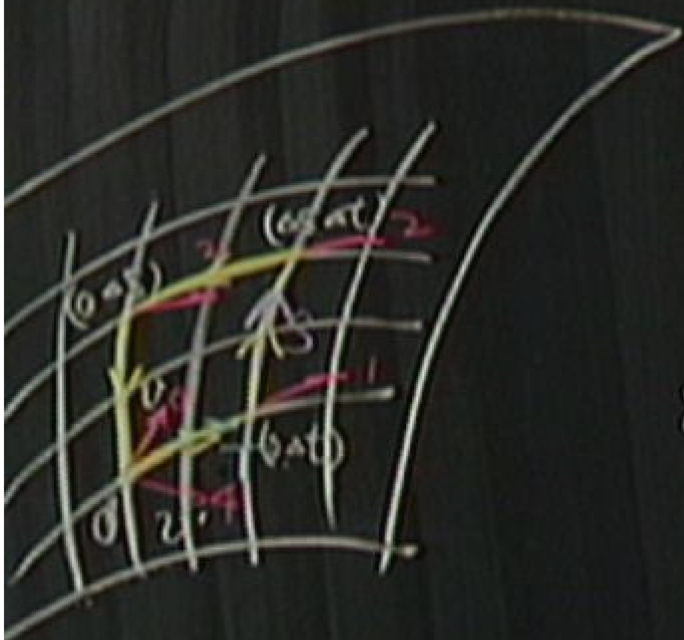
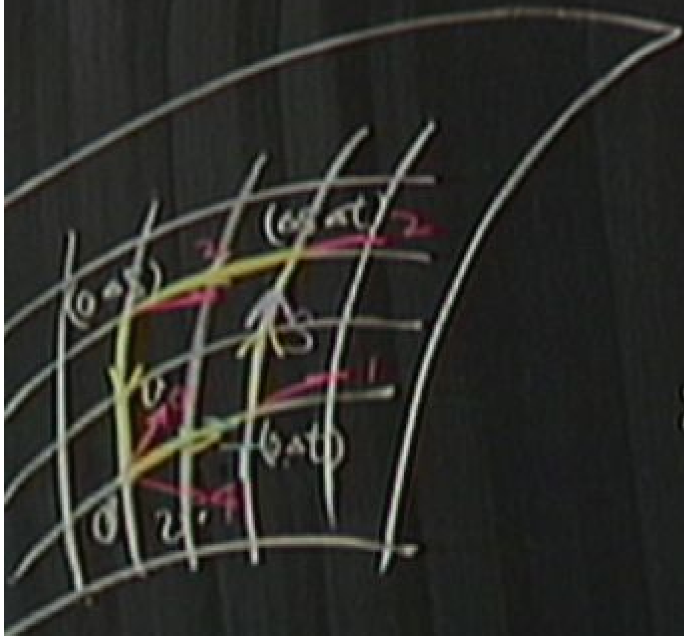


$$\delta v^a = v'^a - v^a$$

$$= \boxed{R_{bcd}{}^{a}}\, T^b S^c v^d \,\Delta s\, \Delta t$$

$$+ \text{higher order in} (\Delta s, \Delta t)$$



$$\delta v^a = v'^a - v^a$$

$$= \boxed{R_{bcd}{}^{a}}\, T^b S^c v^d \,\Delta s\, \Delta t$$

$$+ \text{higher order in } (\Delta s, \Delta t)$$

Riemann curvature tensor

$$\nabla^2 \phi = -4\pi G_N \rho$$

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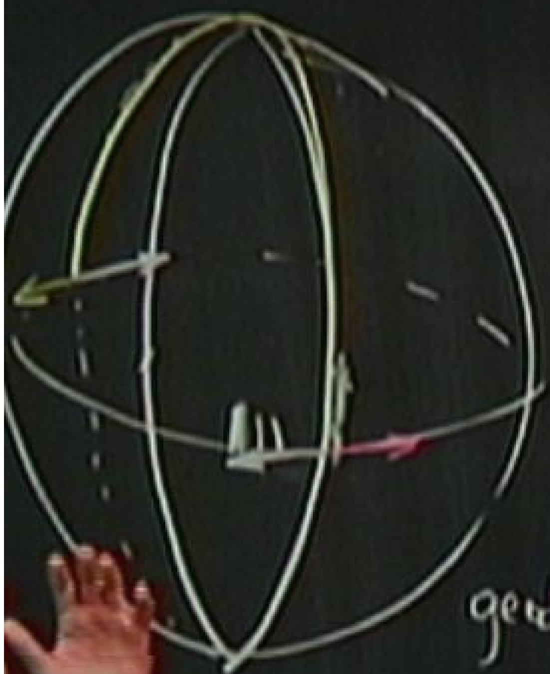
$$g_{\mu\nu}$$

$$\nabla^2 \phi = -4\pi G_N \rho$$

$$g_{\mu\nu}$$



$$x^i(t)$$

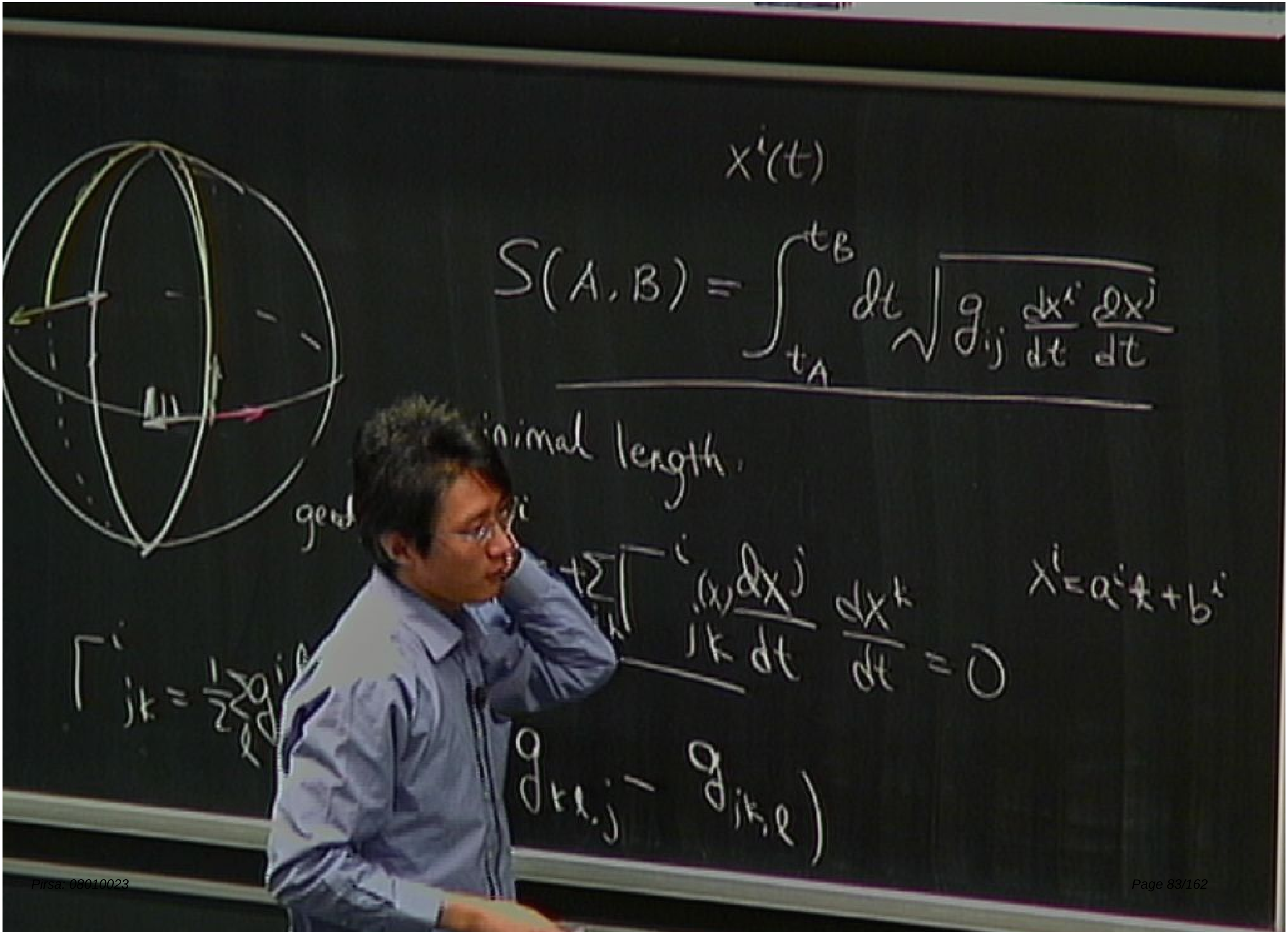
$$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$$

minimal length.

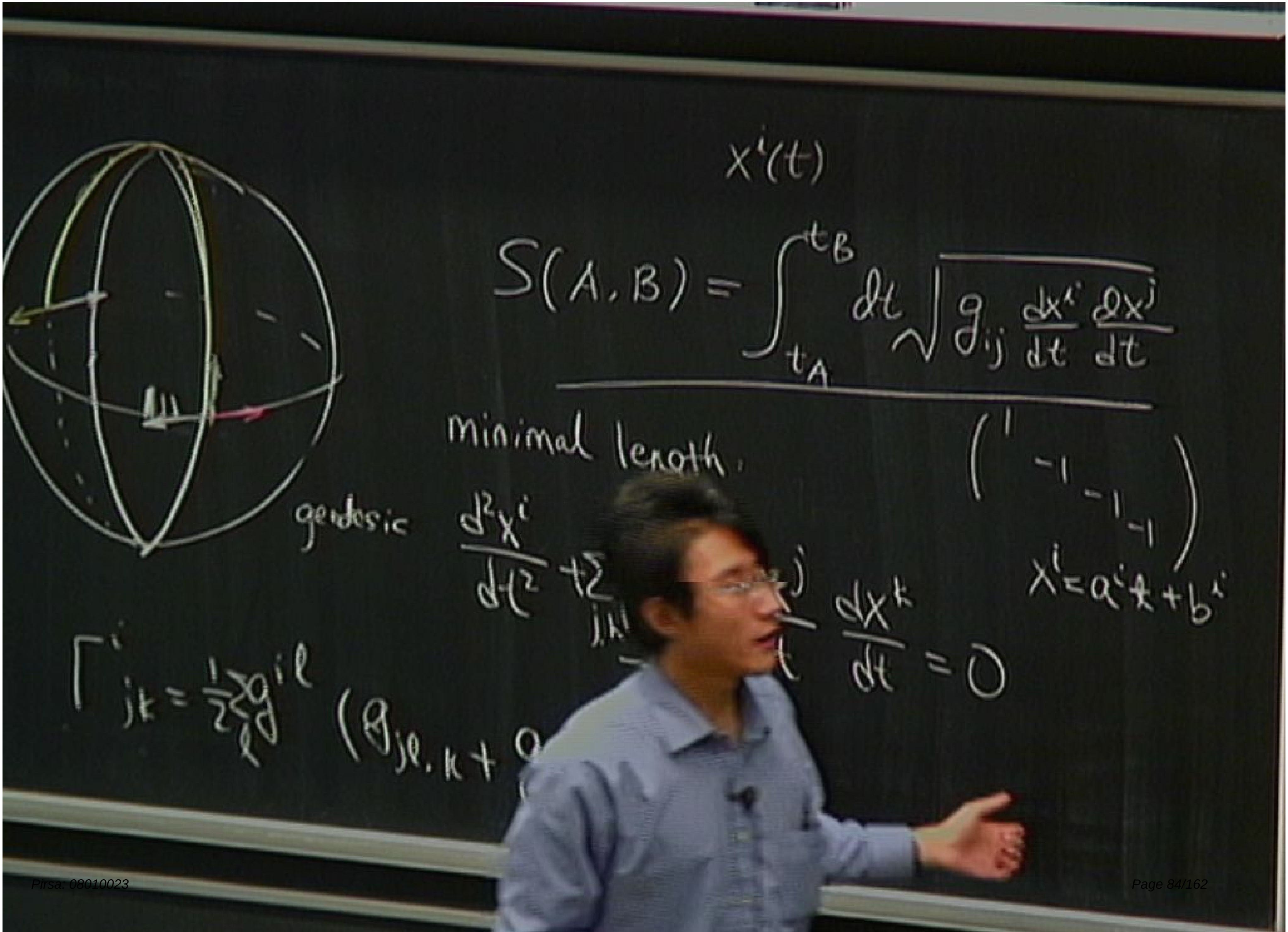
geodesic $$\frac{d^2x^i}{dt^2} + \sum_{jk} \Gamma^i_{jk}(x) \frac{dx^j}{dt} \frac{dx^k}{dt} = 0$$

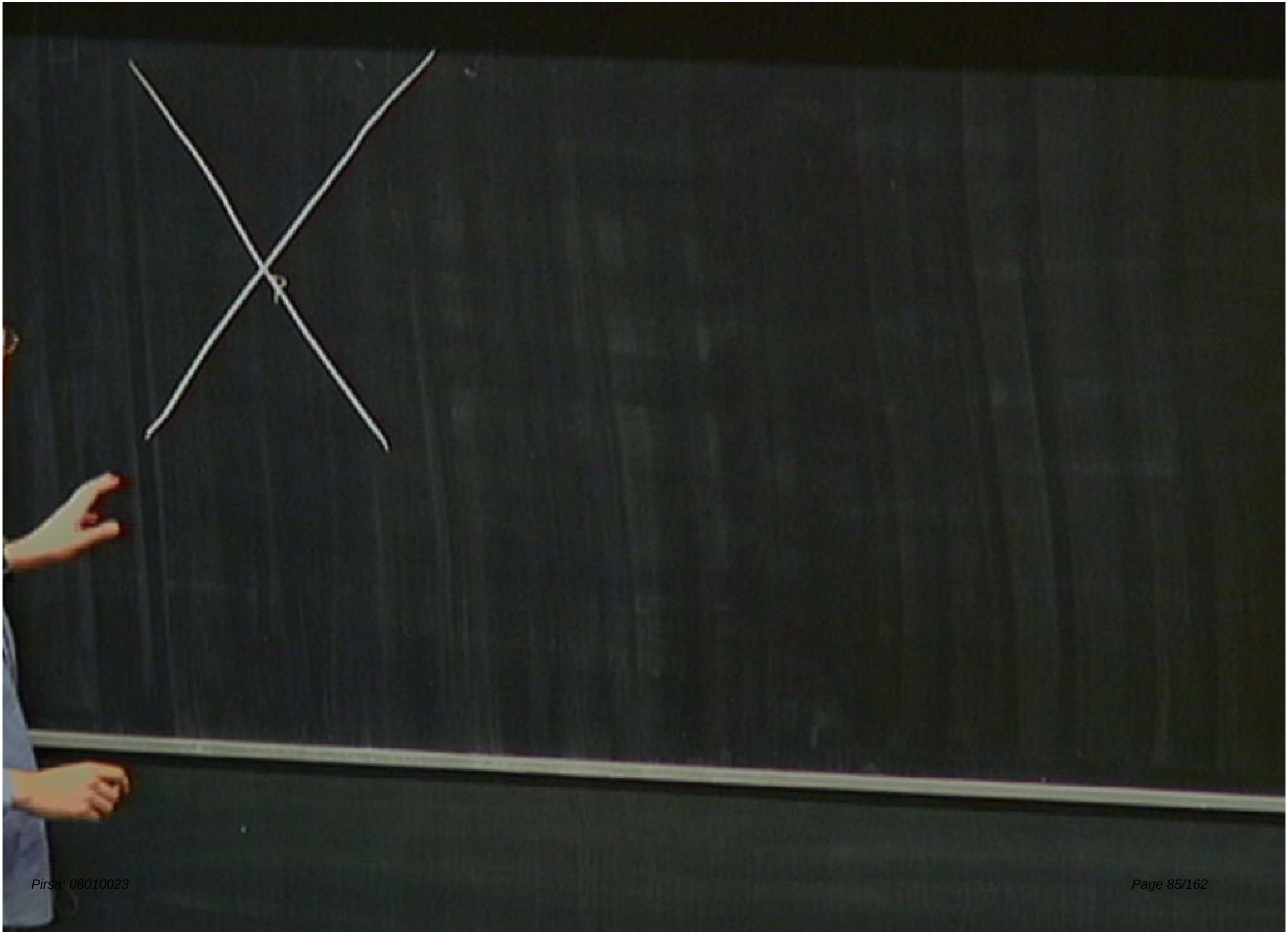
$$x^i = a^i t + b^i$$

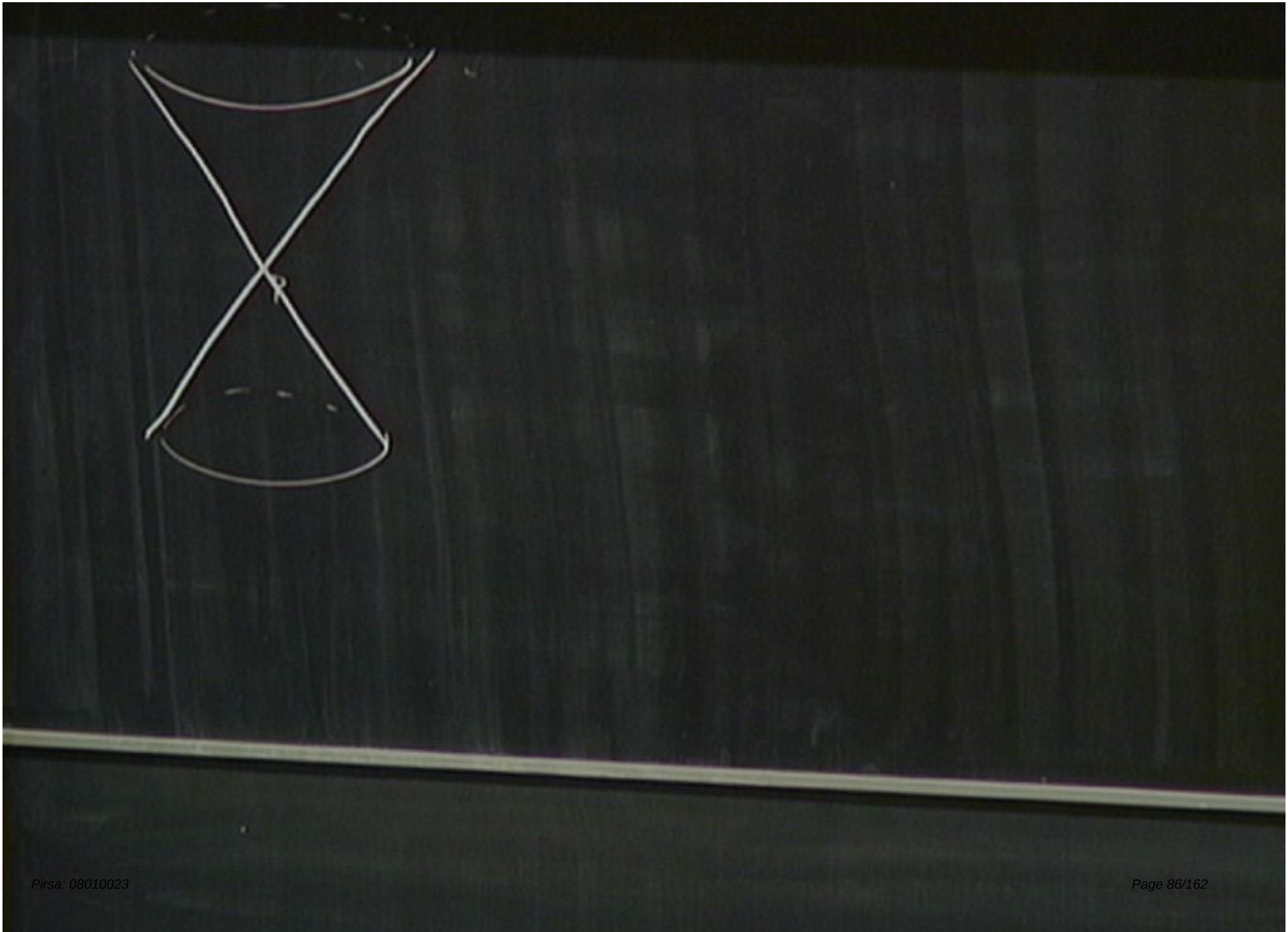
$$\Gamma^i_{jk} = \frac{1}{2} \sum_{l} g^{il} \left(g_{jl,k} + g_{kl,j} - g_{jk,l} \right)$$

