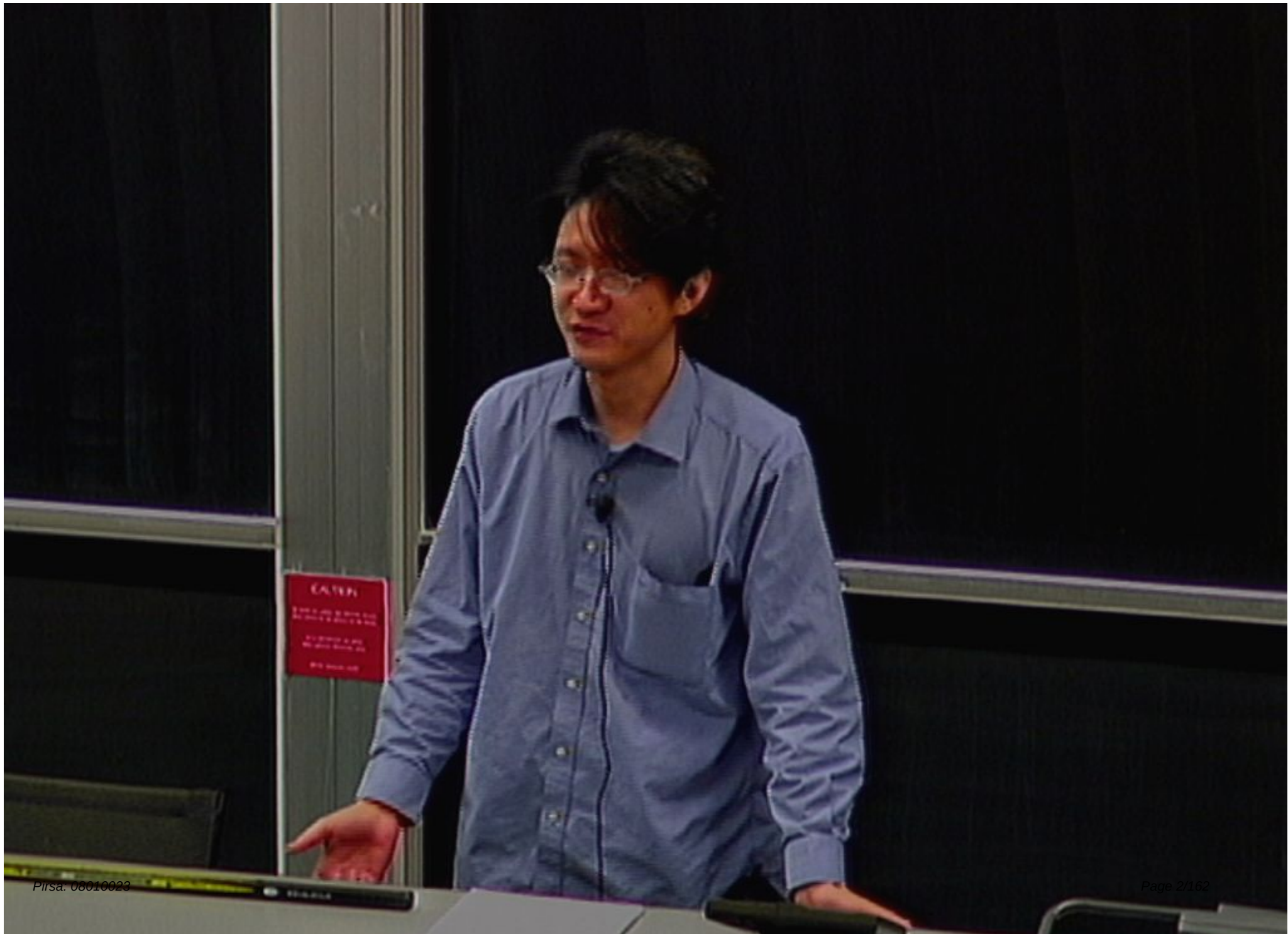


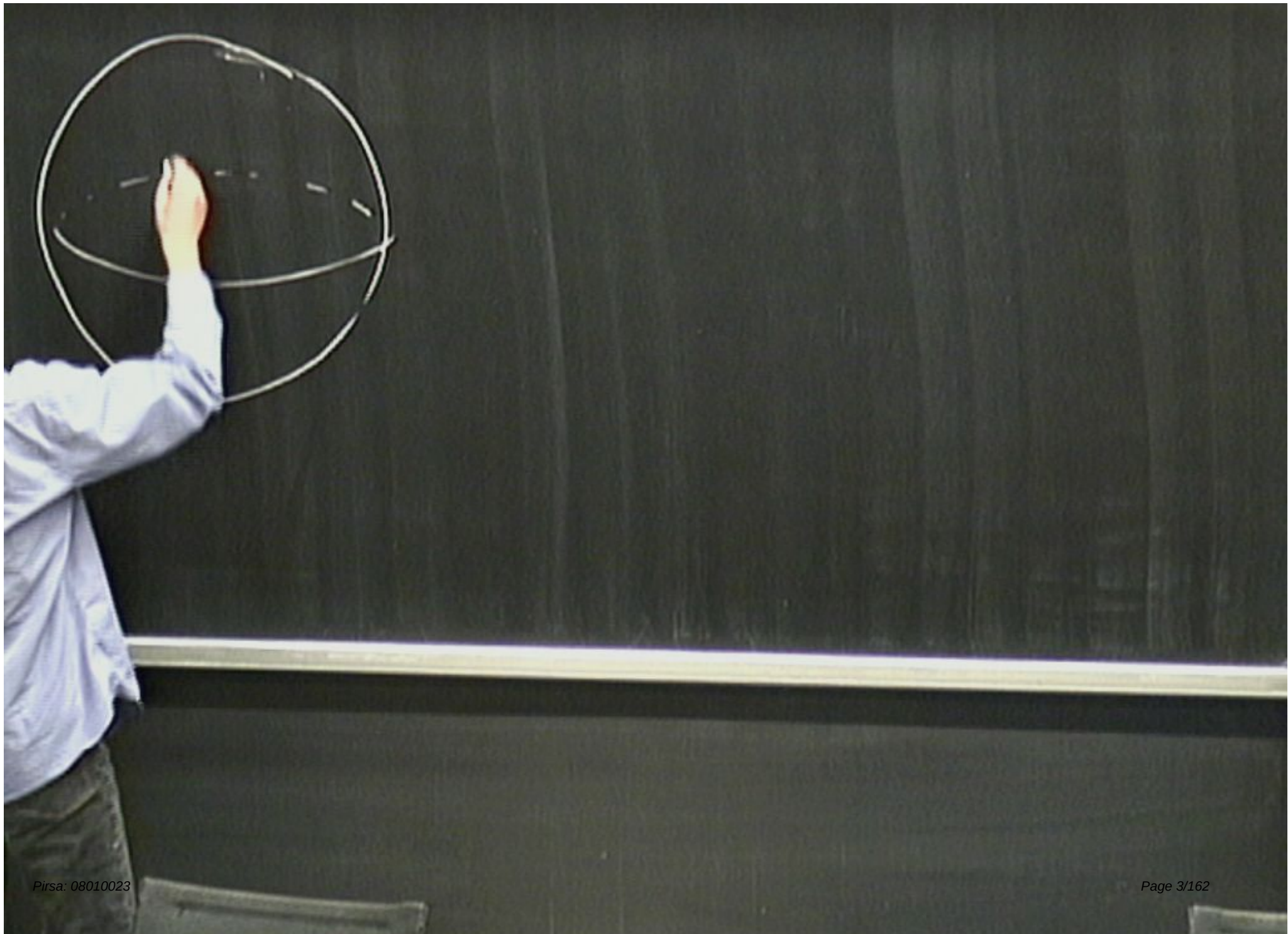
Title: String Theory #2

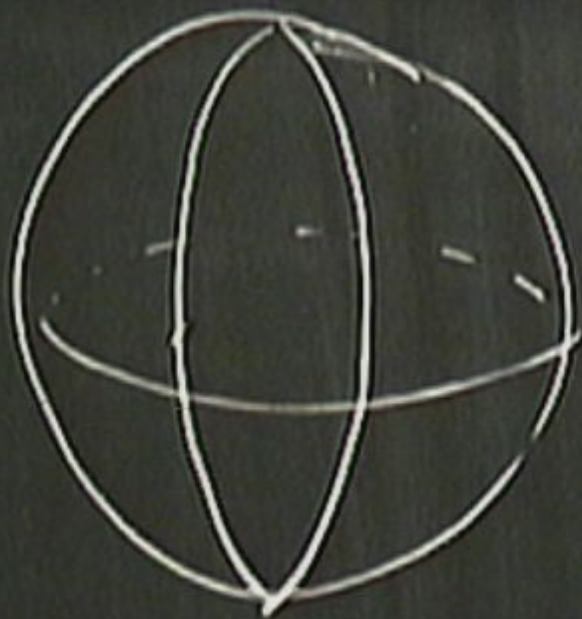
Date: Jan 24, 2008 06:30 PM

URL: <http://pirsa.org/08010023>

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