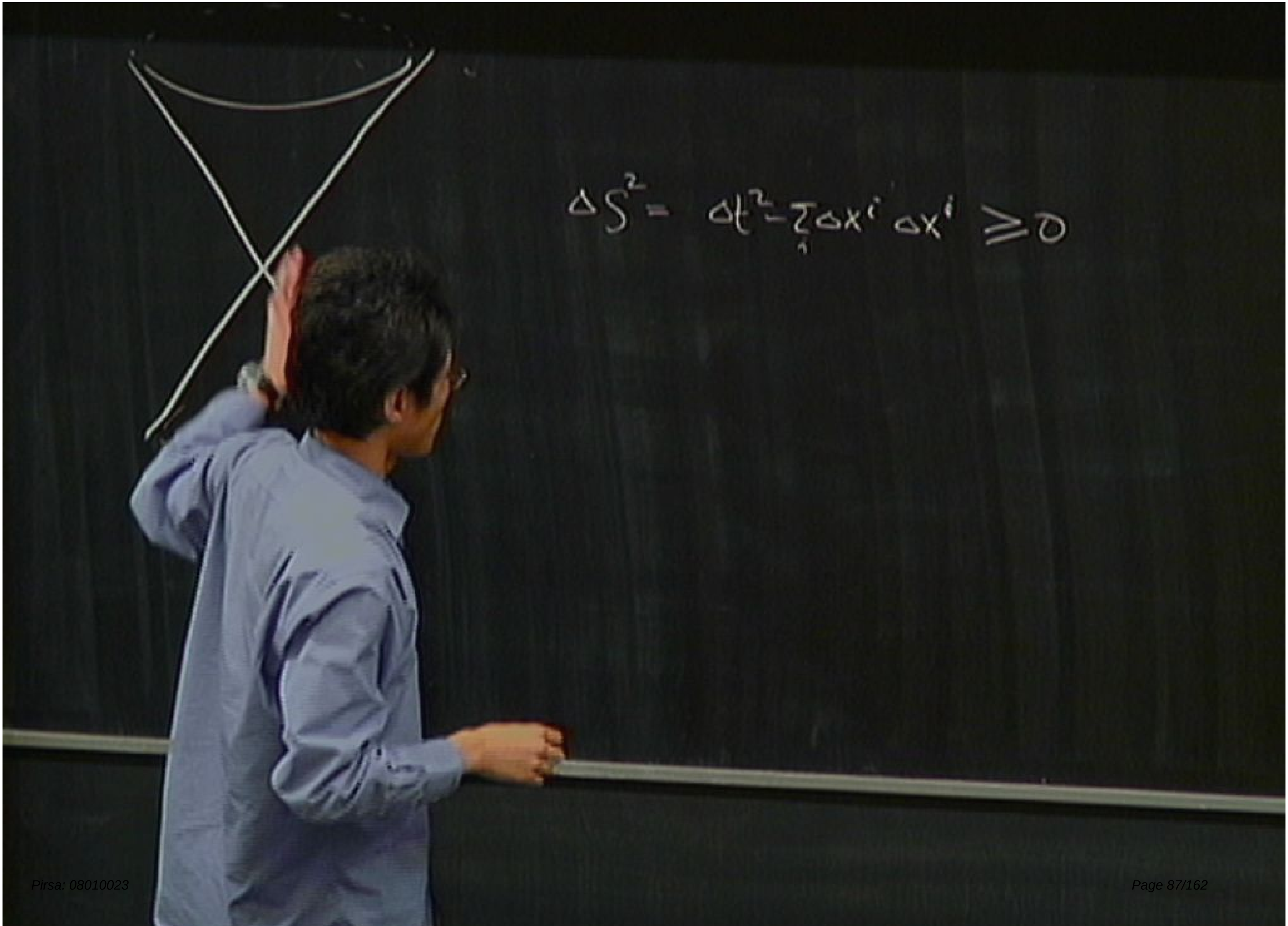


$x^i(t)$
$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$
inimal length.
$\Gamma^i_{(x)jk} \frac{dx^j}{dt} \frac{dx^k}{dt} = 0$
$x^i = a^i t + b^i$
$g_{k\ell,j} - g_{jk,\ell})$


x^i(t)
S(A, B) = ∫_{t_A}^{t_B} dt √(g_ij dx^i/dt dx^j/dt)
minimal length.
geodesic
x^i = a^i t + b^i
= 0






$\Delta s^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$

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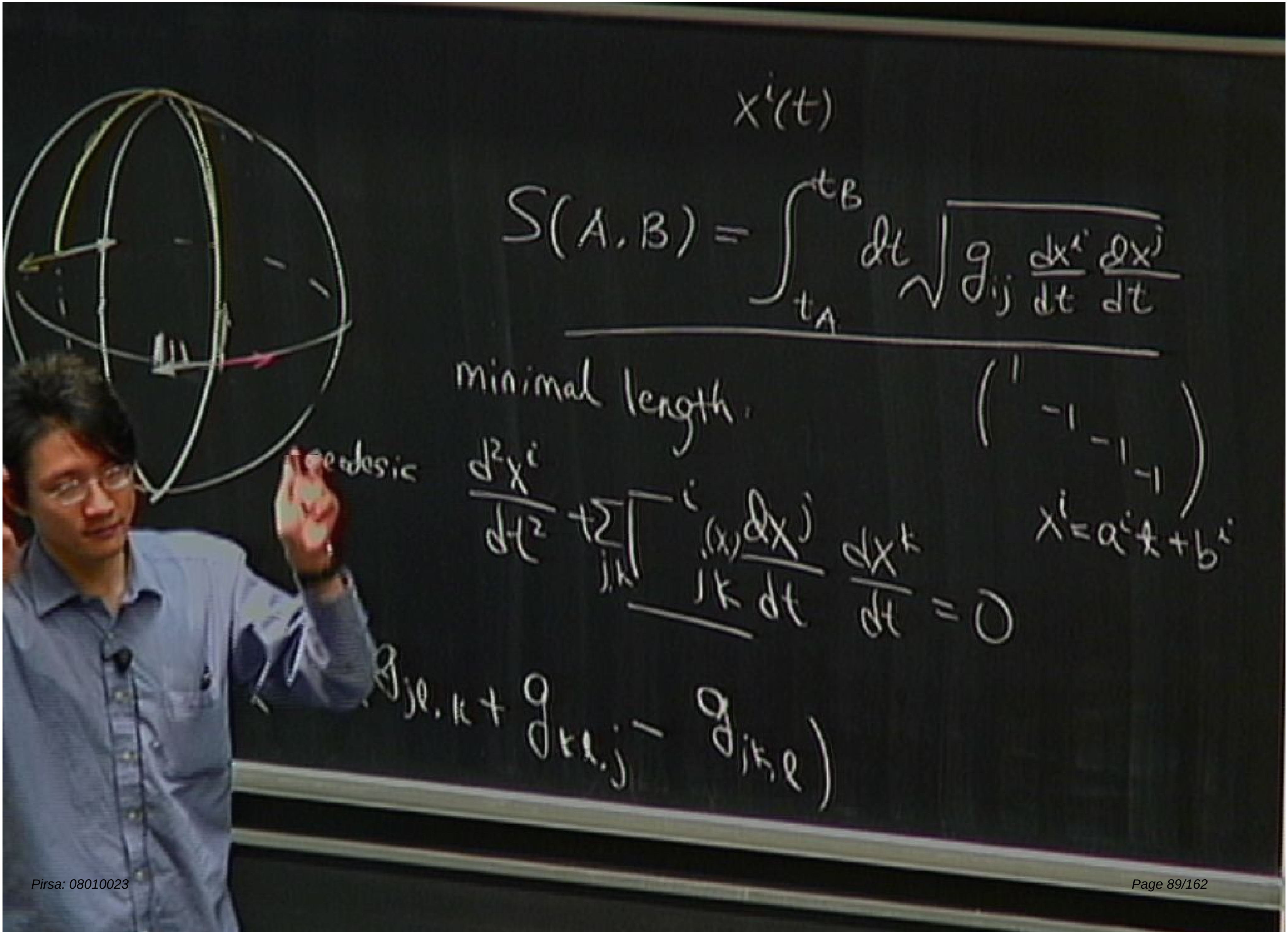
$x^i(t)$
$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$
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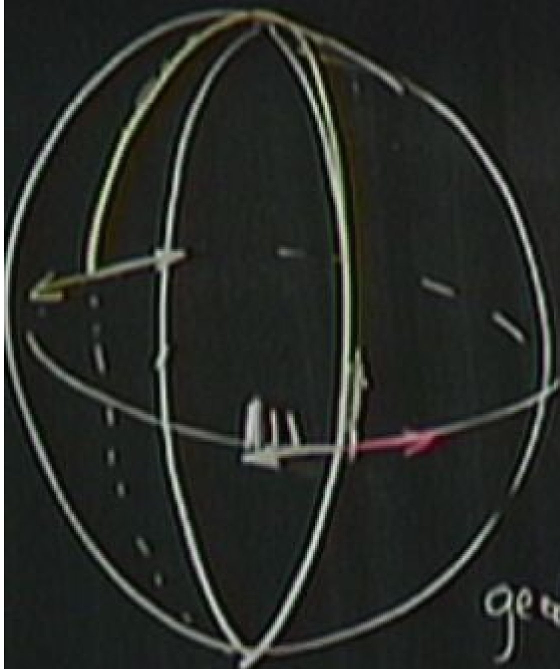
geodesic
$\frac{d^2x^i}{dt^2} + \sum_{jk} \Gamma^i_{jk}(x) \frac{dx^j}{dt} \frac{dx^k}{dt} = 0$
$x^i = a^i t + b^i$
$g_{jl,k} + g_{kl,j} - g_{jk,l})$



$x^i(t)$

$$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij}\frac{dx^i}{dt}\frac{dx^j}{dt}}$$

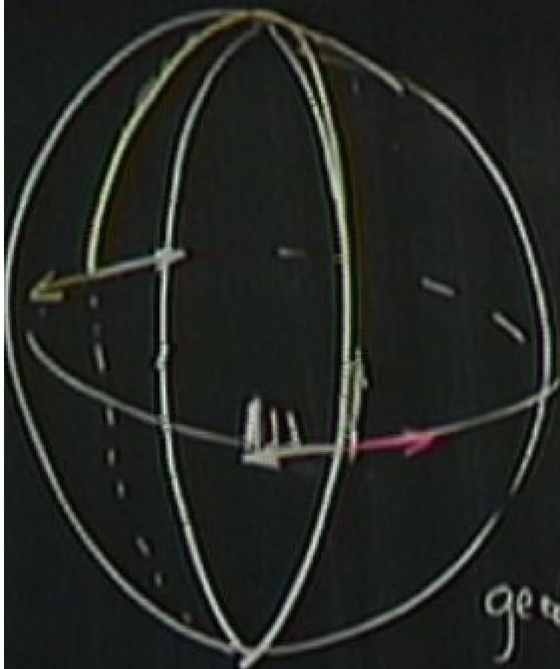
minimal length.

$$\begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix}$$

$x^i = a^i t + b^i$

geodesic $$\frac{d^2x^i}{dt^2} + \sum_{jk} \Gamma^i_{jk}(x)\frac{dx^j}{dt}\frac{dx^k}{dt} = 0$$

$$\Gamma^i_{jk} = \frac{1}{2}\sum_{\ell} g^{i\ell}\left(g_{j\ell,k} + g_{k\ell,j} - g_{jk,\ell}\right)$$



$x^i(t)$

$$S(A,B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij}\frac{dx^i}{dt}\frac{dx^j}{dt}}$$

minimal length.

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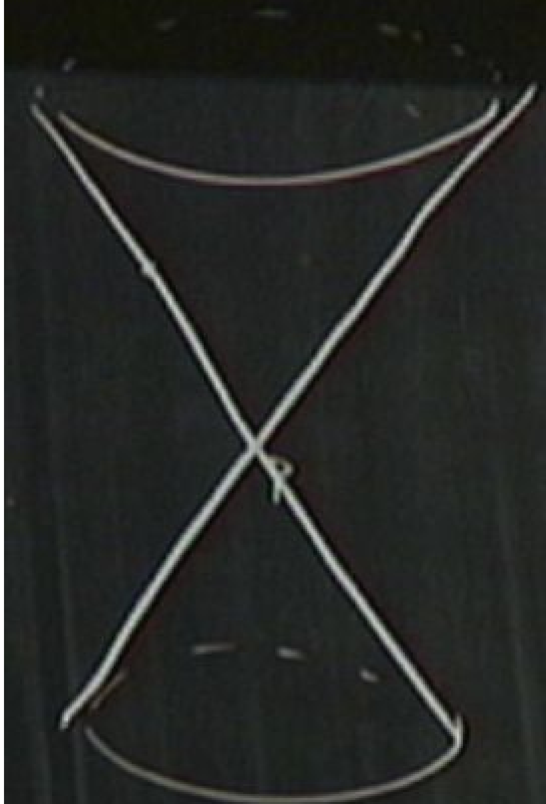
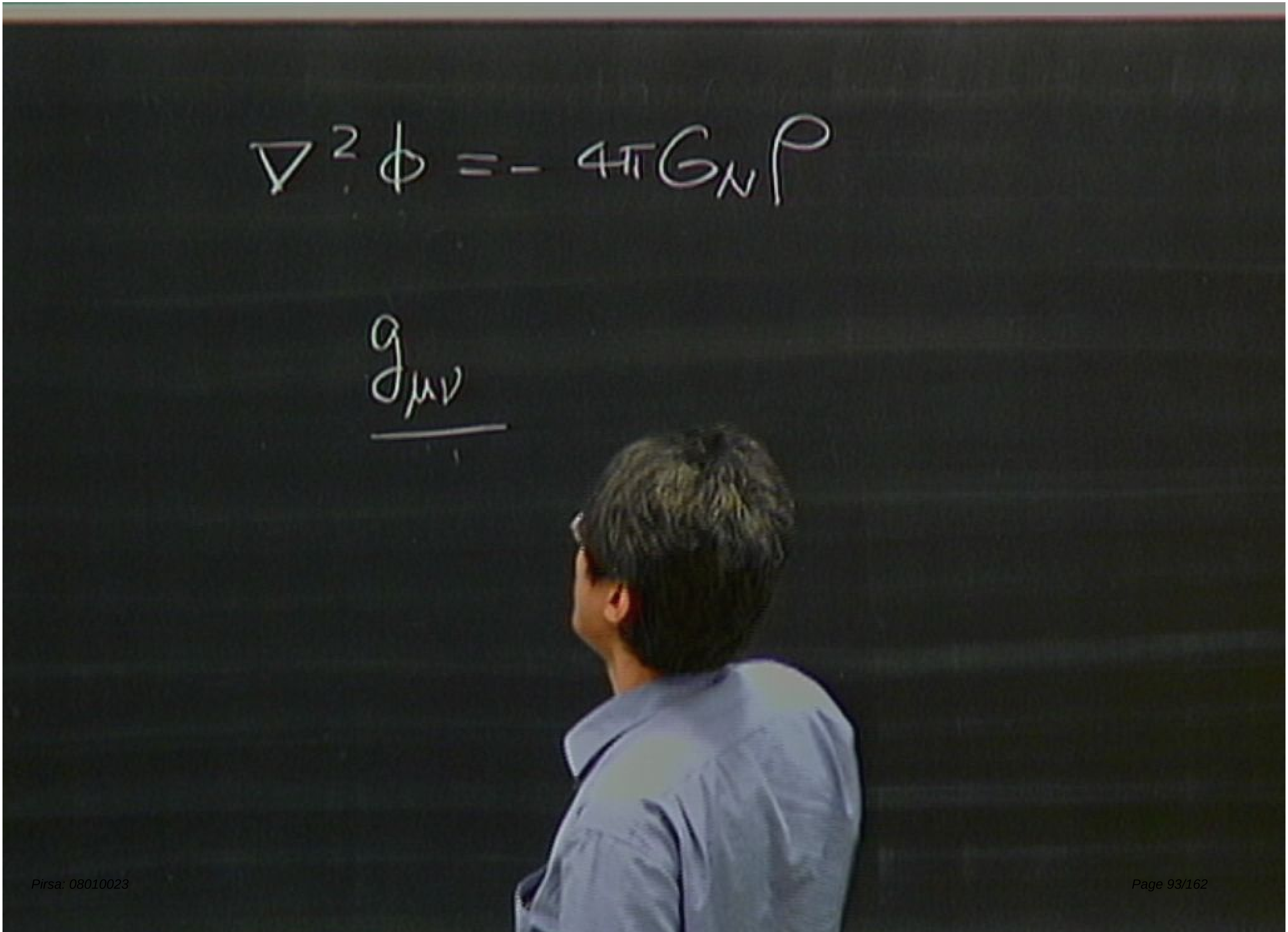


$$\Delta s^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$$


$\nabla^2 \phi = -4\pi G_N \rho$
$g_{\mu\nu}$

$$\nabla^2 \phi = -4\pi G_N \rho$$

$\underline{g_{\mu\nu}}$ $\qquad\qquad$ $T_{\mu\nu}$

$x^0 = t$

$$\nabla^2 \phi = -4\pi G_N \rho$$

D = dim of spacetime

$(1, D-1)$

$g_{\mu\nu}$

$T_{\mu\nu}$

$$\begin{array}{cccc} 0 & 1, & 2, \ldots & D-1 \end{array}$$

$x^0 = t$

$$\nabla^2 \phi = - 4\pi G_N \rho$$

D = dim of spacetime

$(1, D-1)$

$g_{\mu\nu}$ $\qquad$ $T_{\mu\nu}$

$$\begin{pmatrix} \rho & & \\ & & \\ & & \end{pmatrix}$$

$0 \quad 1, \quad 2, \ldots$

$x^0 = t$

$$\nabla^2 \phi = -4\pi G_N \rho$$

D = dim of spacetime

$(1, D-1)$

$g_{\mu\nu}$

$T_{\mu\nu}$

$$\begin{array}{cccc} 0 & 1, & 2, & \cdots \\ \end{array}$$
$$\begin{pmatrix} \rho & & & \\ & & & \\ \end{pmatrix}$$

$x^0 = t$

$$\nabla^2 \phi = -4\pi G_N \rho$$

D = dim of spacetime

$(1, D-1)$

$g_{\mu\nu}$

$T_{\mu\nu}$

$$\begin{array}{ccccc} 0 & 1, & 2, & \cdots & , D-1 \\ \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \end{array}$$

$x^0 = t$

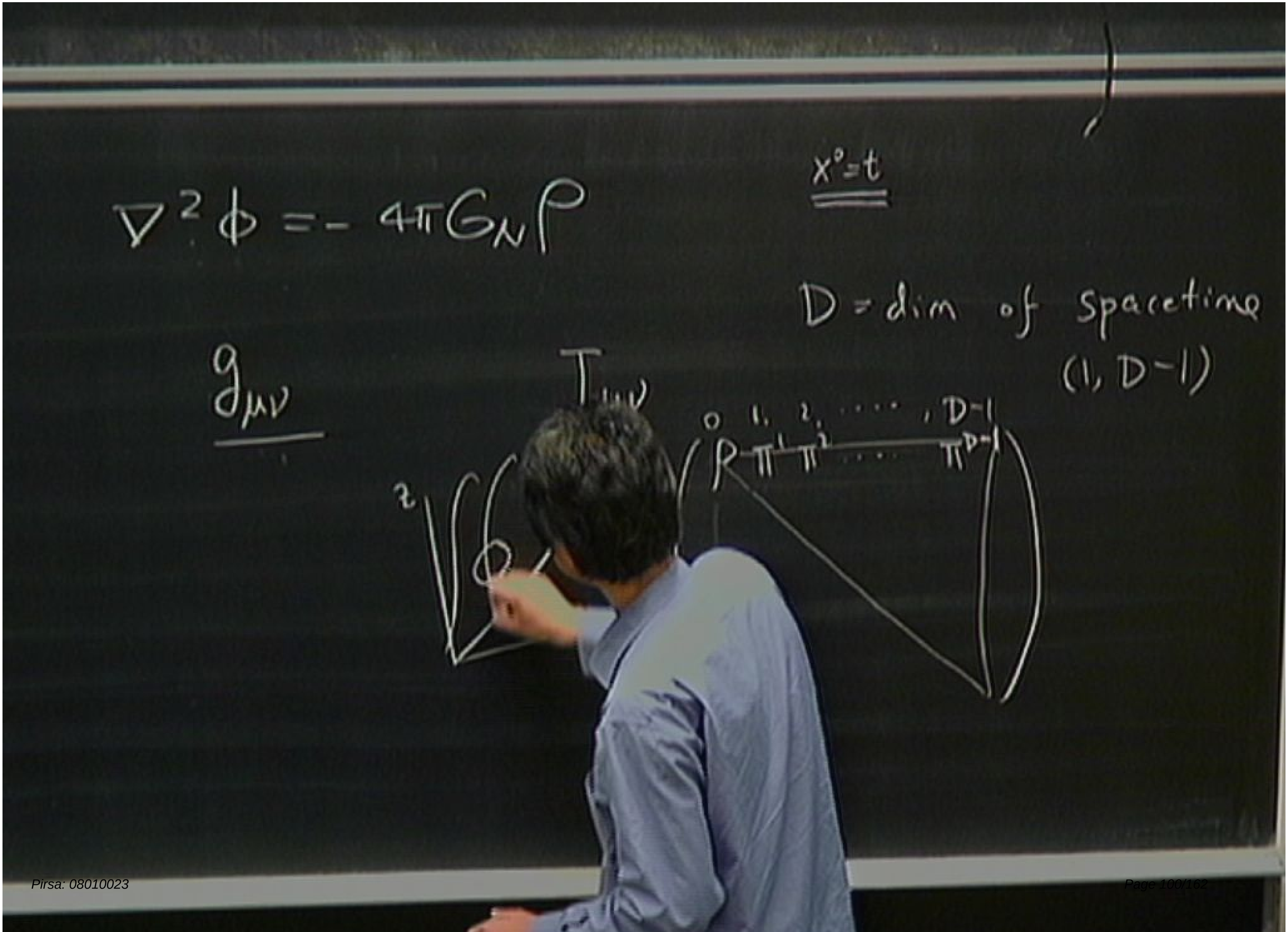
$$\nabla^2 \phi = -4\pi G_N \rho$$

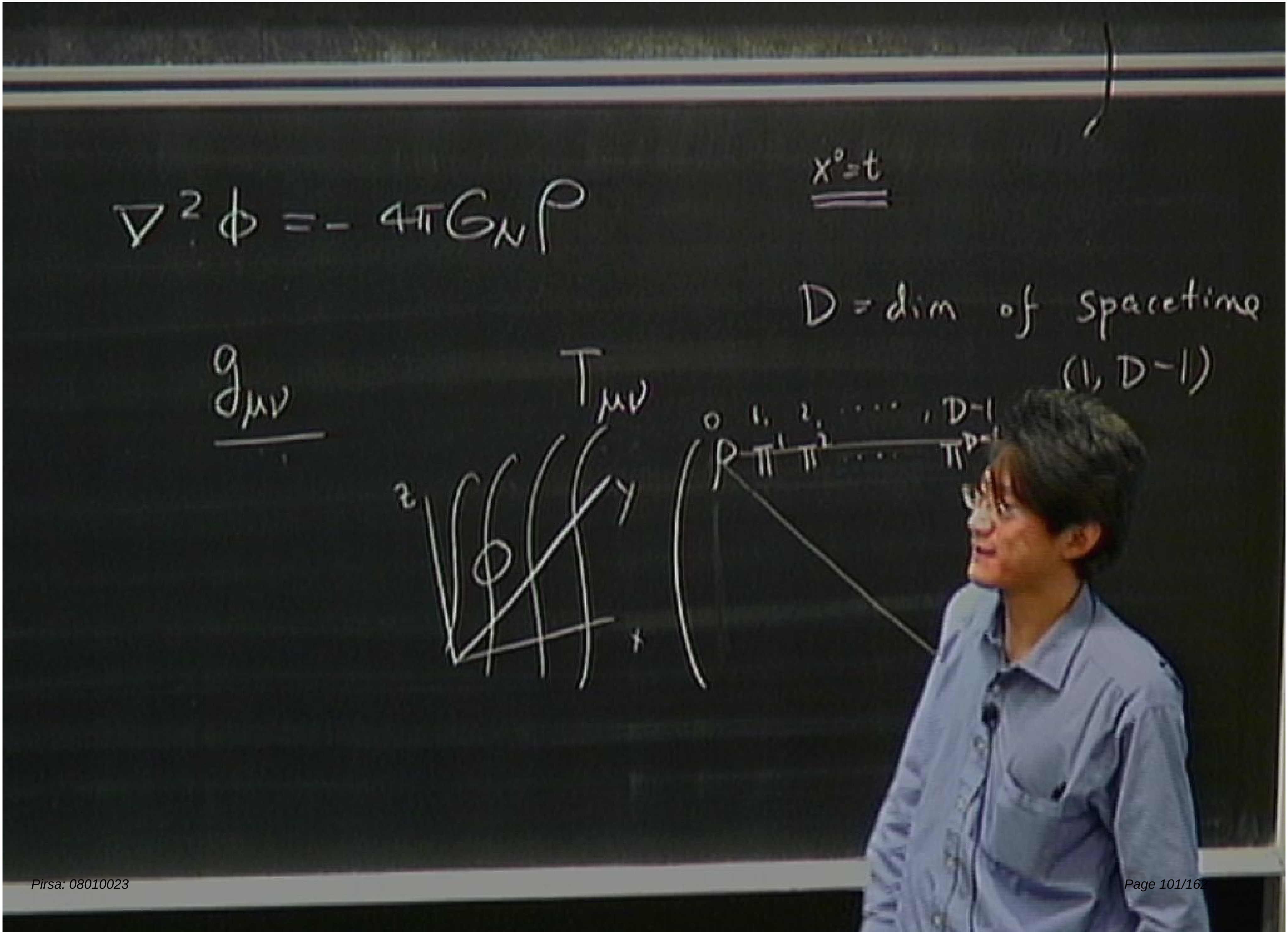
D = dim of spacetime

$(1, D-1)$

$g_{\mu\nu}$ $\qquad$ $T_{\mu\nu}$

$$\begin{array}{ccccc} 0 & 1, & 2, & \cdots & , D-1 \\ \end{array}$$
$$\begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \\ & & & & \end{pmatrix}$$


$\nabla^2 \phi = -4\pi G_N \rho$
$x^0 = t$
D = dim of spacetime
(1, D-1)
$g_{\mu\nu}$
$T_{\mu\nu}$
0 1, 2, ..., D-1
$\rho\ \pi^1\ \pi^2\ \dots\ \pi^{D-1}$


$x^0 = t$
$\nabla^2 \phi = -4\pi G_N \rho$
D = dim of spacetime
$g_{\mu\nu}$
$T_{\mu\nu}$
$(1, D-1)$
$0 \quad 1, \quad 2, \quad \dots, \quad D-1$
$\rho \quad \pi^1 \quad \pi^2 \quad \dots \quad \pi^{D-1}$
z
y
x

$$x^0 = t$$

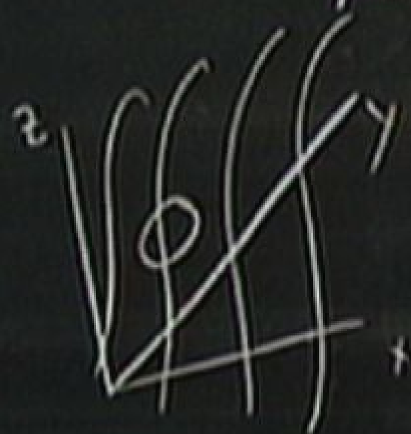
$$\nabla^2 \phi = -4\pi G_N \rho$$

D = dim of spacetime

$(1, D-1)$

$g_{\mu\nu}$

$T_{\mu\nu}$



$$\begin{array}{ccccc} 0 & 1, & 2, & \cdots & , D-1 \\ \end{array}$$
$$\begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \end{pmatrix}$$

$x^0 = t$

$$\nabla^2 \phi = -4\pi G_N \rho$$

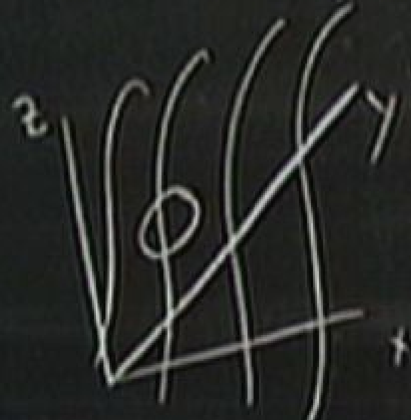
D = dim of spacetime

$(1, D-1)$

$g_{\mu\nu}$

$T_{\mu\nu}$

T_{xy}



$$\begin{array}{c|c}
 & 0 \quad 1, \quad 2, \quad \cdots \quad , D-1 \\
\begin{array}{c} 0 \\ 1 \\ 2 \end{array} & \begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \end{pmatrix}
\end{array}$$

stress

$x^0 = t$

$$\nabla^2 \phi = -4\pi G_N \rho$$

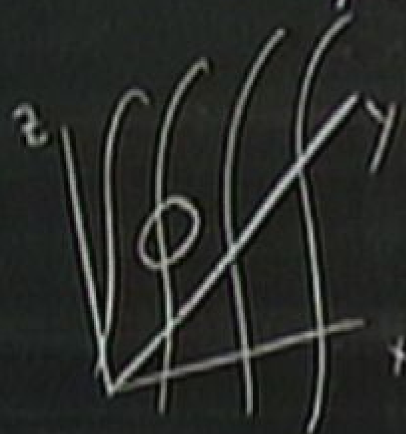
D = dim of spacetime

$(1, D-1)$

$g_{\mu\nu}$

$T_{\mu\nu}$

T_{xy}



$$\begin{array}{c|ccccc} & 0 & 1, & 2, & \cdots & , D-1 \\ \hline 0 & & & & & \\ 1 & & & & & \\ 2 & & & & & \end{array} \quad \begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \\ & & & & \end{pmatrix}$$

stress

$$\nabla^2 \phi = -4\pi G_N \rho$$

$x^0 = t$

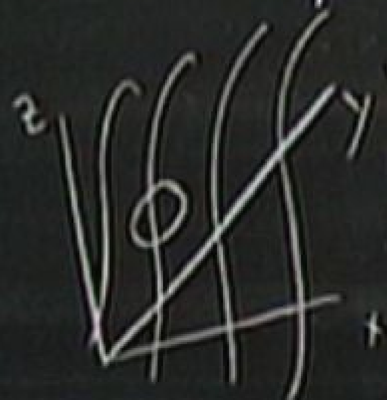
D = dim of spacetime

(1, D-1)

$g_{\mu\nu}$

$T_{\mu\nu}$

T_{xy}



$$\begin{array}{c|c}
 & 0 \quad 1, \quad 2, \quad \cdots \quad, D-1 \\
\begin{array}{c} 0 \\ 1 \\ 2 \\ \vdots \end{array} & \begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \\ & & & & \end{pmatrix}
\end{array}$$

stress

$\underline{\underline{x^0 = t}}$

$$\nabla^2 \phi = -4\pi G_N \rho$$

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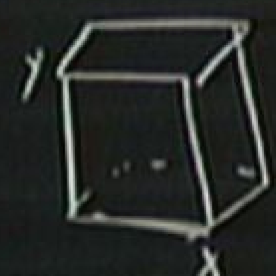
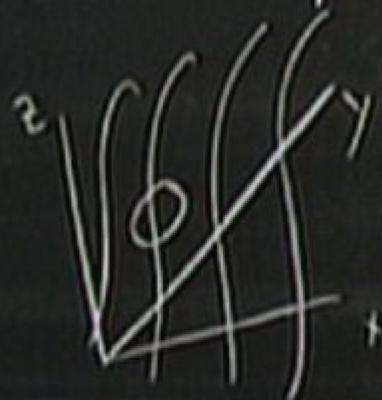
$\underline{g_{\mu\nu}}$

$T_{\mu\nu}$

T_{xy}





$$\begin{array}{c|c} & 0 \quad 1, \quad 2, \quad \cdots, \quad D-1 \\ \hline \begin{matrix} 0 \\ 1 \\ 2 \\ \vdots \end{matrix} & \begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \\ & & & & \end{pmatrix} \end{array}$$

st$\underline{\text{ress}}$

$$x^0 = t$$

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$(1, D-1)$

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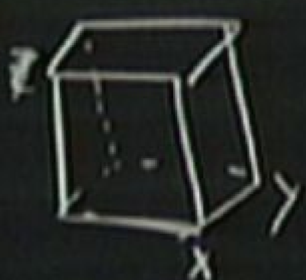
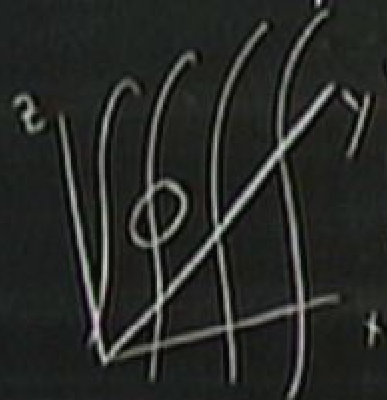
stress

T_{xy}





$$\begin{array}{c|c}
 & 0 \quad 1, \quad 2, \quad \cdots \quad , D-1 \\
\begin{matrix} 0 \\ 1 \\ 2 \end{matrix} & \begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \end{pmatrix}
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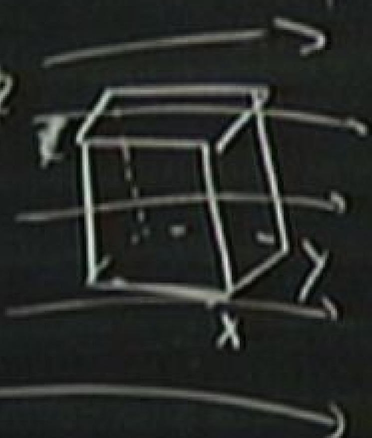
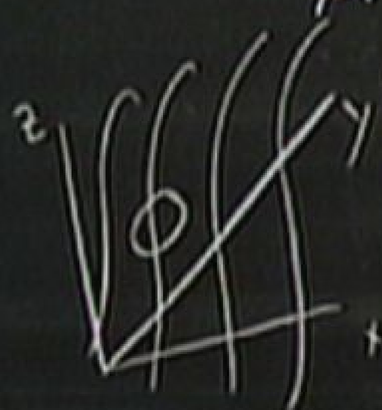
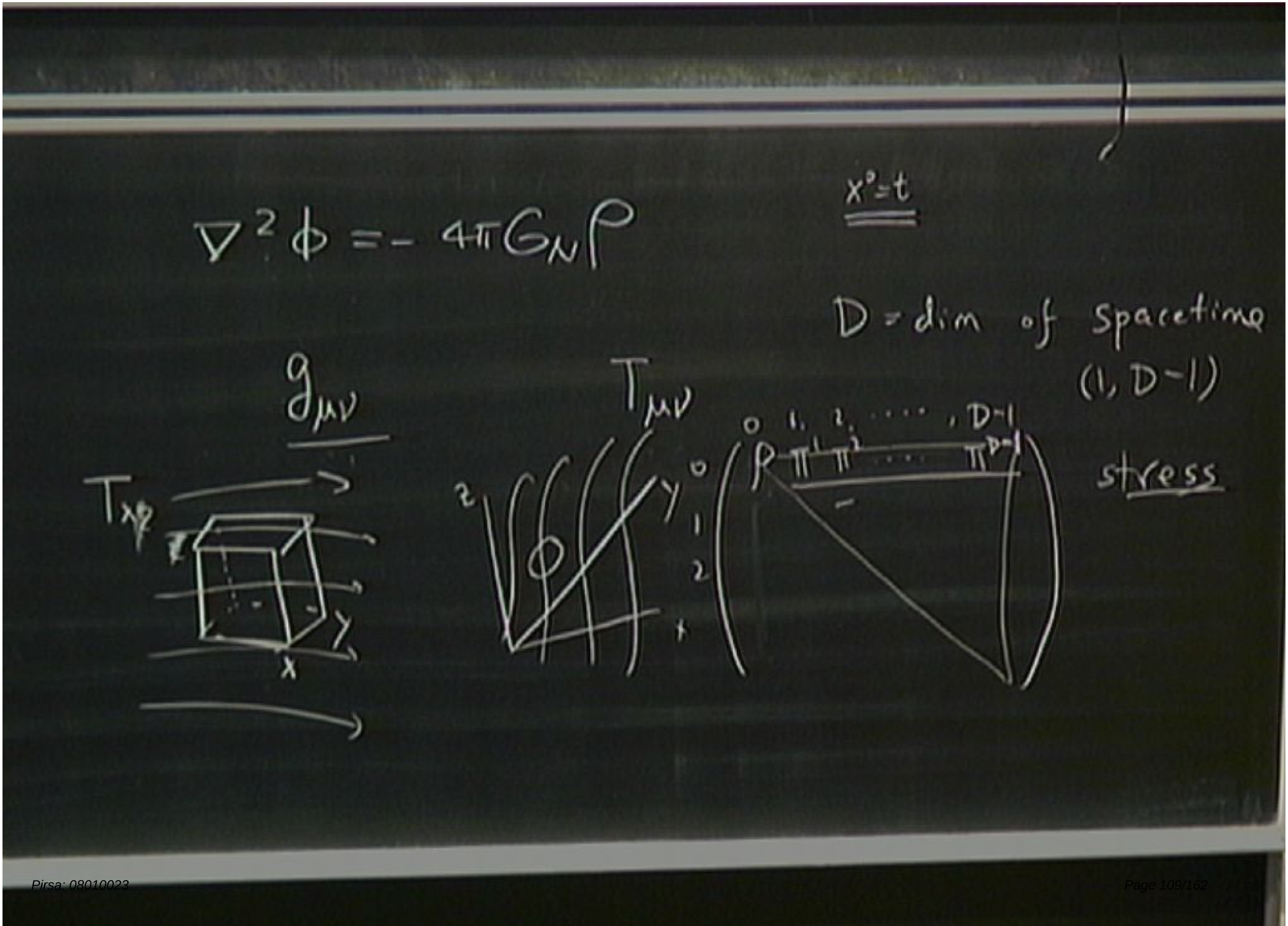
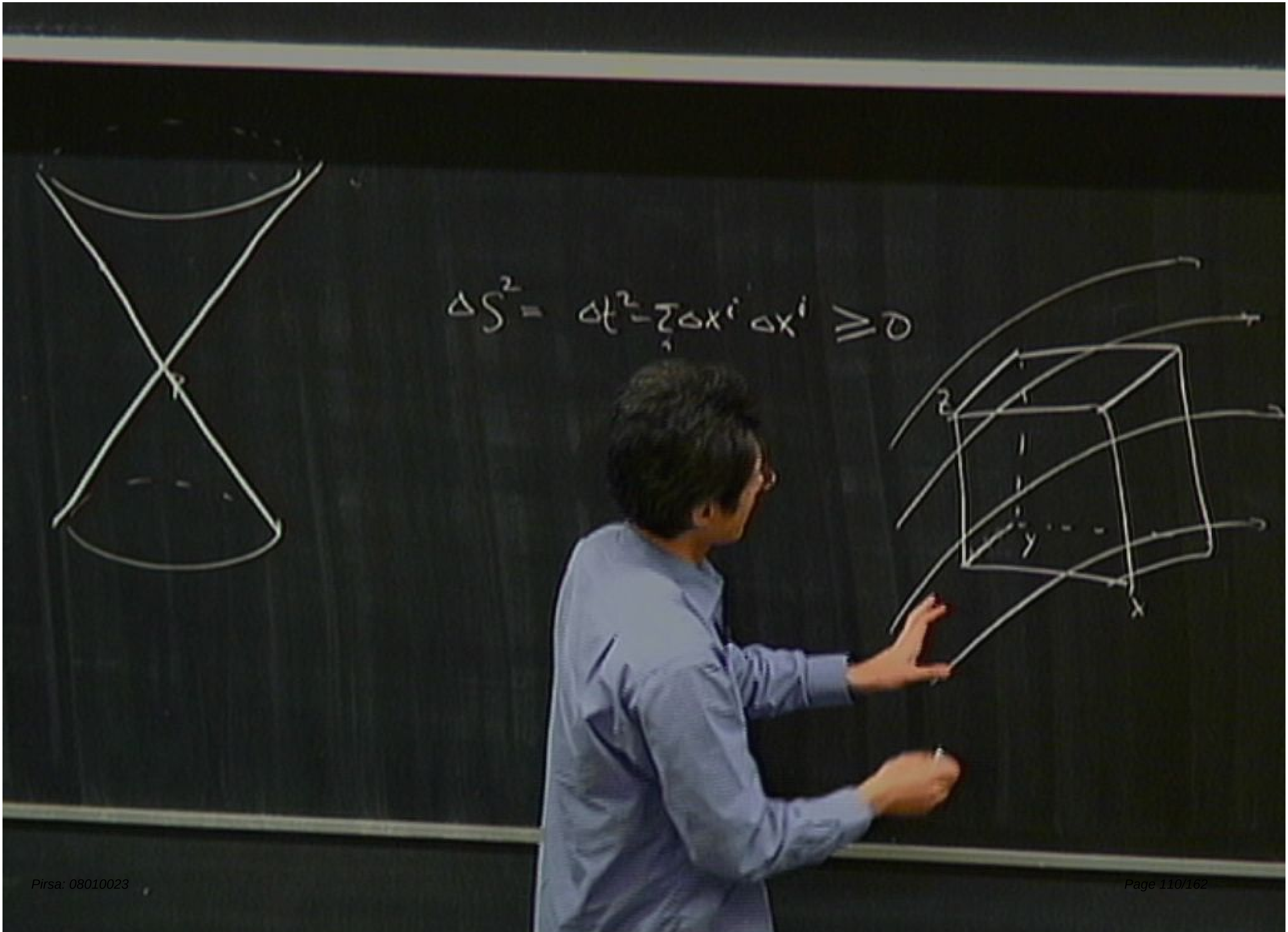