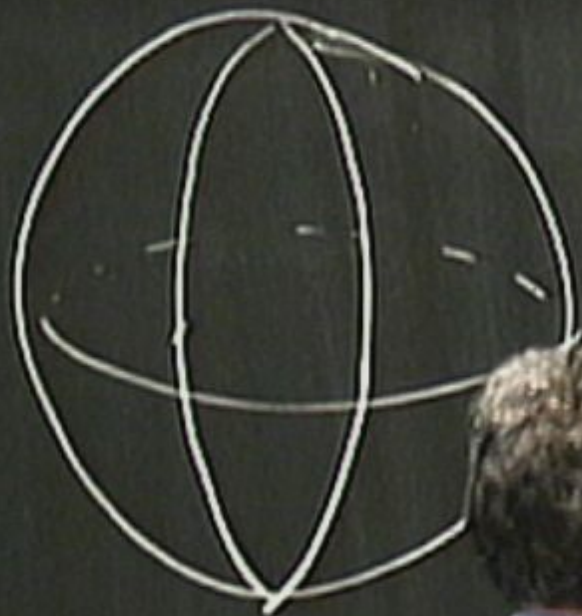






$$x^i(t)$$

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

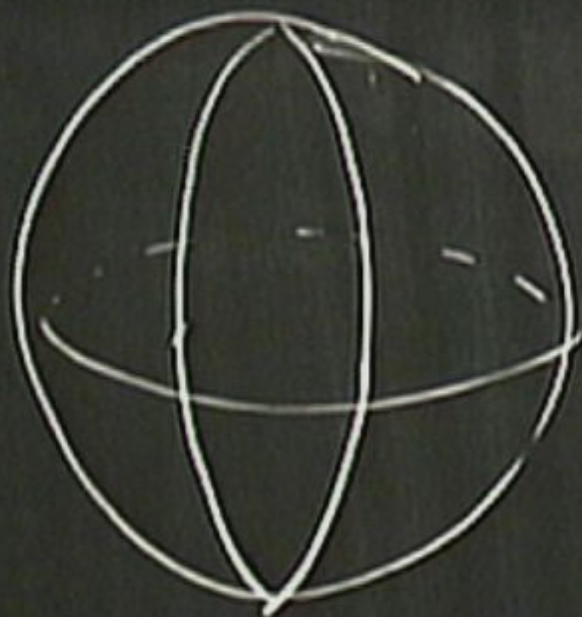


$$x^i(t)$$

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

minimal length.