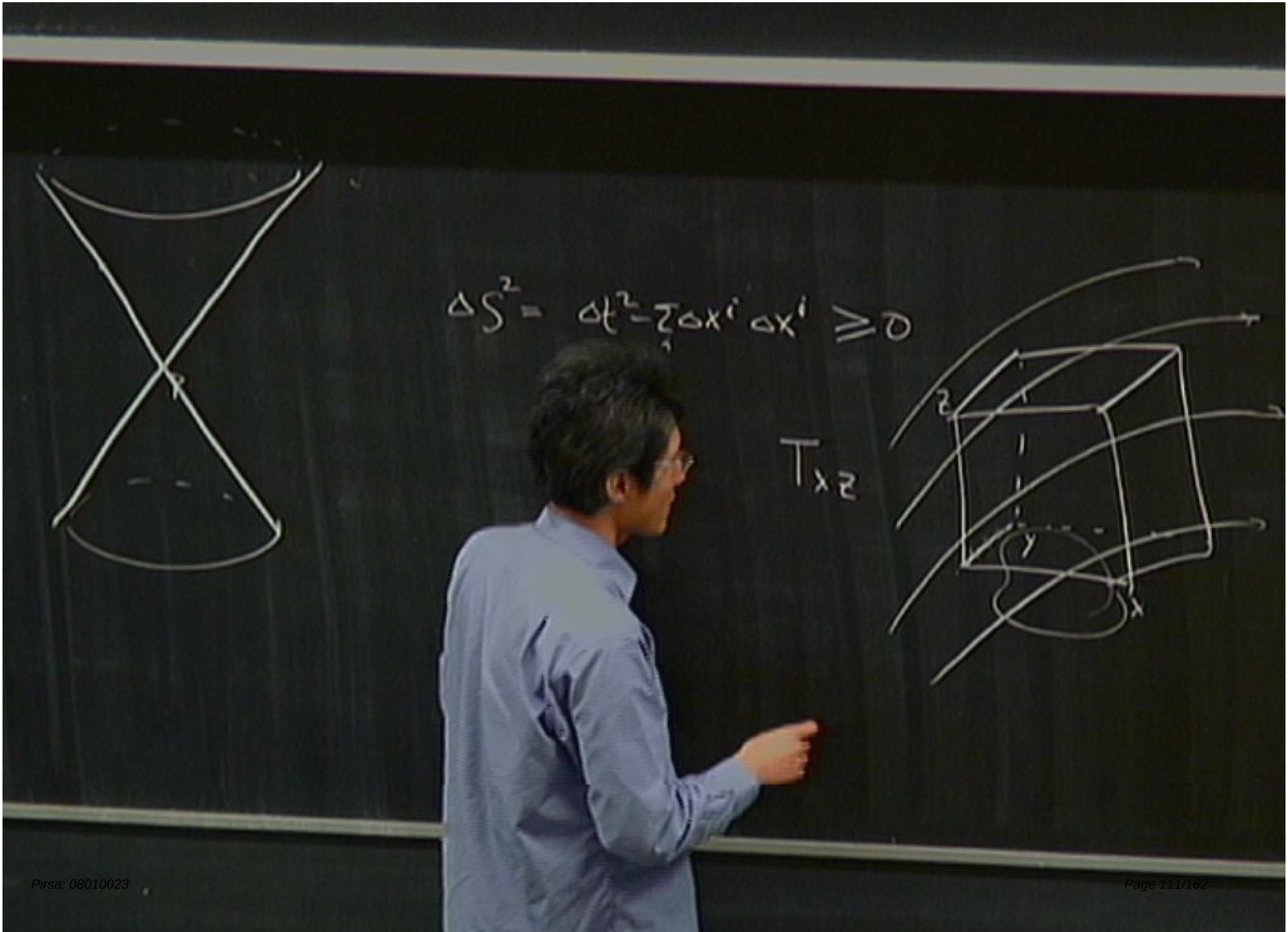


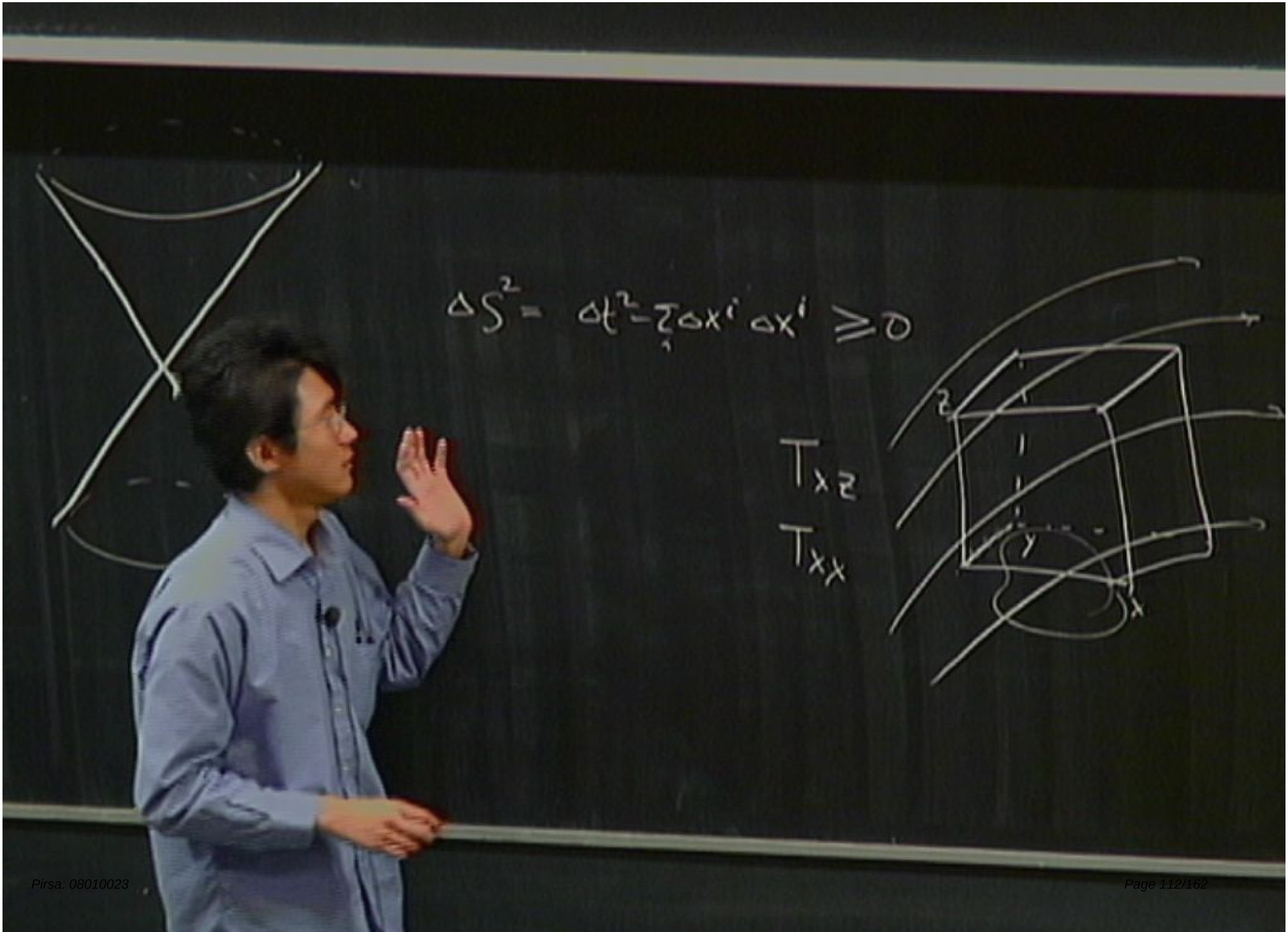
$$\begin{array}{c|c} & 0 \quad 1, \quad 2, \quad \cdots \quad, D-1 \\ \begin{matrix} 0 \\ 1 \\ 2 \\ \vdots \end{matrix} & \begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & \ddots & & & \\ & & & & \end{pmatrix} \end{array}$$

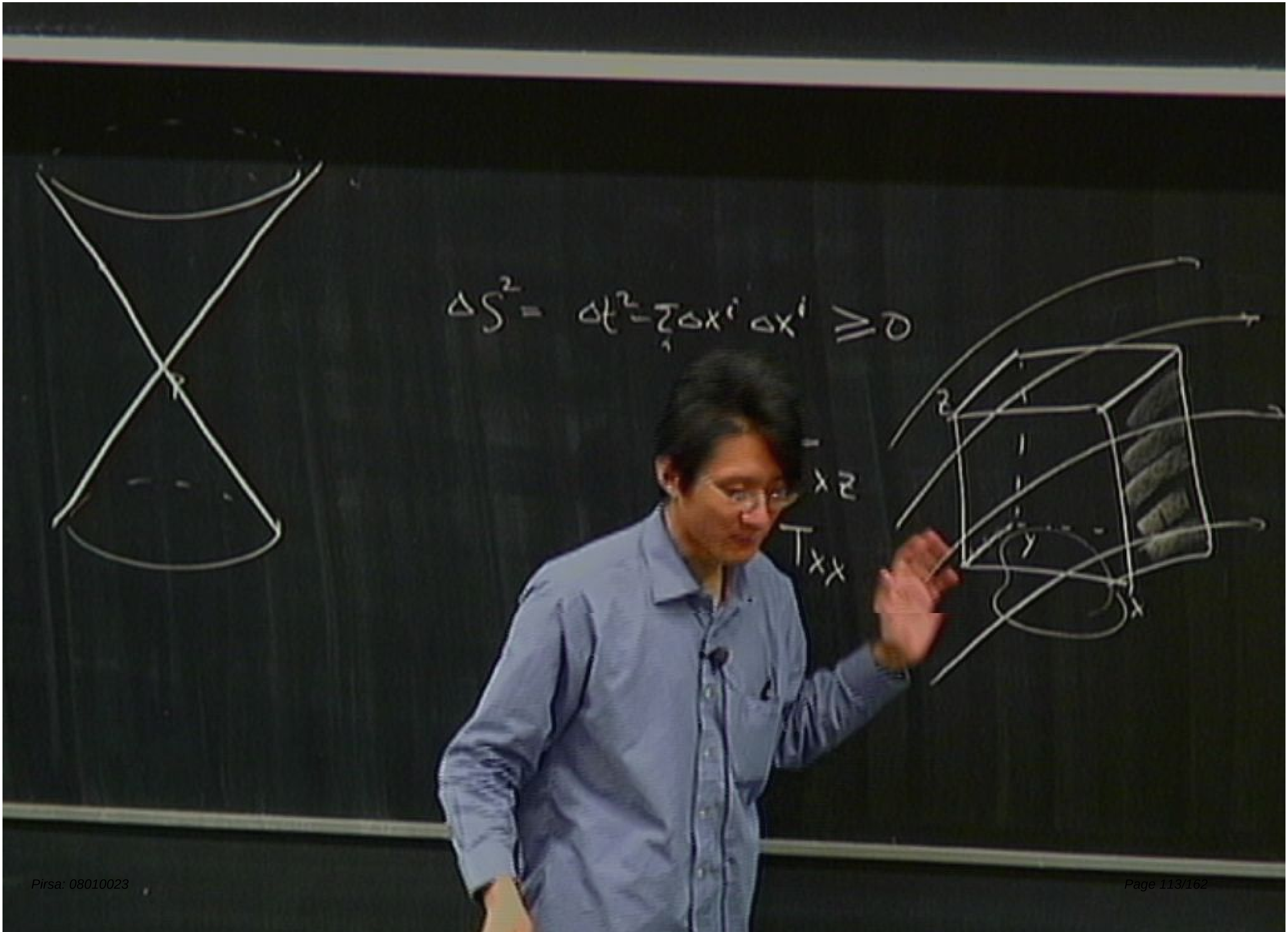
st$\underline{\text{ress}}$

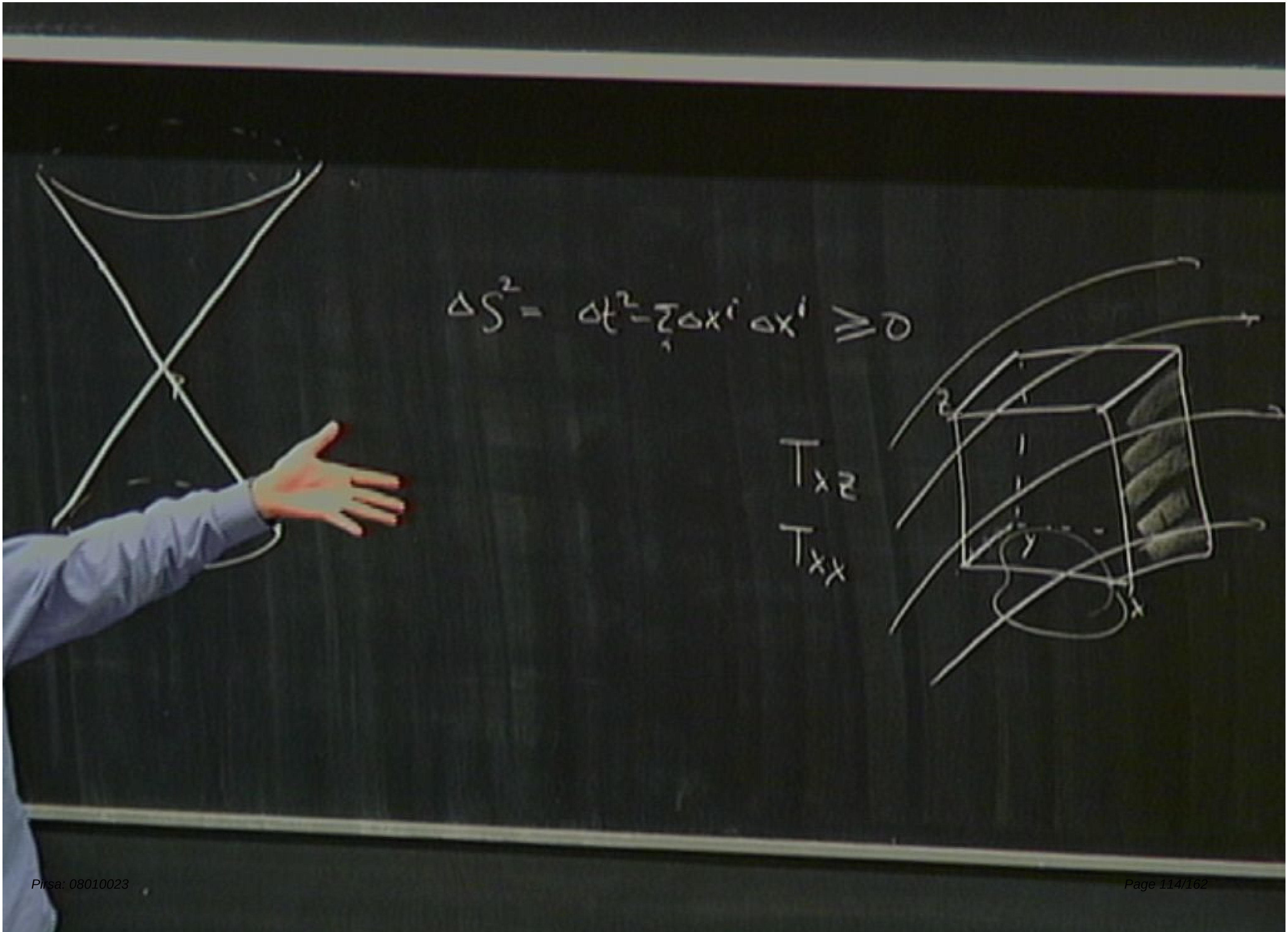

$\nabla^2 \phi = -4\pi G_N \rho$
$x^0 = t$
D = dim of Spacetime
$(1, D-1)$
$g_{\mu\nu}$
$T_{\mu\nu}$
T_{xy}
stress
$\rho \quad \pi^1 \quad \pi^2 \quad \cdots \quad \pi^{D-1}$
0 1, 2, ... , D-1

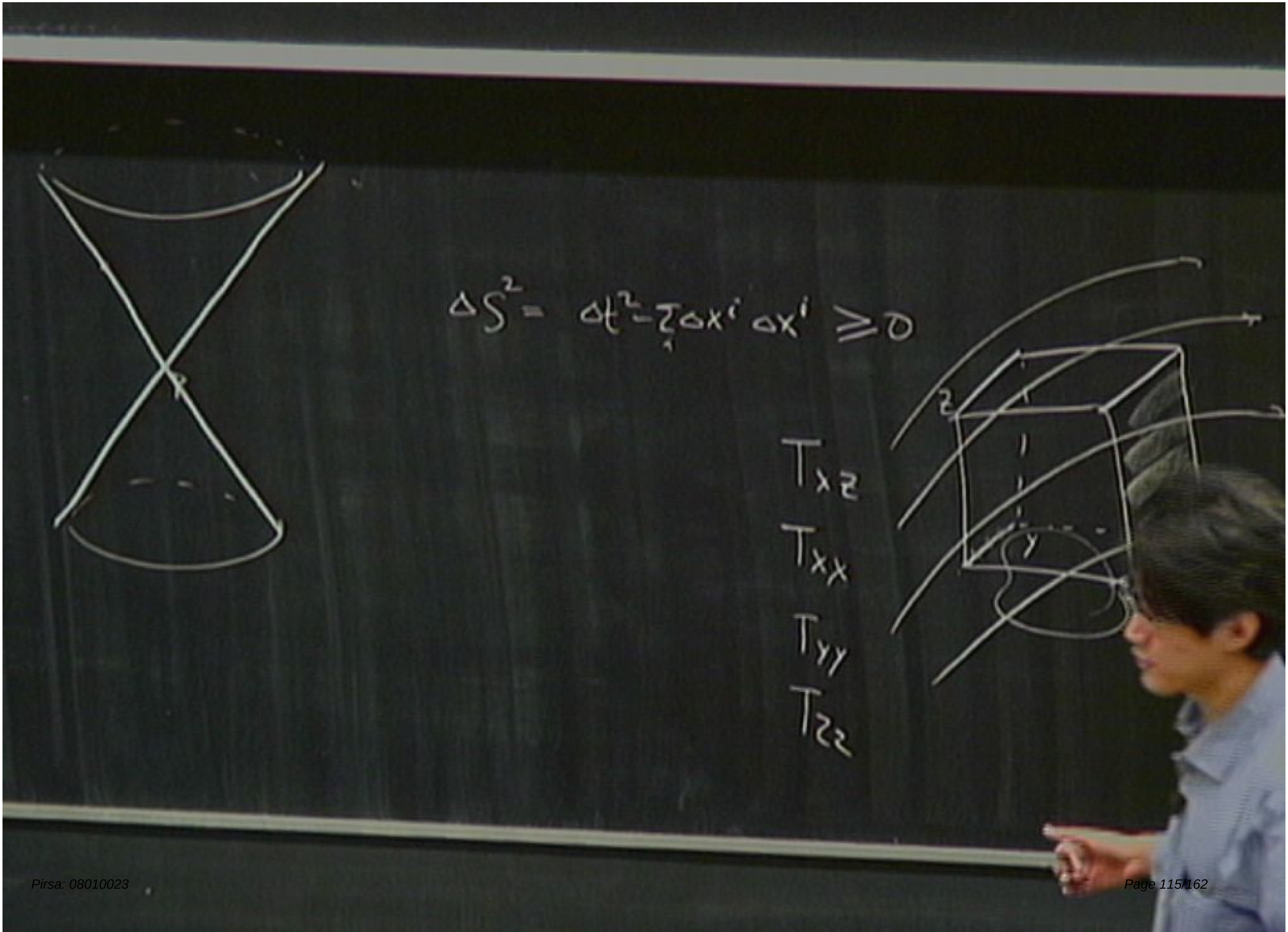

$\Delta s^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$
z
y
x


$\Delta S^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$
T_{xz}
z
y
x


$\Delta S^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$
T_{xz}
T_{xx}
z
y
x


$\Delta s^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$
T_{xz}
T_{xx}
z
y
x


$\Delta S^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$
T_{xz}
T_{xx}
z
y
x


$\Delta S^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$
T_{xz}
T_{xx}
T_{yy}
T_{zz}
z
y

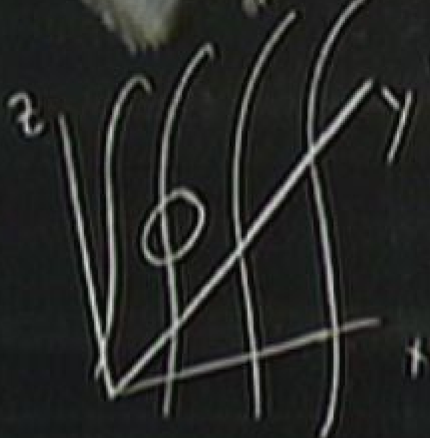
$x^0 = t$

$$\nabla^2 \phi = -4\pi G_N \rho$$

D = dim of Spacetime

$(1, D-1)$

$g_{\mu\nu}$ ... $G_N T_{\mu\nu}$



$$\begin{array}{c|c} & 0 \quad 1, \quad 2, \quad \cdots, \quad D-1 \\ \hline \begin{array}{c} 0 \\ 1 \\ 2 \end{array} & \begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \end{pmatrix} \end{array}$$

stress

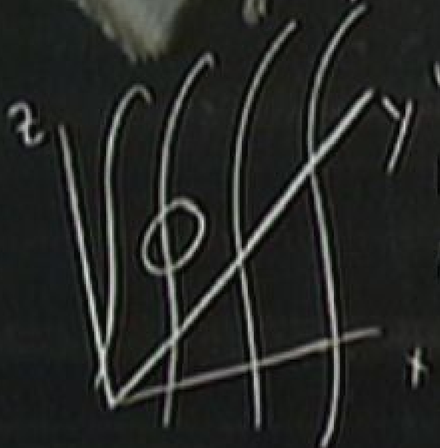
$$\nabla^2 \phi = -4\pi G_N \rho$$

$$\underline{\underline{x^0 = t}}$$

D = dim of spacetime

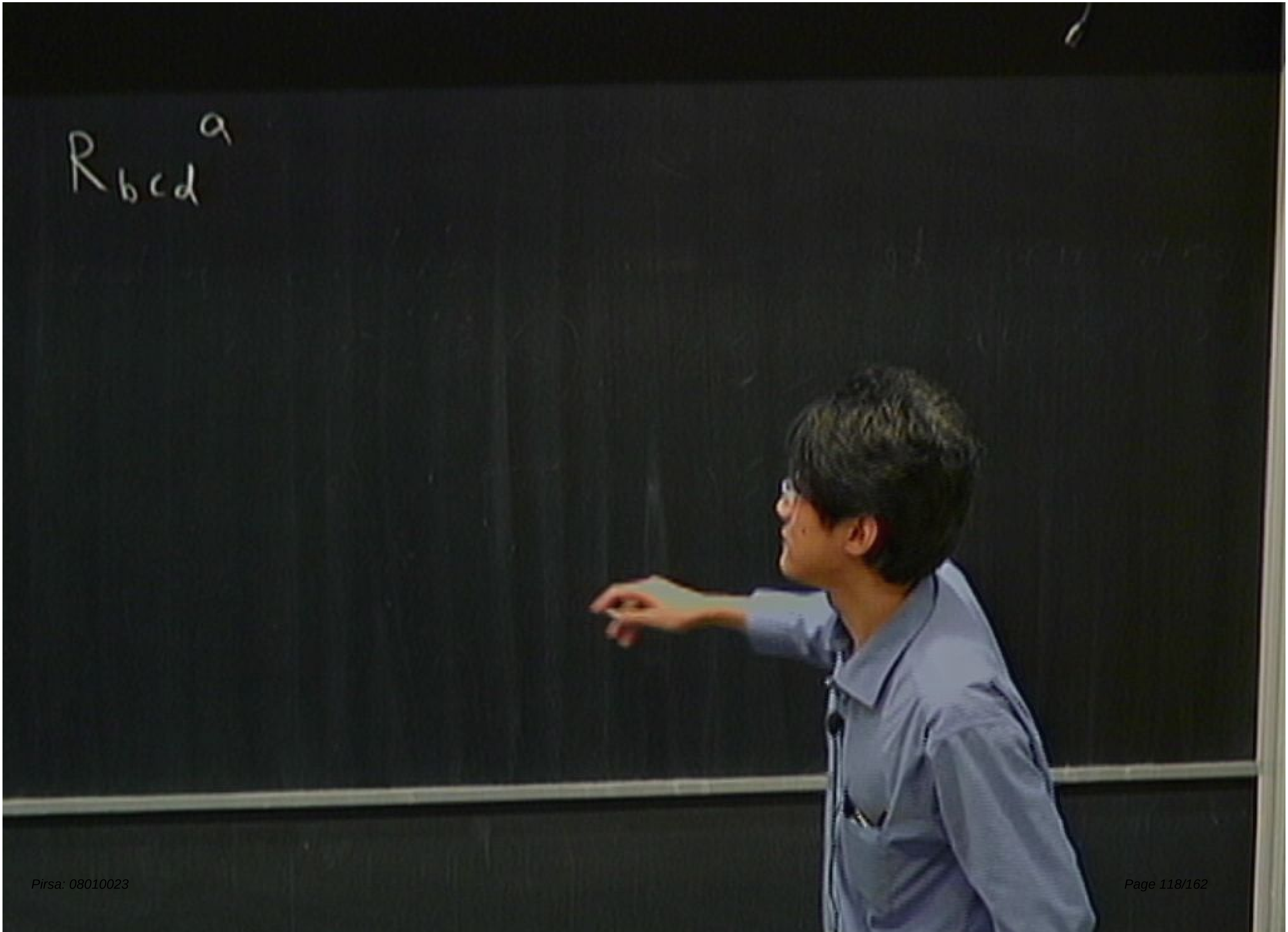
(1, D − 1)

$$\underline{g_{\mu\nu}} \quad \pi G_N T_{\mu\nu}$$



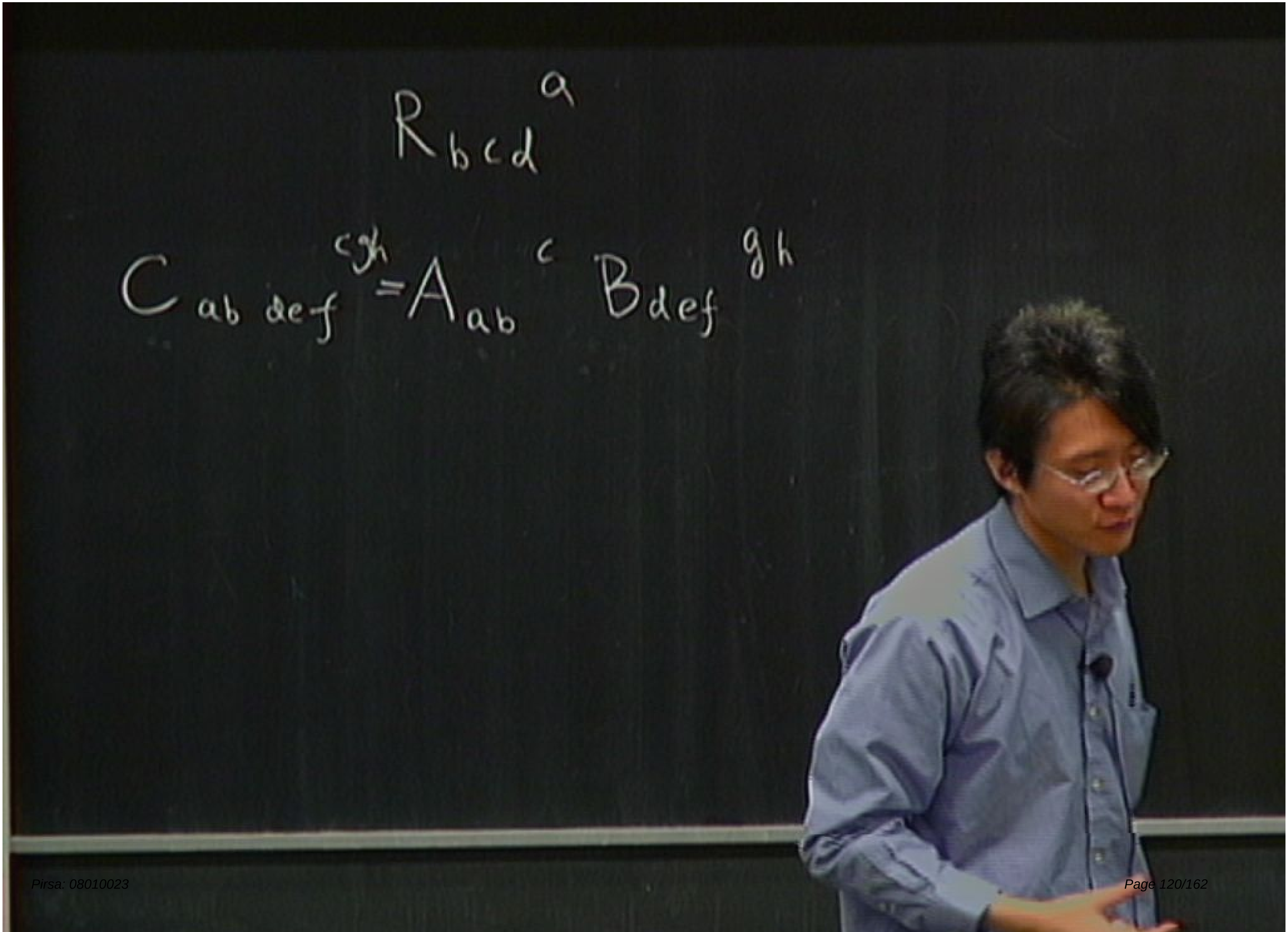
$$\begin{array}{c|c} & \begin{array}{ccccc} 0 & 1, & 2, & \cdots & , D-1 \end{array} \\ \begin{array}{c} 0 \\ 1 \\ 2 \\ \\ \\ \end{array} & \begin{pmatrix} \rho & \pi^1 & \pi^2 & \cdots & \pi^{D-1} \\ & & & & \\ & & & & \\ & & & & \\ & & & & \end{pmatrix} \end{array}$$