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

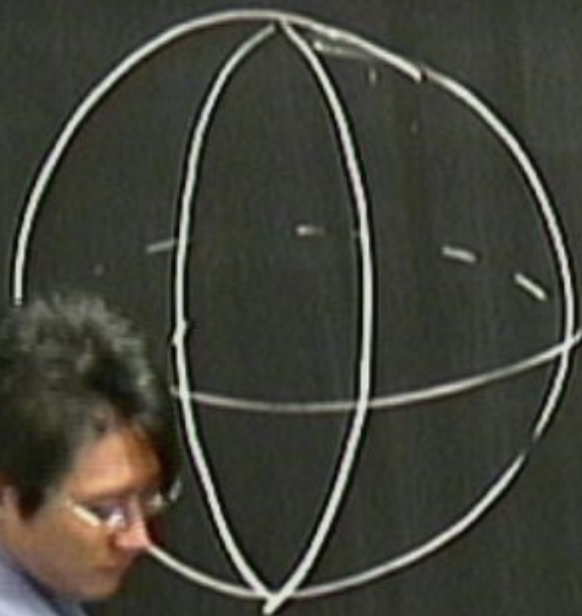


$$x^i(t)$$

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

minimal length.

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



$$x^i(t)$$

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$$\Gamma_{jk}^i = \frac{1}{2} \sum_l g^{il} (g_{je,k} + g_{ke,j} - g_{jk,e})$$



$$x^i(t)$$

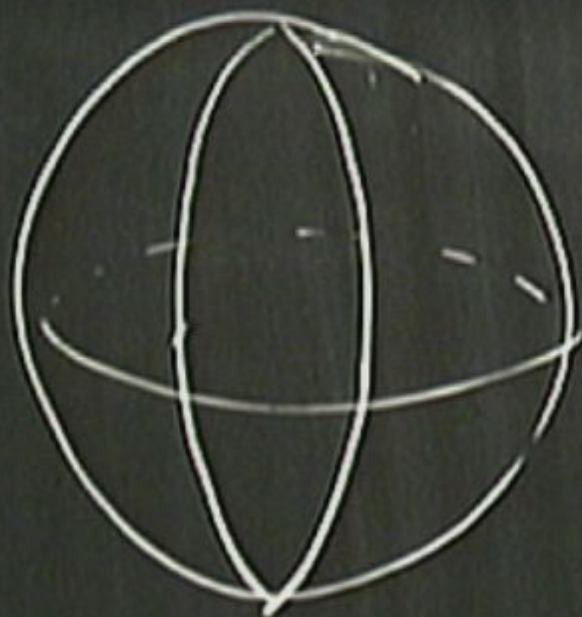
$$S(A, B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$$

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

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

$$= \frac{1}{2} \sum_l g^{il} (g_{je,k} + g_{ke,j} - g_{jke})$$



$$x^i(t)$$

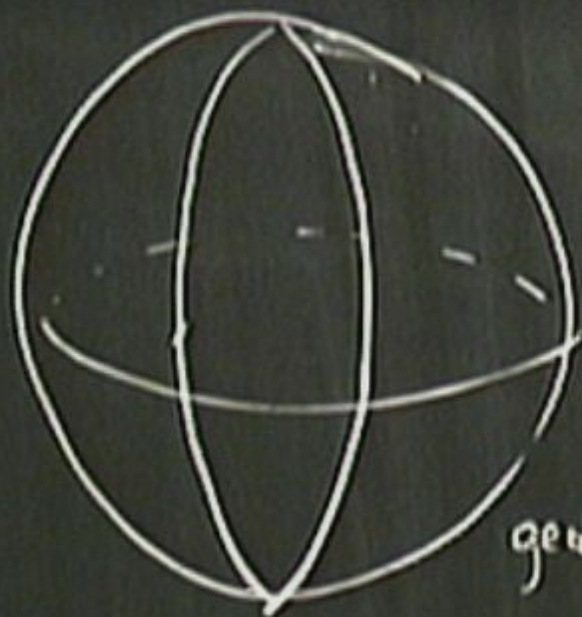
$$S(A, B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$$

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geodesic

minimal length.

$$x^i(t)$$

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

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

$$v^i = x^i(t) - y^i(t)$$



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

$$v^i = x^i(t) - y^i(t)$$

d


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

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

d



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

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

$$a^i =$$



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

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

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



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

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

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



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

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

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

A

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

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

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

A

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

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

(1,3) tensor

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

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

(1,3) tensor

$$\boxed{R^a{}_{bcd}(x)} X^c T^b T^d$$



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

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

(1,3) tensor

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



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

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

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$$x^i(t)$$

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

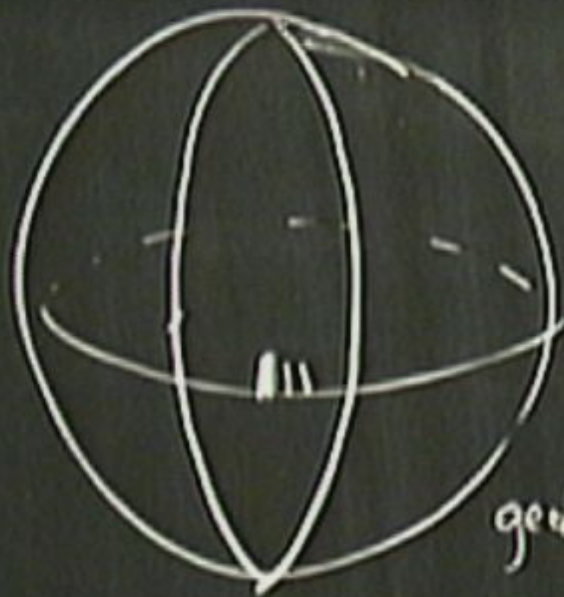
minimal length.