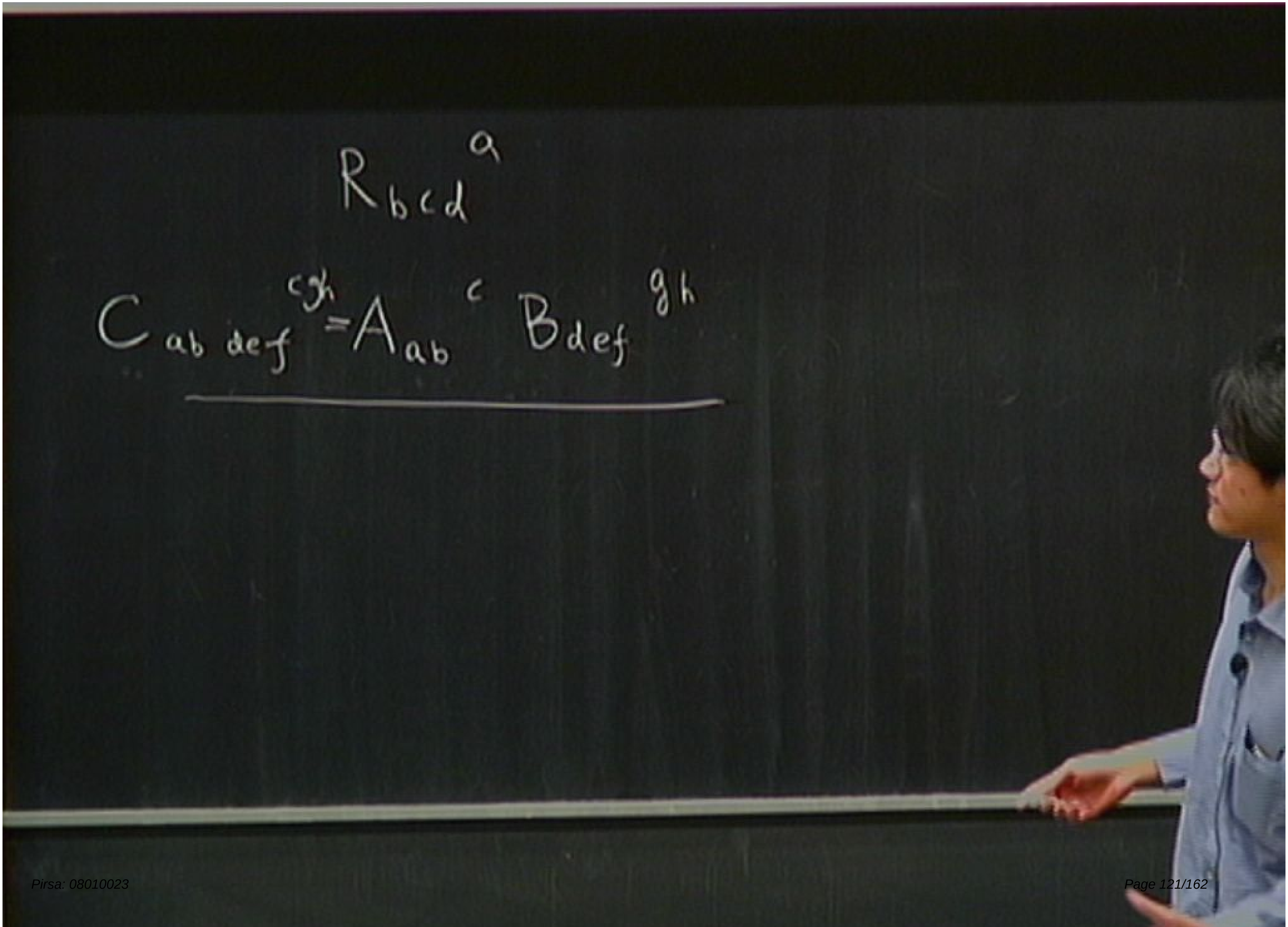
st<u>ress</u>


$R_{bcd}{}^{a}$

$$R_{bcd}{}^{a}$$

$$A_{ab}{}^{c}\, B_{def}{}^{gh}$$

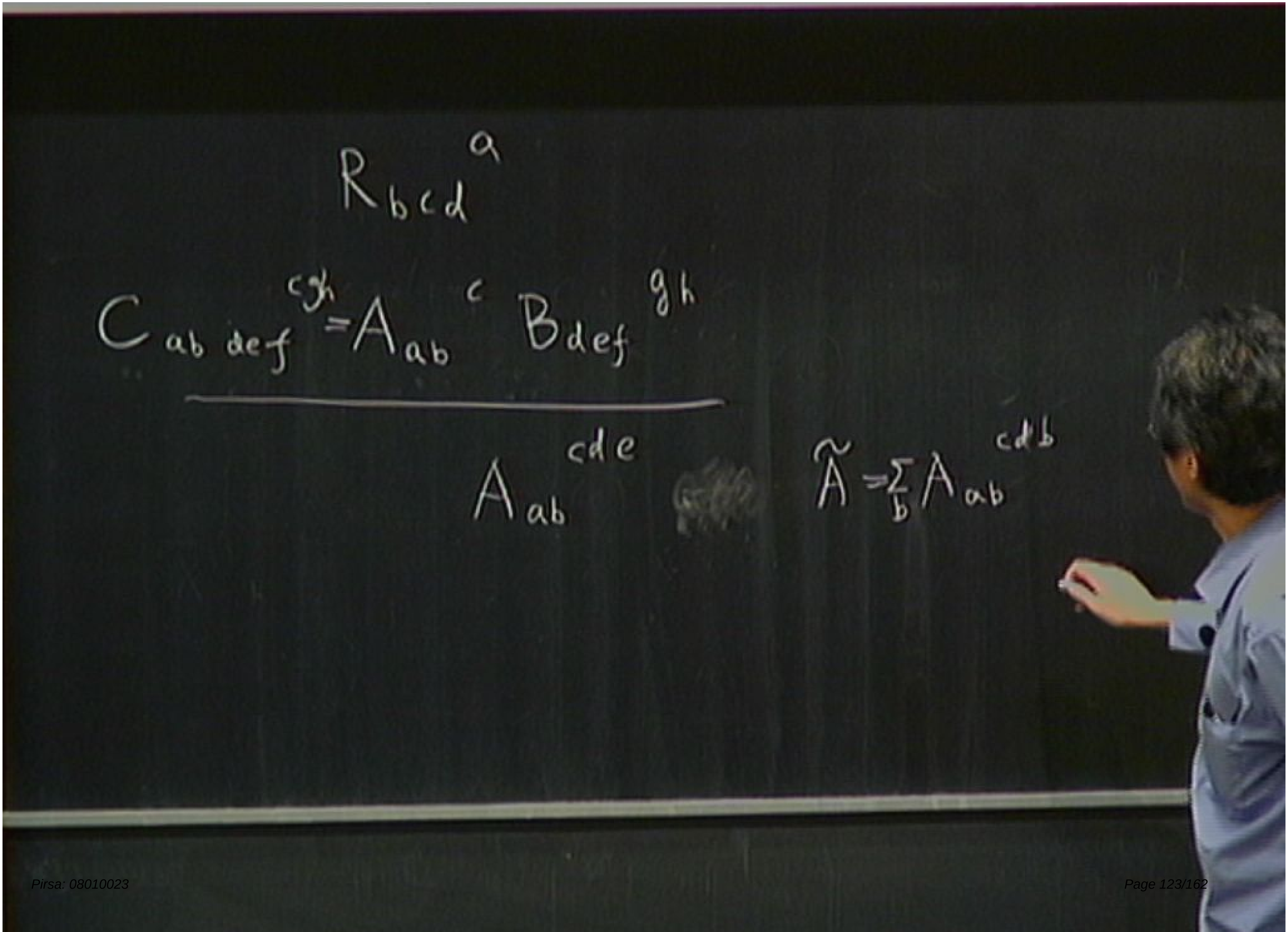

$R_{bcd}{}^{a}$
$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$

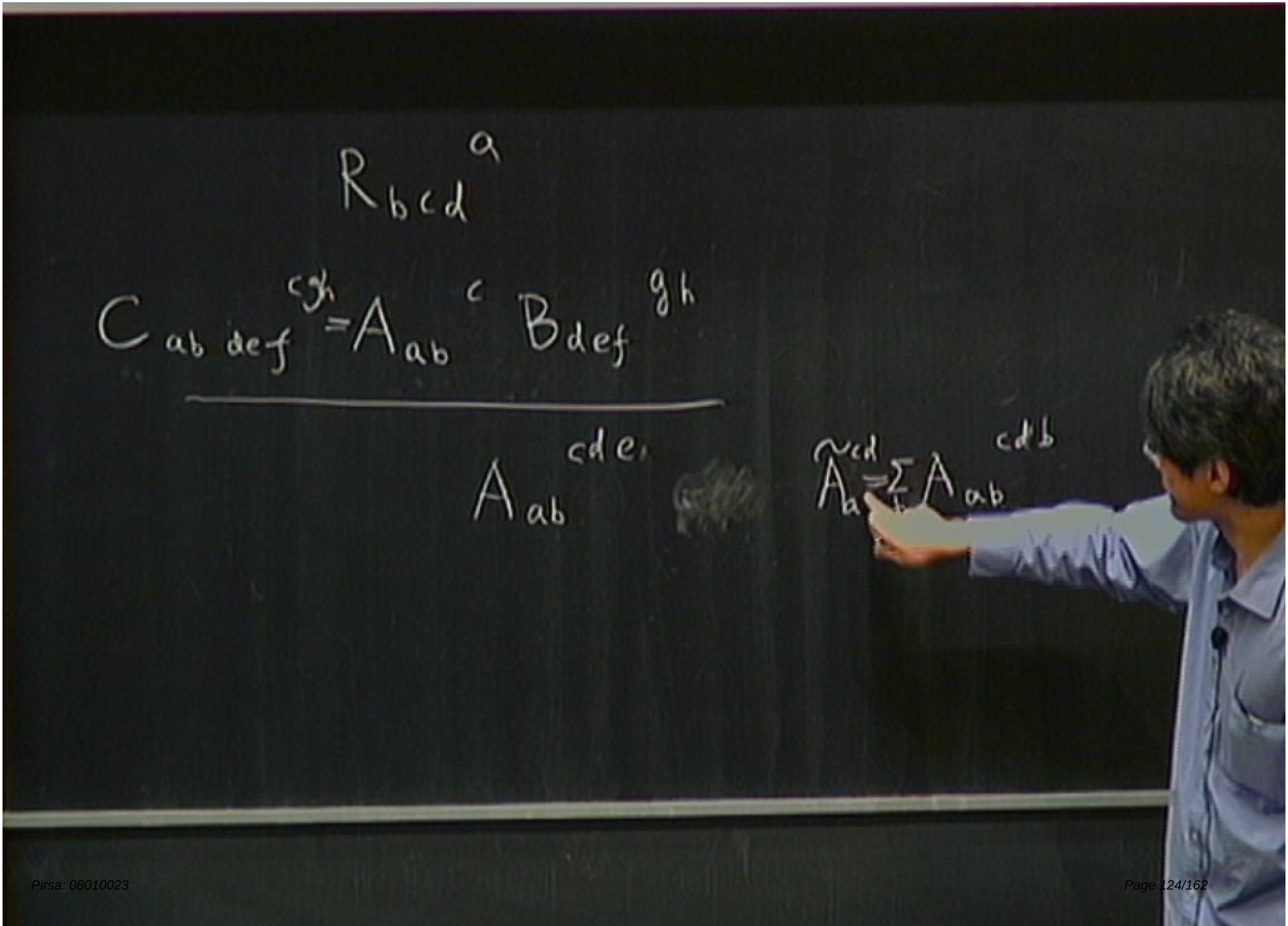


$R_{bcd}{}^{a}$
$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c} B_{def}{}^{gh}$

$$R_{bcd}{}^{a}$$

$$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$$


$R_{bcd}{}^{a}$
$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$
$A_{ab}{}^{cde}$
$\tilde{A} = \sum_b A_{ab}{}^{cdb}$


$R_{bcd}{}^{a}$
$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$
$A_{ab}{}^{cde}$
$\tilde{A}_{a}{}^{cd} = \sum_{b} A_{ab}{}^{cdb}$

$$R_{bcd}{}^{a}$$

$$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$$

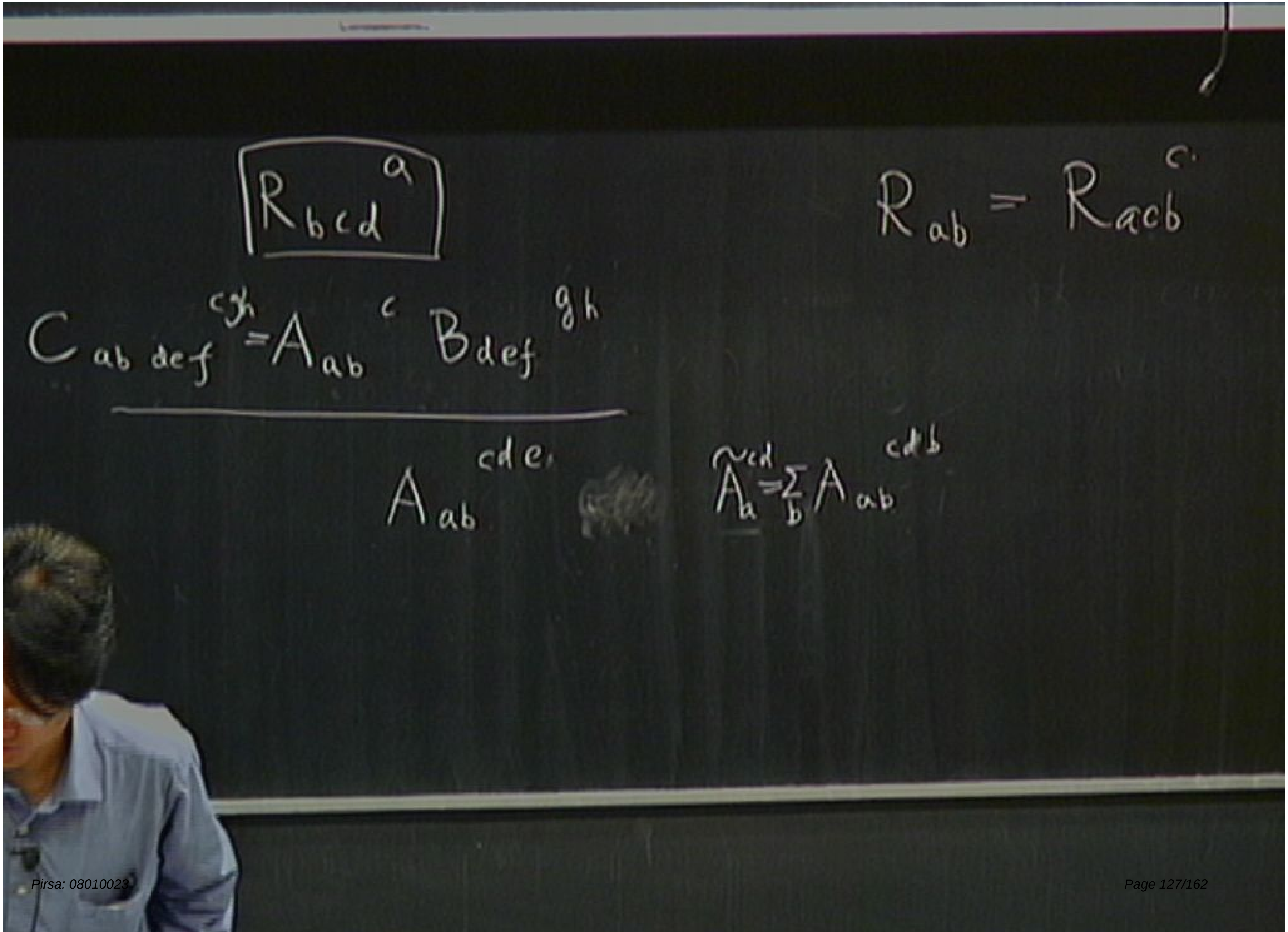
$$A_{ab}{}^{cde}$$

$$\tilde{A}_{a}{}^{cd} = \sum_{b} A_{ab}{}^{cdb}$$

$$\boxed{R_{bcd}{}^{a}}$$

$$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$$

$$A_{ab}{}^{cde} \qquad \tilde{A}_{a}{}^{cd} = \sum_{b} A_{ab}{}^{cdb}$$


$\boxed{R_{bcd}{}^{a}}$
$R_{ab} = R_{acb}{}^{c}$
$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c} B_{def}{}^{gh}$
$A_{ab}{}^{cde}$
$\tilde{A}_{a}{}^{cd} = \sum_{b} A_{ab}{}^{cdb}$

$$\boxed{R_{bcd}{}^{a}}$$

$$R_{ab} = R_{acb}{}^{c}$$

Ricci Tensor

$$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$$

$$A_{ab}{}^{cde}$$

$$\tilde{A}_{a}{}^{cd} = \sum_{b} A_{ab}{}^{cdb}$$

$$\boxed{R_{bcd}{}^{a}}$$

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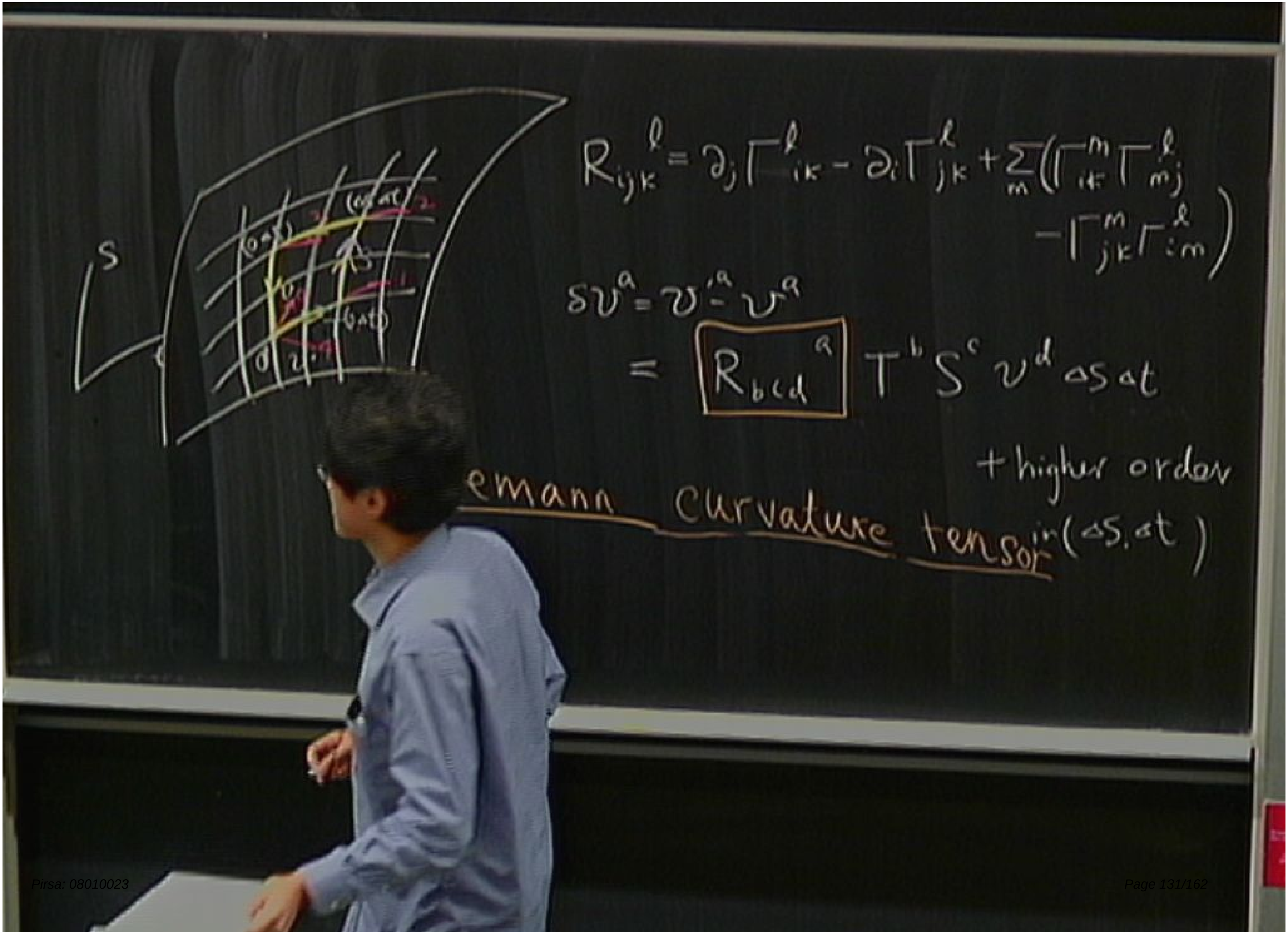
S
$(0,\Delta t)$
$(\Delta s,\Delta t)$
$(\Delta s,0)$
$R_{ijk}{}^{l} = \partial_j \Gamma^{l}_{ik} - \partial_i \Gamma^{l}_{jk} + \sum_m \left(\Gamma^{m}_{ik} \Gamma^{l}_{mj} - \Gamma^{m}_{jk} \Gamma^{l}_{im} \right)$
$\delta v^a = v'^a - v^a$
$= \boxed{R_{bcd}{}^{a}}\, T^b S^c v^d \Delta s \Delta t$
+ higher order in $(\Delta s, \Delta t)$
emann curvature tensor

$$\boxed{R_{bcd}{}^{a}}$$

$$R_{ab} = R_{acb}{}^{c}$$

Ricci Tensor

$$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$$

$$A_{ab}{}^{cde}$$

$$\tilde{A}_{a}{}^{cd} = \sum_{b} A_{ab}{}^{cdb}$$

$$R_{ab} \stackrel{?}{=} 8\pi G_N T_{ab}$$

$$\boxed{R_{bcd}{}^{a}}$$

$$R_{ab} = R_{acb}{}^{c}$$

Ricci Tensor

$$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$$

$$A_{ab}{}^{cde}$$

$$\tilde{A}_{a}{}^{cd} = \sum_{b} A_{ab}{}^{cdb}$$

$$\nabla^{b}\, T_{ab} = 0$$

$$R_{ab} \overset{?}{=} 8\pi G_N T_{ab}$$

$$\boxed{R_{bcd}{}^{a}}$$

$$C_{ab\,def}{}^{cgh} = A_{ab}{}^{c}\, B_{def}{}^{gh}$$

$$A_{ab}{}^{cde}$$

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Ricci Tensor

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Ricci Tensor

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$$R_{ab} \overset{?}{=} 8\pi G_N T_{ab}$$

$R = R_{ab}\, g^{ab}$ Ricci scalar

$$R = R_{ab}\, g^{ab} \qquad \text{Ricci scalar}$$

$$\boxed{g_{ab}\, g^{bc} = \delta_a{}^c}$$

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$\underline{R = R_{ab}\, g^{ab}}$ Ricci scalar

$$\boxed{g_{ab}\, g^{bc} = \delta_a{}^c}$$

$R = R_{ab} g^{ab}$ Ricci scalar

$$\boxed{g_{ab}\, g^{bc} = \delta_a^{\ c}}$$

$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$ Einstein Tensor

$\underline{R = R_{ab}\, g^{ab}}$ Ricci scalar

$$\boxed{g_{ab}\, g^{bc} = \delta_a^{\;c}}$$

$= R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$ Einstein Tensor

$G_{\mu\nu} = 0$

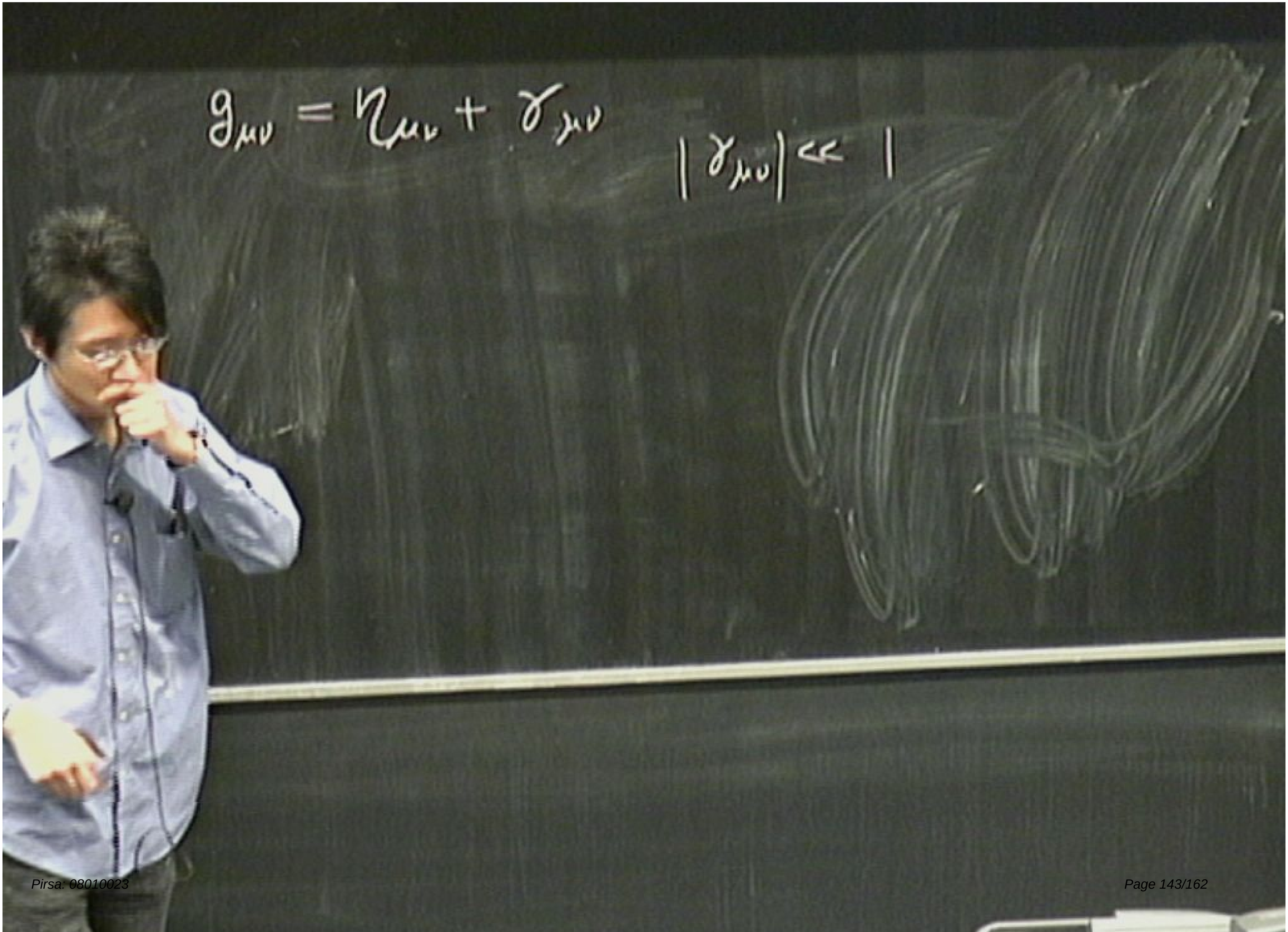
$R = R_{ab}\, g^{ab}$ Ricci scalar

$$\boxed{g_{ab}\, g^{bc} = \delta_a^{\;c}}$$

$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \cdot R$ Einstein Tensor

$\nabla^\mu G_{\mu\nu} = 0$

$$\boxed{G_{\mu\nu} = 8\pi G_N T_{\mu\nu}}$$


$g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$
$|\gamma_{\mu\nu}| \ll 1$