geodesic

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

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

$$\Gamma_{jk}^i = \frac{1}{2} \sum_l g^{il} (g_{jl,k} + g_{kl,j} - g_{ik,l})$$



geodesic

$$x^i(t)$$

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

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

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

(1,3) tensor

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

$$= - \boxed{R^a_{bcd}(x)} \delta x^c T^b T^d$$



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

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

(1,3) tensor

$$x^a \rightarrow y^a \quad \partial^a \frac{\delta x^a}{t^2}$$

$$= - \boxed{R_{bcd}{}^a} \delta x^c T^b T^d$$

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



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

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

(1,3) tensor

$$a^R = \frac{d^2 s}{d\tau^2}$$

$$- \boxed{R_{bcd}{}^a} \delta x^c T^b T^d$$

$$x^a \rightarrow y^a$$

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

$$R_{\bar{b}\bar{c}\bar{d}}{}^{\bar{a}}$$



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

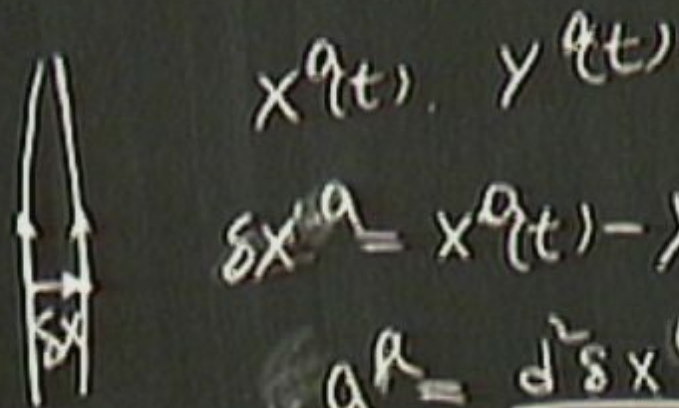
$$\delta x^a = x^a(t) - y^a(t)$$

(1,3) tensor

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

$x^a \rightarrow y^a$

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



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

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

(1,3) tensor

$$a^R = \frac{d^2 \delta x^a}{dt^2} = - \boxed{R_{bcd}{}^a} \tau^b \tau^d$$

$$x^a \rightarrow y^a$$

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



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

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(1,3) tensor

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

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

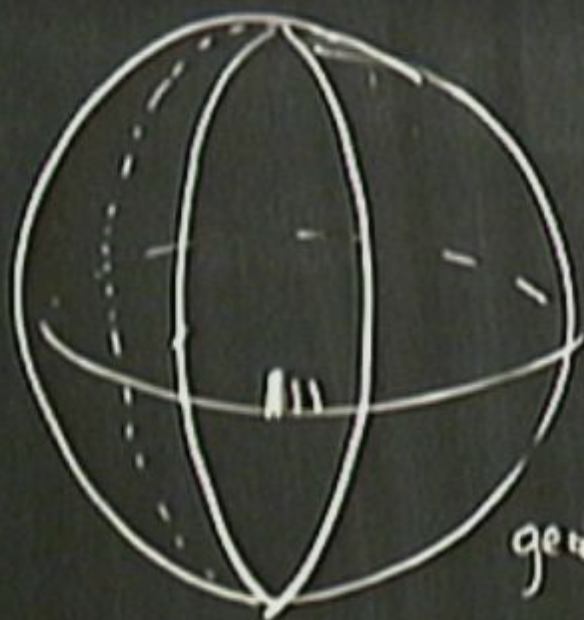
$$\delta x^a = x^a(t) - y^a(t)$$

(1,3) tensor

$$x^a \rightarrow y^a$$

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

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



geodesic

minimal length.