$$g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$$

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$$g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$$

$$|\gamma_{\mu\nu}| \ll 1$$

$$\partial_\mu A^\mu = 0$$

$$A^- = 0$$

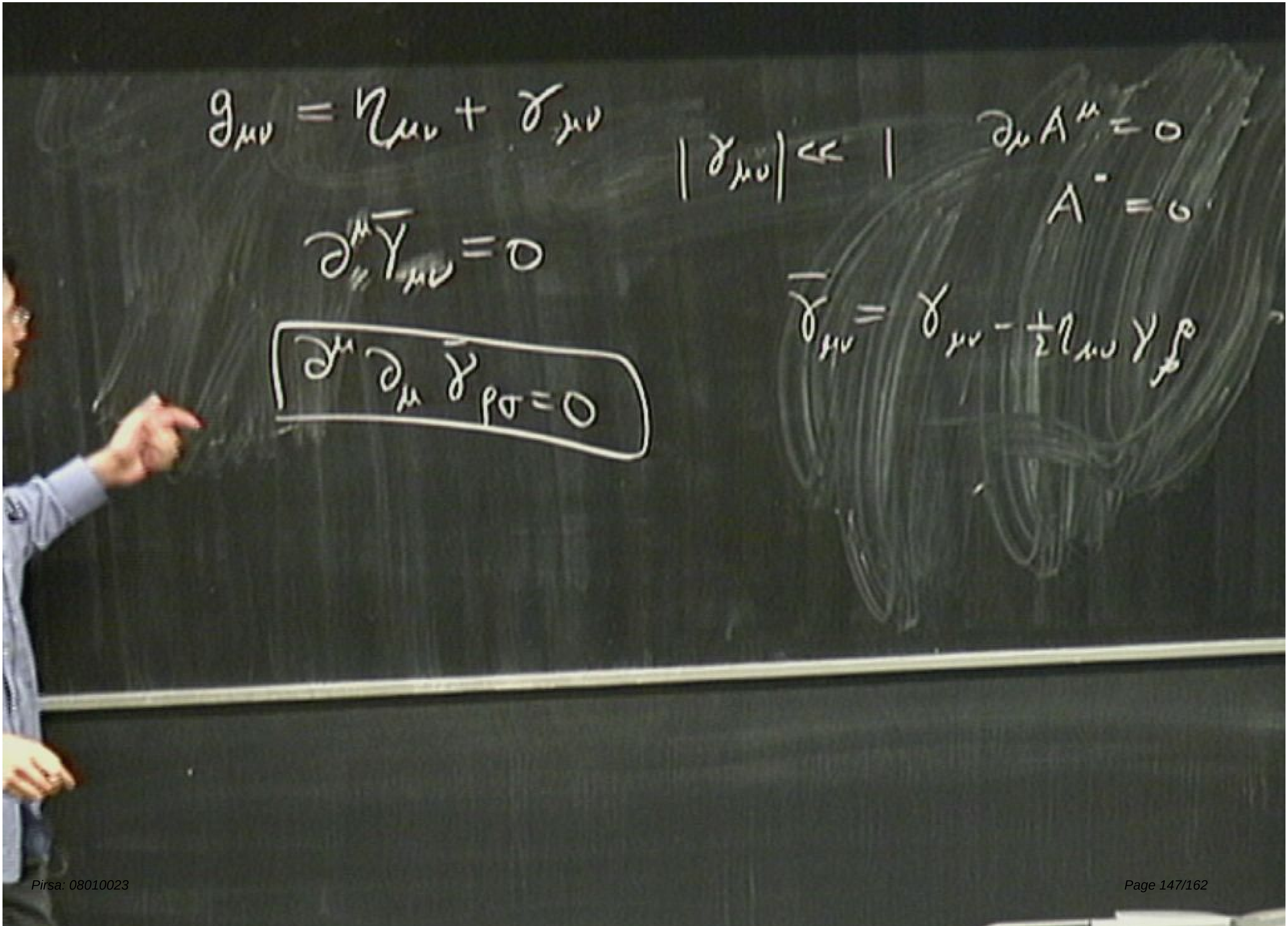
$$g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$$

$$|\gamma_{\mu\nu}| \ll 1$$

$$\partial_\mu A^\mu = 0$$

$$A^0 = 0$$

$$\partial^\mu \bar{\gamma}_{\mu\nu} = 0$$


$g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$
$|\gamma_{\mu\nu}| \ll 1$
$\partial_\mu A^\mu = 0$
$A^0 = 0$
$\partial^\mu \bar{\gamma}_{\mu\nu} = 0$
$\bar{\gamma}_{\mu\nu} = \gamma_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}\gamma^\rho_\rho$
$\boxed{\partial^\mu \partial_\mu \bar{\gamma}_{\rho\sigma} = 0}$

Einstein Equ

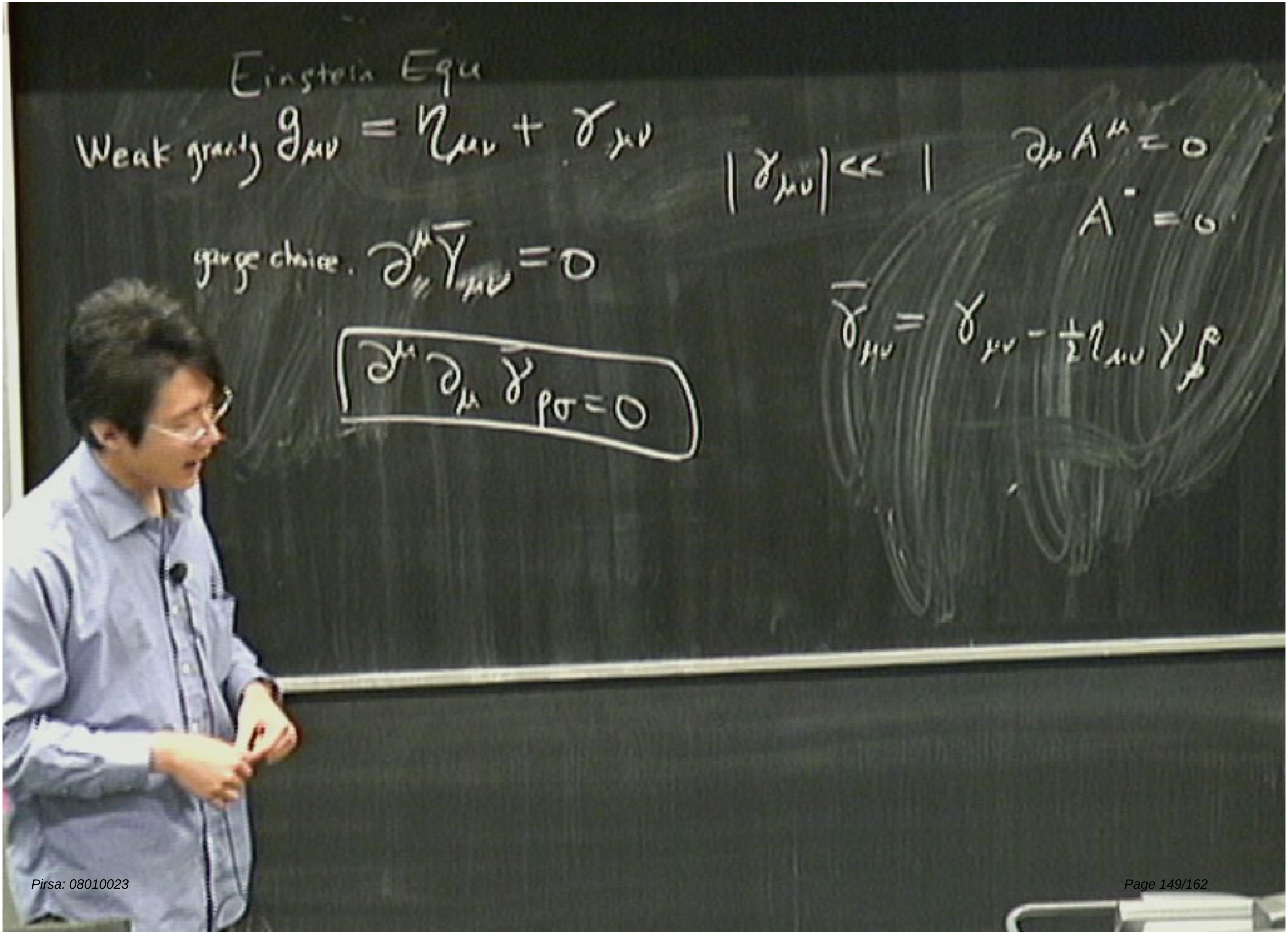
Weak gravity $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$ $\quad |\gamma_{\mu\nu}| \ll 1$ $\quad \partial_\mu A^\mu = 0$

$A^0 = 0$

gauge choice. $\partial^\mu \bar{\gamma}_{\mu\nu} = 0$

$\bar{\gamma}_{\mu\nu} = \gamma_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}\gamma_\rho{}^\rho$

$$\boxed{\partial^\mu \partial_\mu \bar{\gamma}_{\rho\sigma} = 0}$$


Einstein Equ
Weak gravity $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$
$|\gamma_{\mu\nu}| \ll 1$
$\partial_\mu A^\mu = 0$
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$\bar{\gamma}_{\mu\nu} = \gamma_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}\gamma_\rho^\rho$
$\boxed{\partial^\mu \partial_\mu \bar{\gamma}_{\rho\sigma} = 0}$

Einstein Equ

Weak gravity $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$

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$\partial_\mu A^\mu = 0$

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Einstein Equ

Weak gravity $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$

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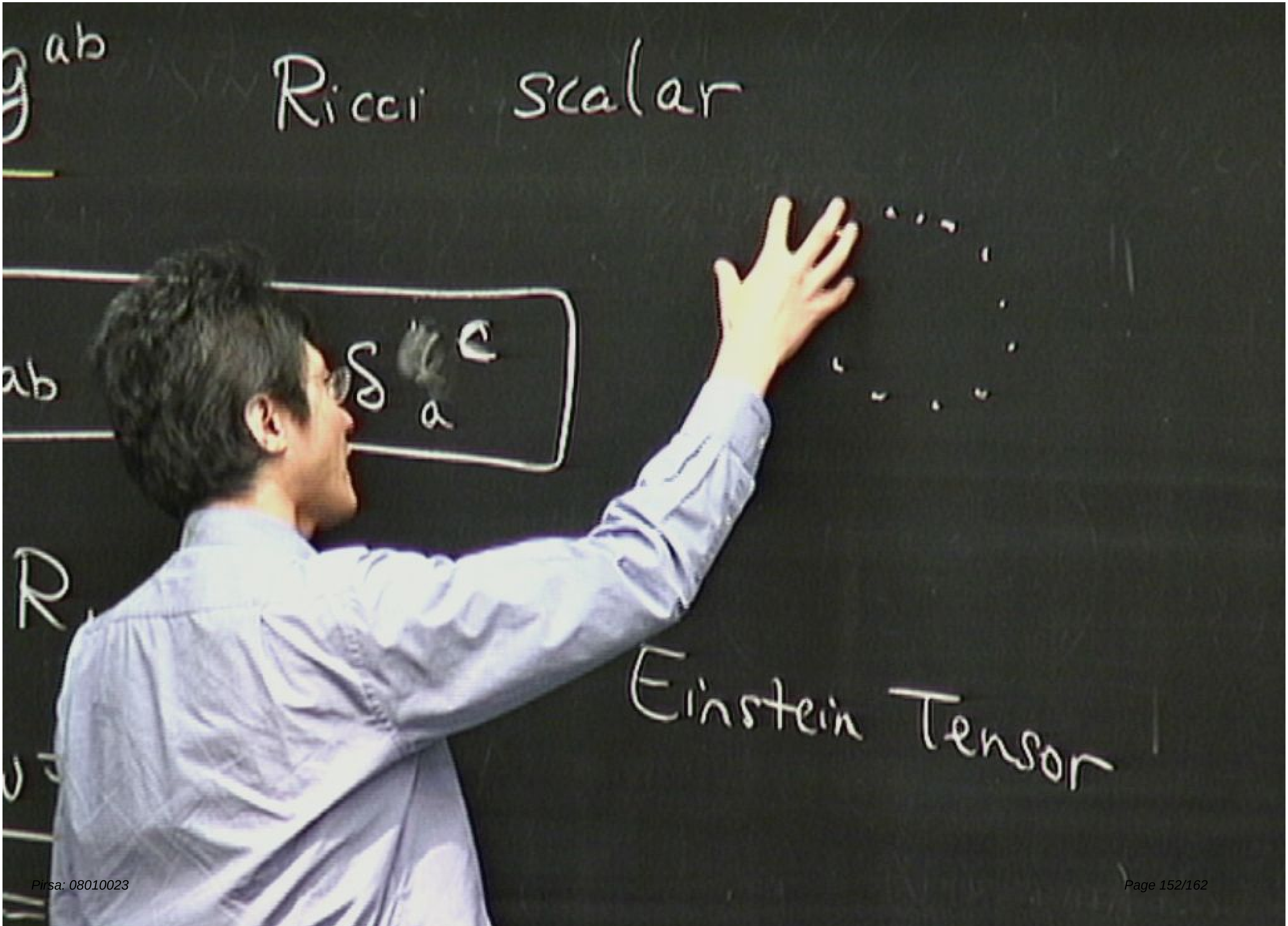
gauge choice. $\partial^\mu \bar{\gamma}_{\mu\nu} = 0$

$\bar{\gamma}_{\mu\nu} = \gamma_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}\gamma_\rho^\rho$

$$\boxed{\partial^\mu \partial_\mu \bar{\gamma}_{\rho\sigma} = 0}$$

$5 - 3 = \underline{2}$


Ricci scalar
Einstein Tensor

g^{ab} Ricci scalar

$\boxed{{}_{ab}\; g^{bc} = \delta_a^{\,c}}$

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \cdot R$ Einstein Tensor

$\nu = 0$

$= 8\pi G T$

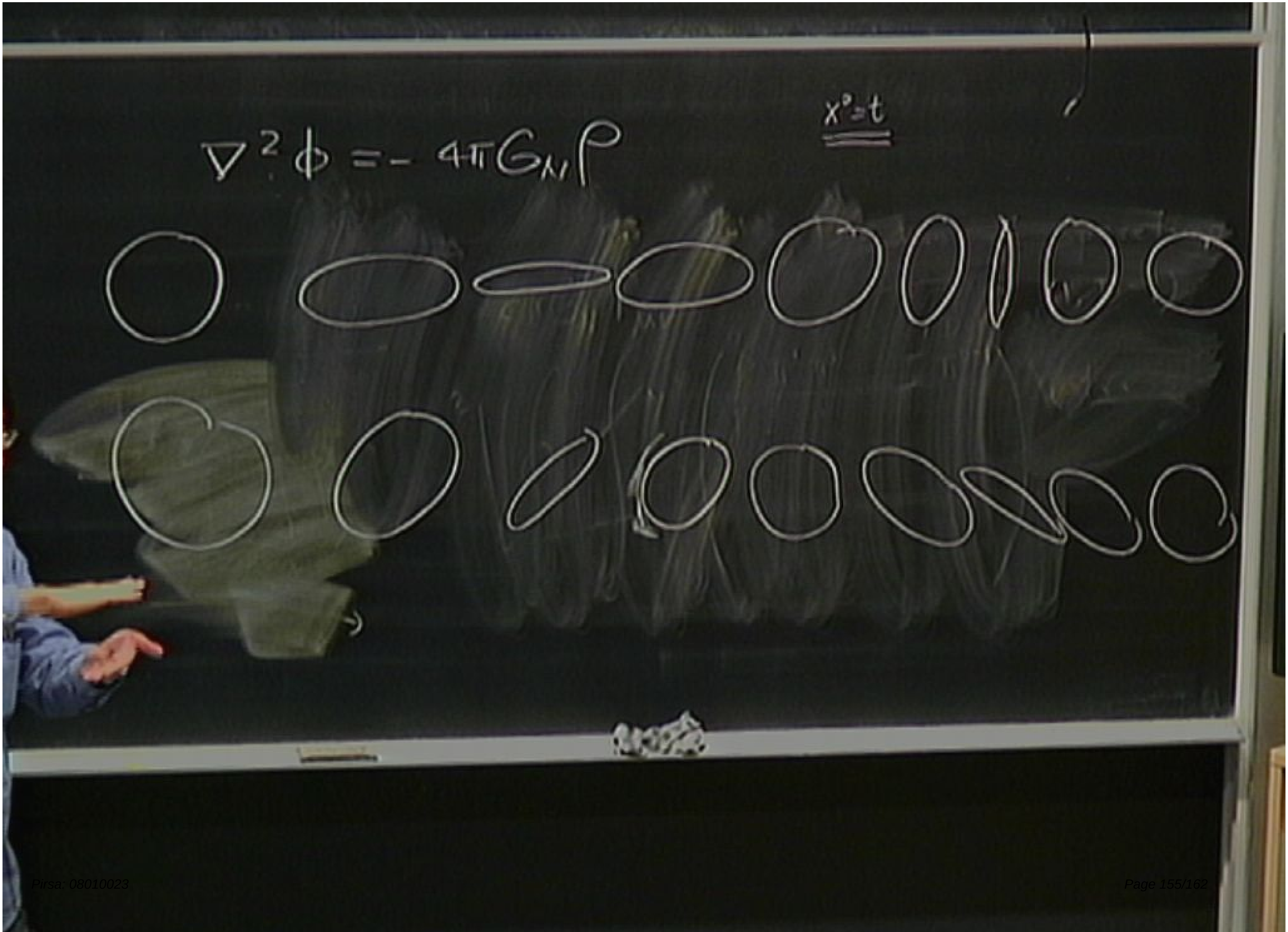
g^{ab} Ricci scalar

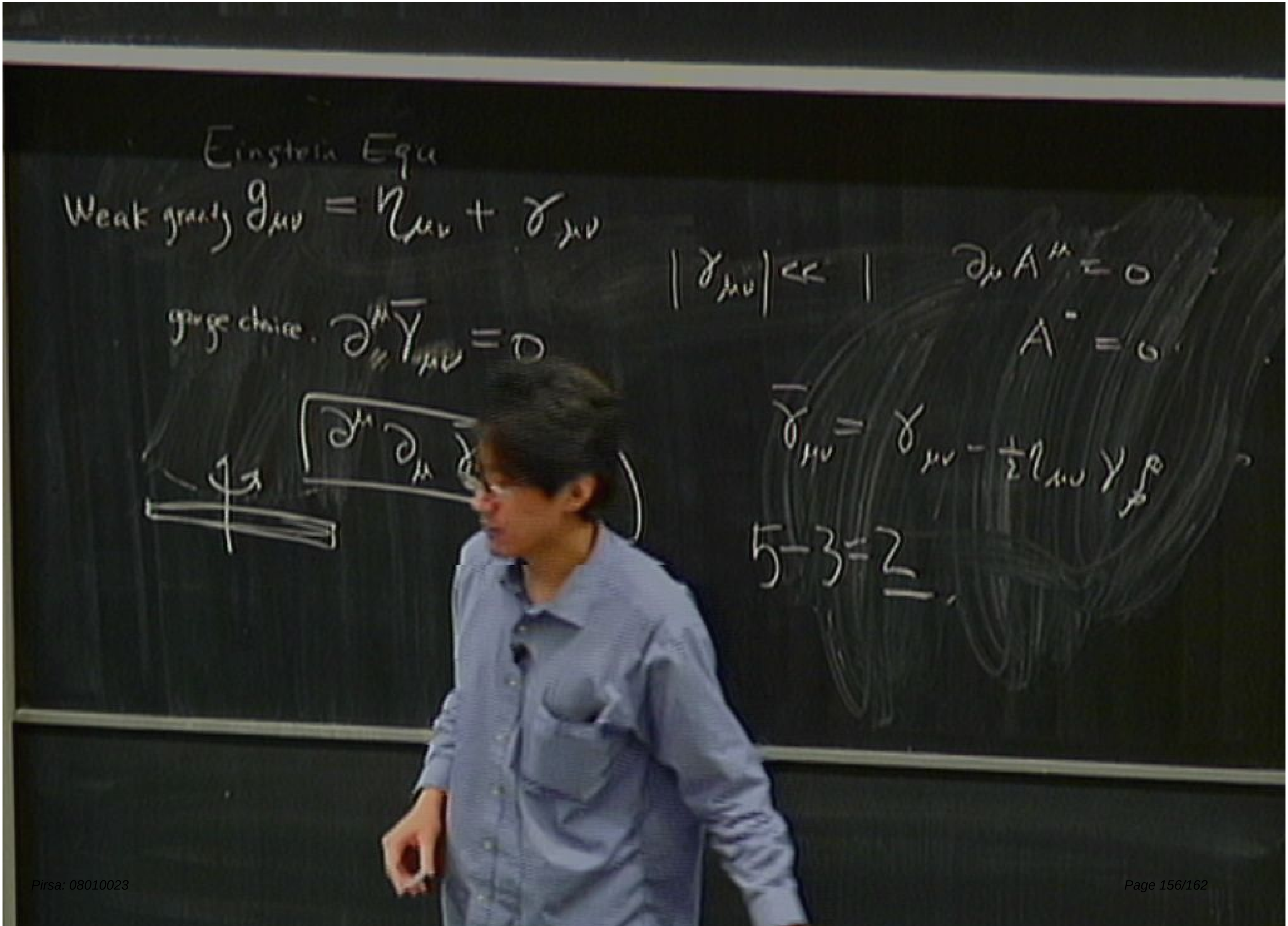
$$\boxed{g_{ab}\, g^{bc} = \delta_a{}^c}$$