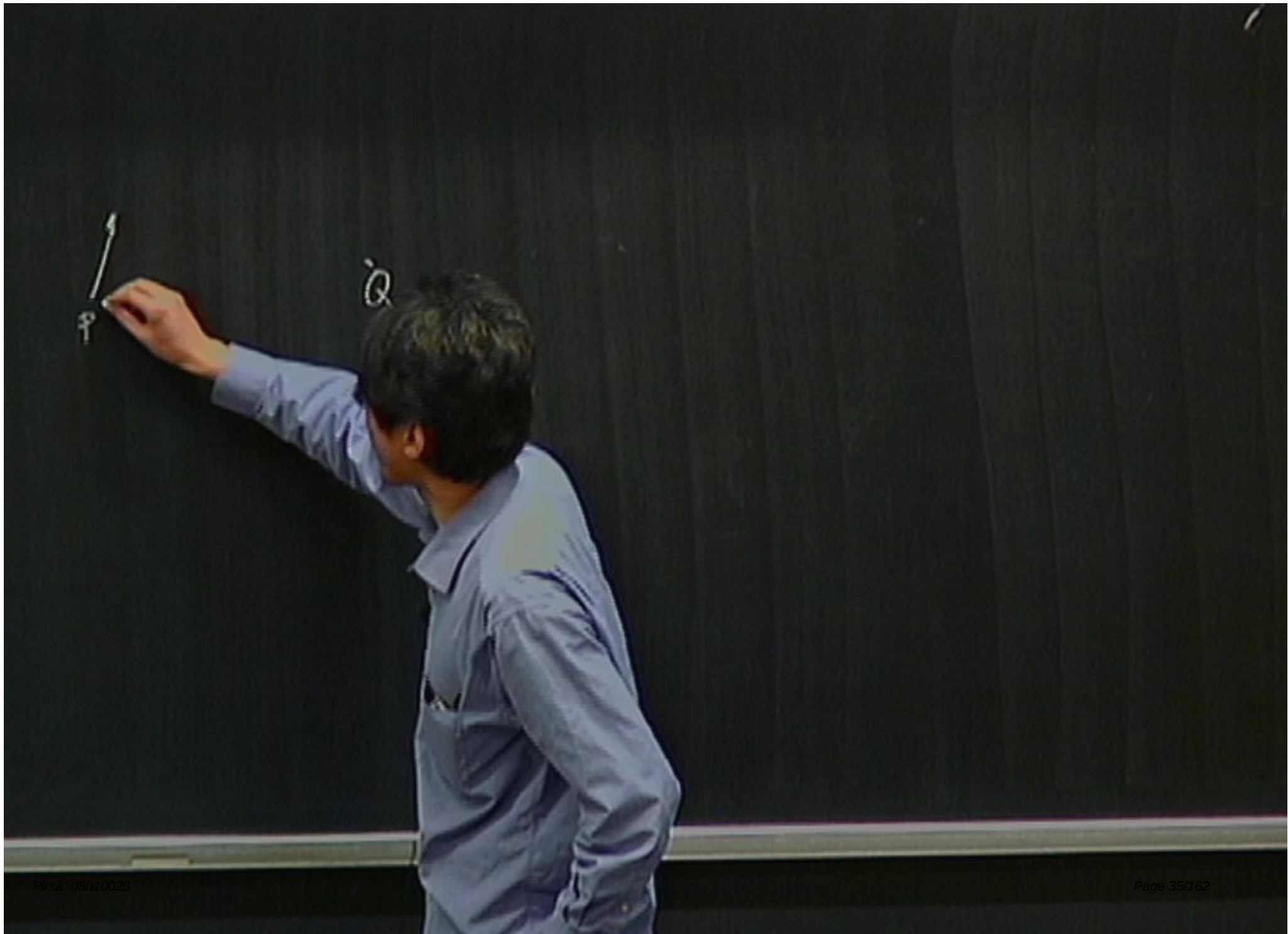
$$\frac{d^2 x^i}{dt^2} + \sum_{j,k} \Gamma_{jk}^i(x) \frac{dx^j}{dt} \frac{dx^k}{dt} = 0$$

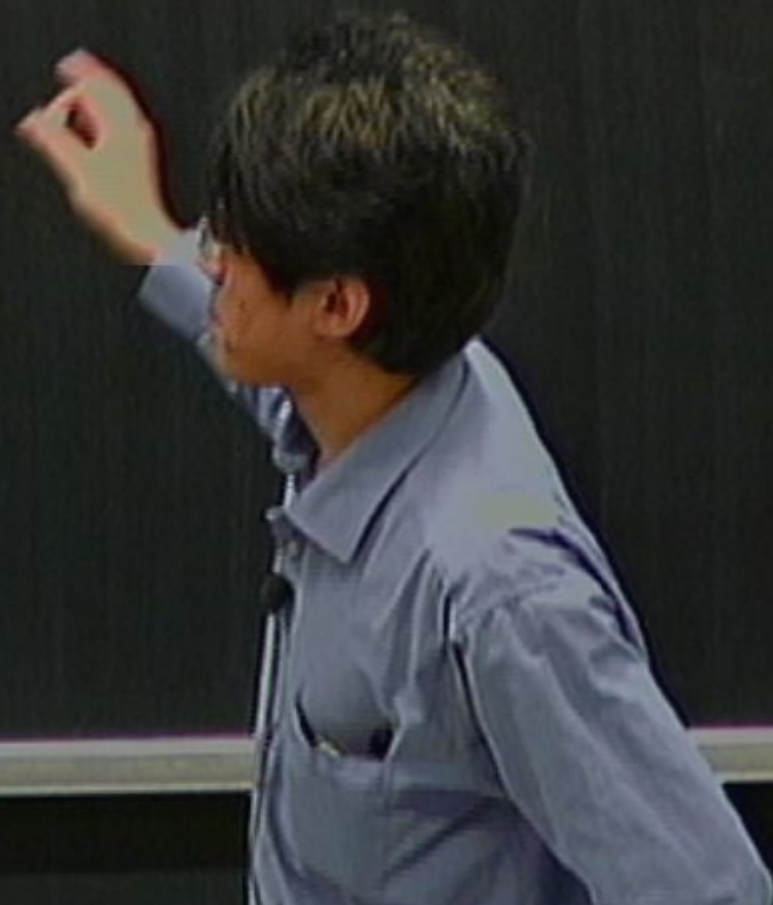
$$x^i = a^i t + b^i$$

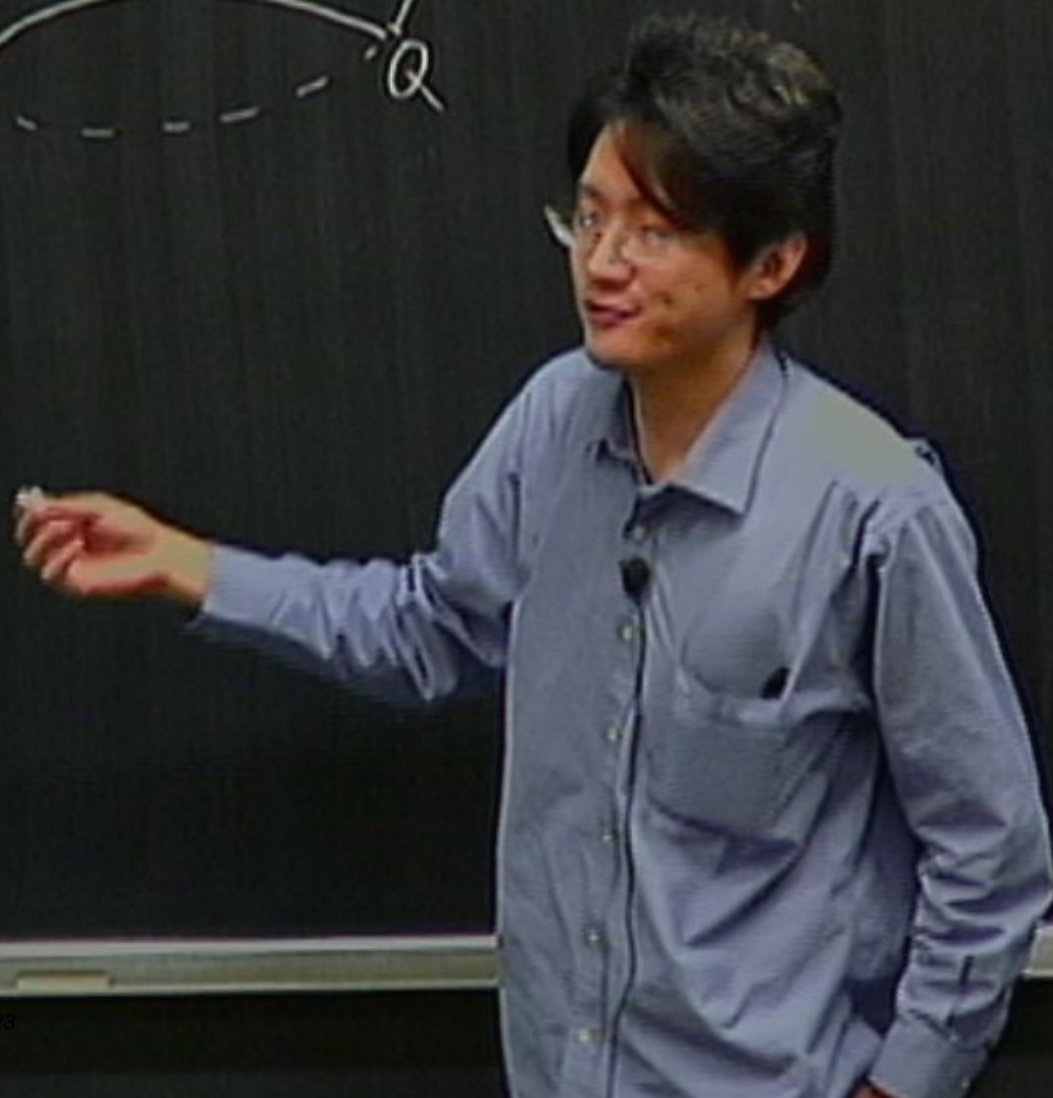
$$\Gamma_{jk}^i = \frac{1}{2} \sum_l g^{il} (g_{je,k} + g_{ke,j} - g_{jk,e})$$

$$x^i(t)$$

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









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



$$v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (i, j) = 1, \dots, N$$



$$v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (j) = 1, \dots, N$$



$$\Rightarrow v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (i, j) = 1, \dots, N$$



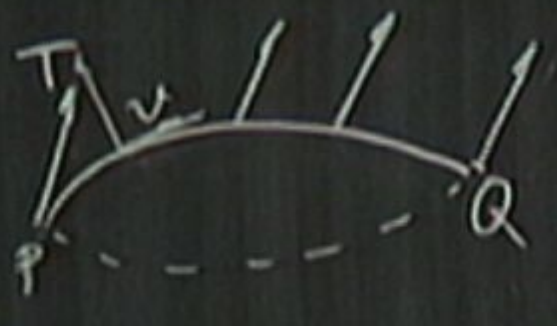
A diagram on a chalkboard showing a curve segment between two points, P and Q. A dashed line connects P and Q. A solid curve starts at P and ends at Q. At point P, a vector labeled T is tangent to the curve, pointing upwards and to the right. At point Q, a vector labeled $\bar{T}$ is tangent to the curve, pointing upwards and to the left. A vector labeled v is shown at point P, pointing upwards and to the right, parallel to T . Several other vectors are shown along the curve, all pointing in the same general direction as T and v .