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \cdot R$ Einstein Tensor

$\nu = 0$

$= 8\pi G\, T$


$\nabla^2 \phi = - 4\pi G_N \rho$
$x^0 = t$


Einstein Equ
Weak gravity $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$
$|\gamma_{\mu\nu}| \ll 1$
$\partial_\mu A^\mu = 0$
gauge choice. $\partial^\mu \bar{\gamma}_{\mu\nu} = 0$
$A^0 = 0$
$\bar{\gamma}_{\mu\nu} = \gamma_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}\gamma^\rho_\rho$
$5-3=2$

Einstein Equ

Weak gravity $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$

$|\gamma_{\mu\nu}| \ll 1$ $\quad \partial_\mu A^\mu = 0$

gauge choice. $\partial^\mu \bar{\gamma}_{\mu\nu} = 0$ $\quad A^0 = 0$

$$\boxed{\partial^\mu \partial_\mu \bar{\gamma}_{\rho\sigma} = 0}$$

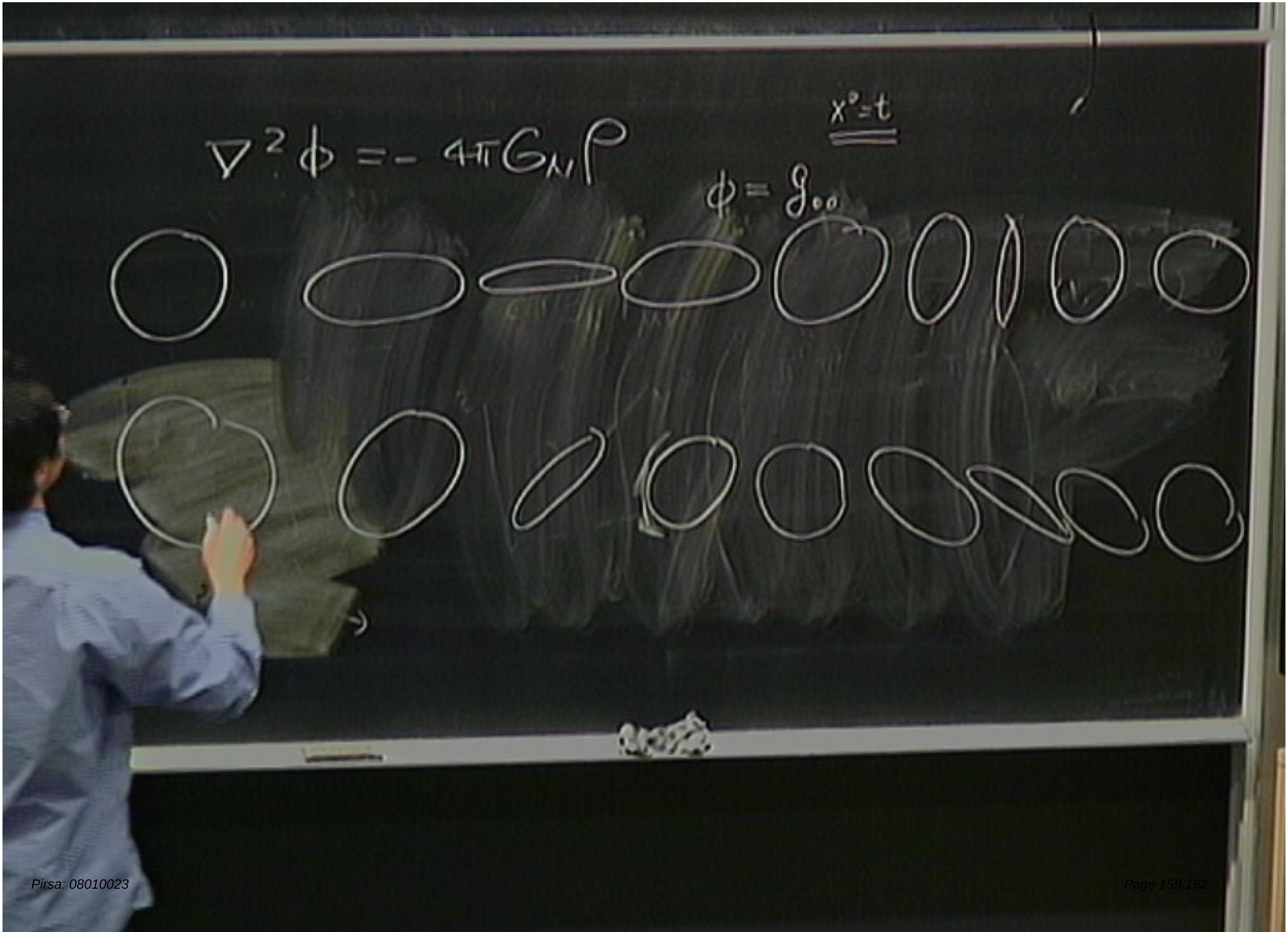
$$\bar{\gamma}_{\mu\nu} = \gamma_{\mu\nu} - \tfrac{1}{2}\eta_{\mu\nu}\gamma_\rho^\rho$$

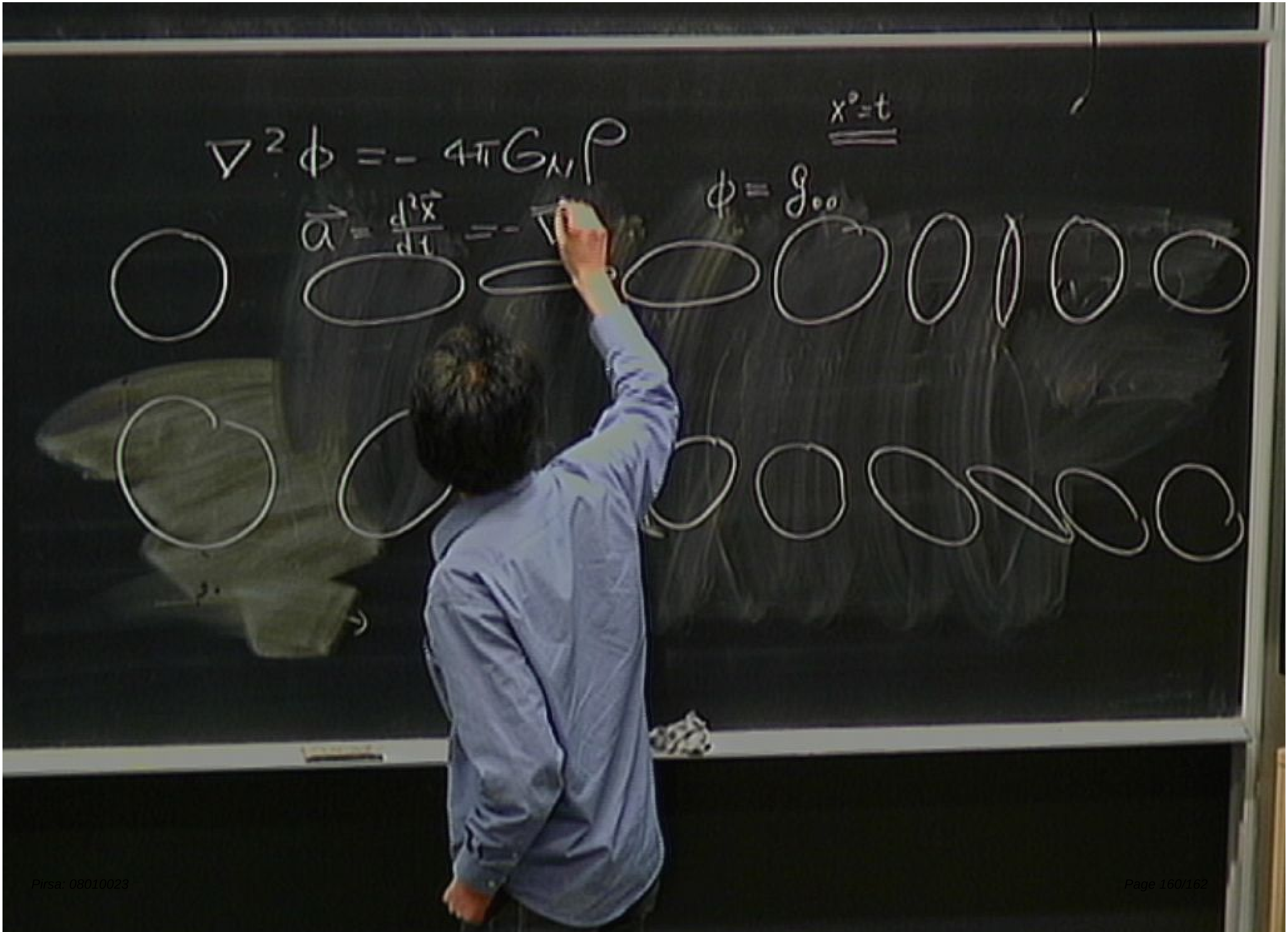
$5 - 3 = 2$

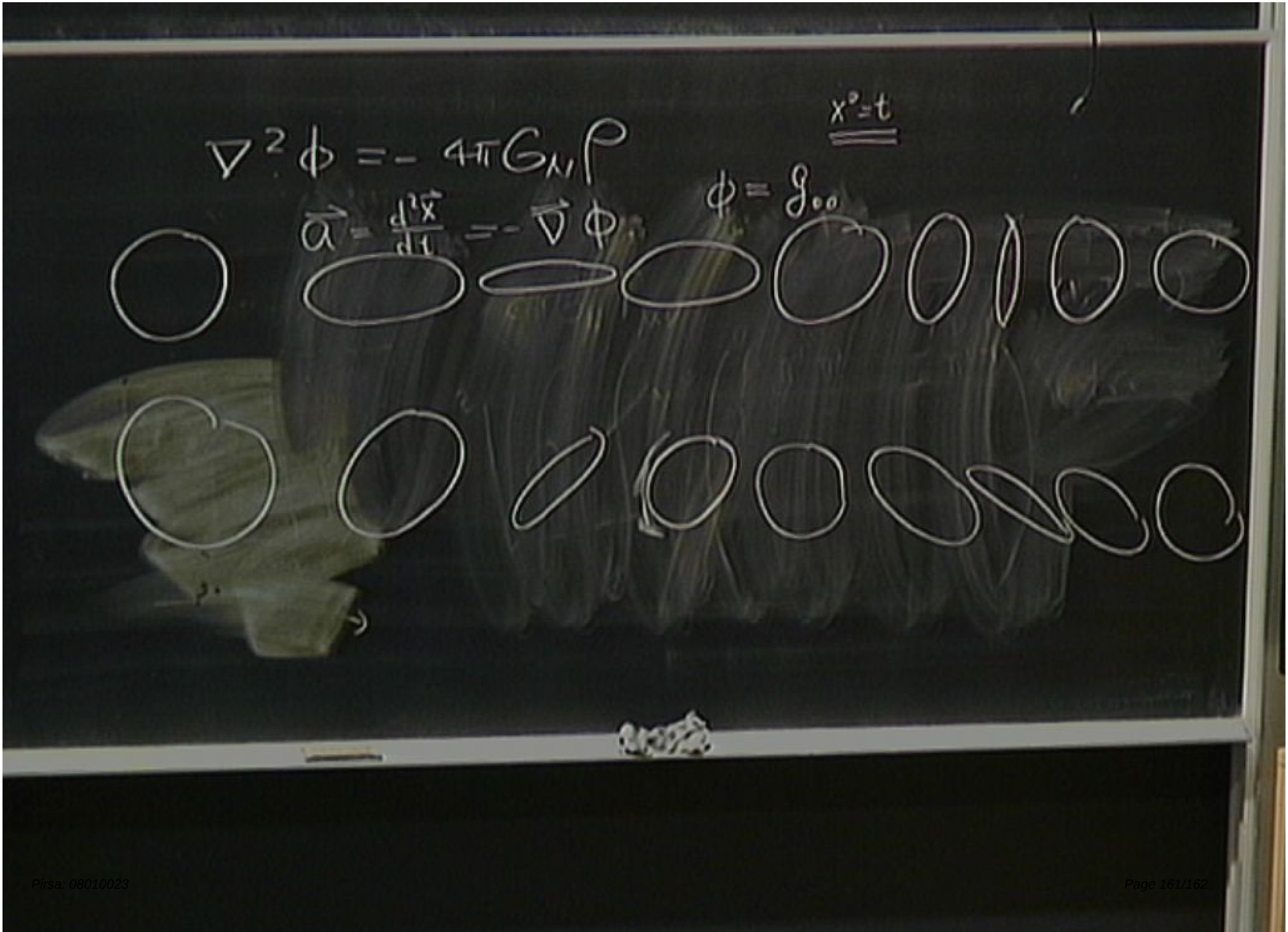
$$x^0 = t$$

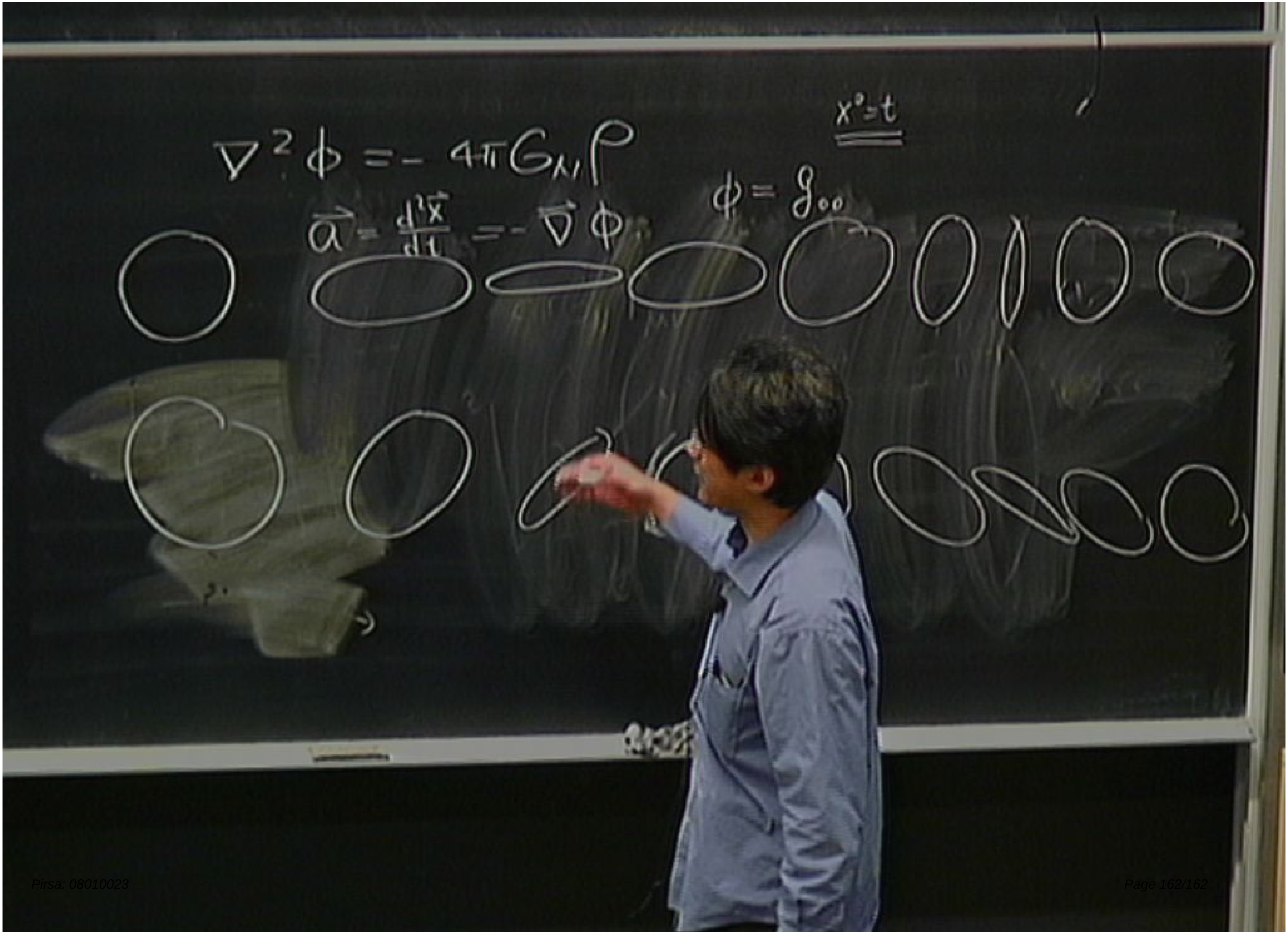
$$\nabla^2 \phi = -4\pi G_N \rho$$

$$\phi = g_{00}$$


$\nabla^2 \phi = -4\pi G_N \rho$
$x^0 = t$
$\phi = g_{00}$


$\nabla^2 \phi = -4\pi G_N \rho$
$x^0 = t$
$\phi = g_{00}$
$\vec{a} = \frac{d^2\vec{x}}{dt^2} = -\nabla$


$x^0 = t$
$\nabla^2 \phi = -4\pi G_N \rho$
$\phi = g_{00}$
$\vec{a} = \frac{d^2\vec{x}}{dt^2} = -\vec{\nabla}\phi$


$x^0 = t$
$\nabla^2 \phi = -4\pi G_N \rho$
$\phi = g_{00}$
$\vec{a} = \frac{d^2\vec{x}}{dt^2} = -\vec{\nabla}\phi$