$$\Leftrightarrow v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (i, j) = 1, \dots, N$$



$$\Rightarrow v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (i, j) = 1, \dots, N$$

$$v^i = (1, \dots)$$



A diagram showing a curved path from point P to point Q. Several tangent vectors are drawn along the curve. To the right of the diagram is the equation:

$$v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (i, j) = 1, \dots, N$$

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

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

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

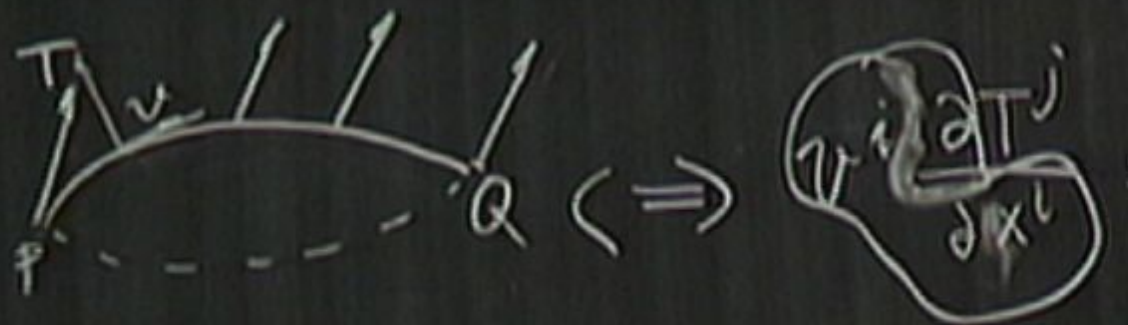


$$P \text{---} Q \Leftrightarrow v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (j=1, \dots, N)$$

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

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

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



$$v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (i, j) = 1, \dots, N$$

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

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

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

$$\rightarrow v^i \nabla_i$$



A diagram showing a curve segment between points P and Q . At point P , a tangent vector v and a normal vector T are shown. At point Q , a normal vector n is shown. The curve is represented by a solid line above a dashed line.

$$\Leftrightarrow v^i \frac{\partial T^j}{\partial x^i} = 0 \quad (i,j) = 1, \dots, N$$

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

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

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

$$\rightarrow v^i \nabla_i$$

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

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

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

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

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma_{i\ell}^j T_\ell^j$$

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

$$\nabla_i T^j = \frac{\partial T^j}{\partial x^i} + \Gamma_{il}^j T^l_k$$

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

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

$$\nabla_i T_j$$

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

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

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma_{ij}^k T_k$$

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$$\nabla_i T^j_k = \frac{\partial T^j_k}{\partial x^i} + \Gamma_{il}^j T^l_k - \Gamma_{ik}^l T^j_l$$

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

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

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma_{ij}^k T_k$$

$$\frac{\partial T_k^j}{\partial x^i} + \Gamma_{il}^j T_k^l - \Gamma_{ikl}^l T^j$$

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

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

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma_{ij}^k T_k$$

$$\nabla_i T^j_k = \frac{\partial T^j_k}{\partial x^i} + \Gamma_{il}^j T^l_k - \Gamma_{ikl} T^j_l$$

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

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

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma_{ij}^k T_k$$

$$\nabla_i T^j_k = \frac{\partial T^j_k}{\partial x^i} + \Gamma_{il}^j T^l_k - \Gamma_{ik}^l T^j_l$$

⋮

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

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

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma_{ij}^k T_k$$

$$\nabla_i T^j_k = \frac{\partial T^j_k}{\partial x^i} + \Gamma_{il}^j T^l_k - \Gamma_{ik}^l T^j_l$$

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

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$$\nabla_i T^j_k = \frac{\partial T^j_k}{\partial x^i} + \Gamma_{ik}^l T^l_j - \Gamma_{ik}^l T^j_l$$

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

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

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

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma_{ij}^k T_k$$

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

∇T

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

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

$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma_{ij}^k T_k$$

$$\nabla_i T^j_k = \frac{\partial T^j_k}{\partial x^i} + \Gamma_{ik}^l T^j_l - \Gamma_{ij}^l T^j_l$$

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

geodesic
2nd def for

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

$\frac{dT^j}{ds}$

$\Gamma_{ik}^j T^k$

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

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

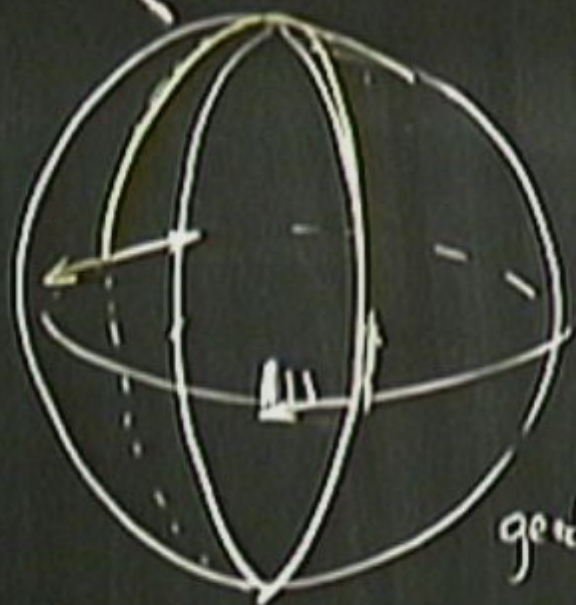
$$\nabla_i T_j = \frac{\partial T_j}{\partial x^i} - \Gamma_{ij}^k T_k$$

$$\nabla_i T^j = \frac{\partial T^j_k}{\partial x^i} + \Gamma_{il}^j T^l_k - \Gamma_{ikl} T^j_l$$

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

geodesic
2nd def for

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



geodesic

$$x^i(t)$$

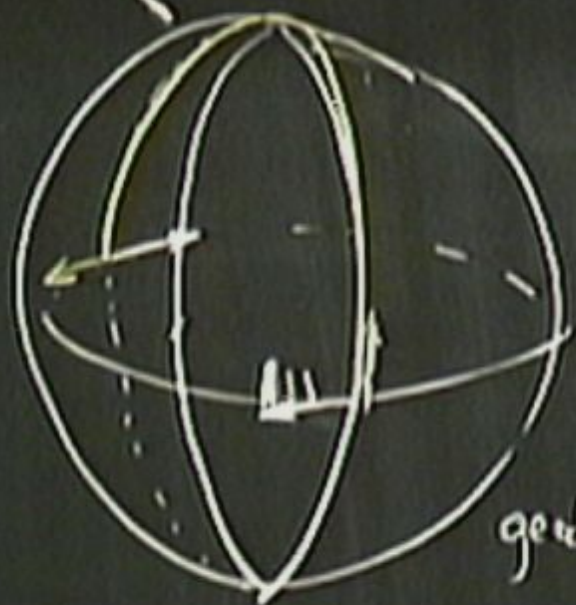
$$S(A, B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$$

minimal length.

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

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

$$\Gamma_{jk}^i = \frac{1}{2} \sum_l g^{il} (g_{je,k} + g_{ke,j} - g_{ik,e})$$



$$x^i(t)$$

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

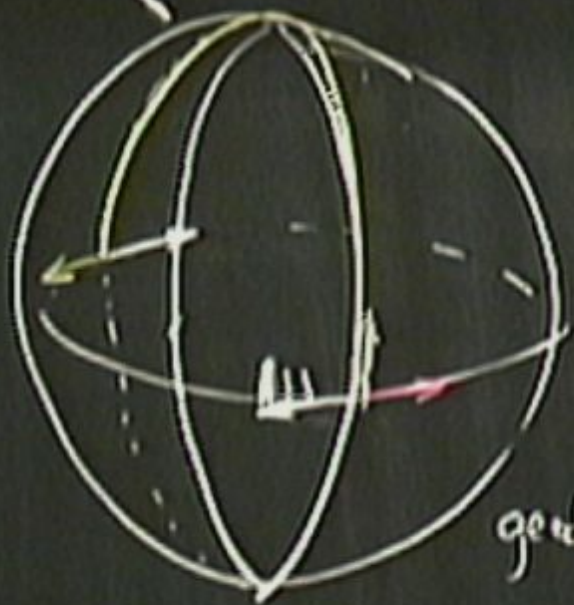
minimal length.

geodesic

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

$$\Gamma_{jk}^i = \frac{1}{2} g^{il} (g_{je,k} + g_{ke,j} - g_{jk,e})$$



geodesic

$$x^i(t)$$

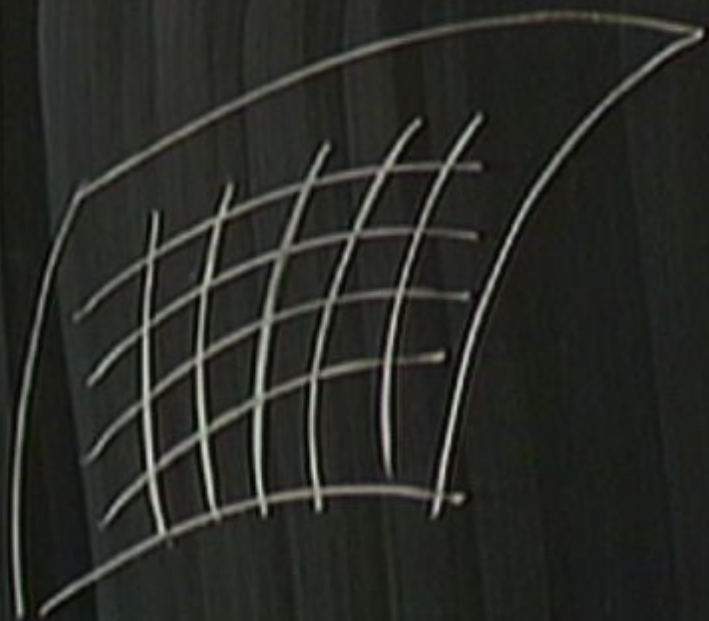
$$S(A, B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$$

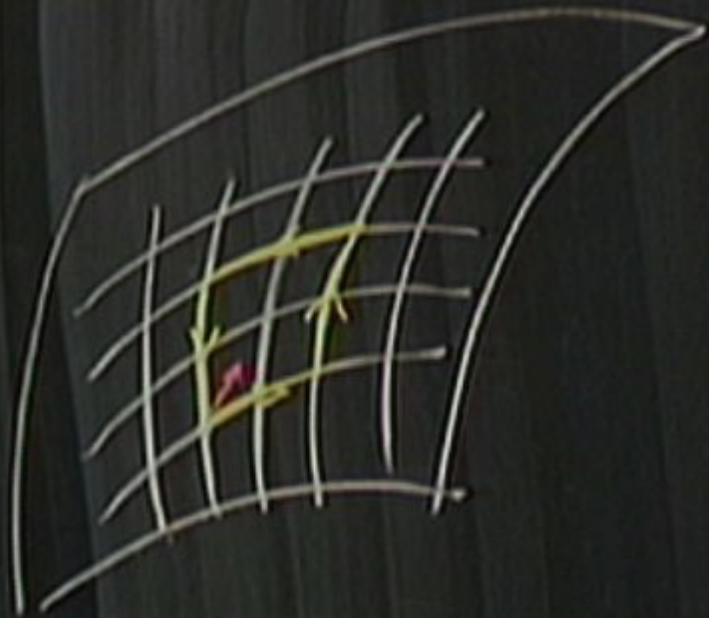
minimal length.

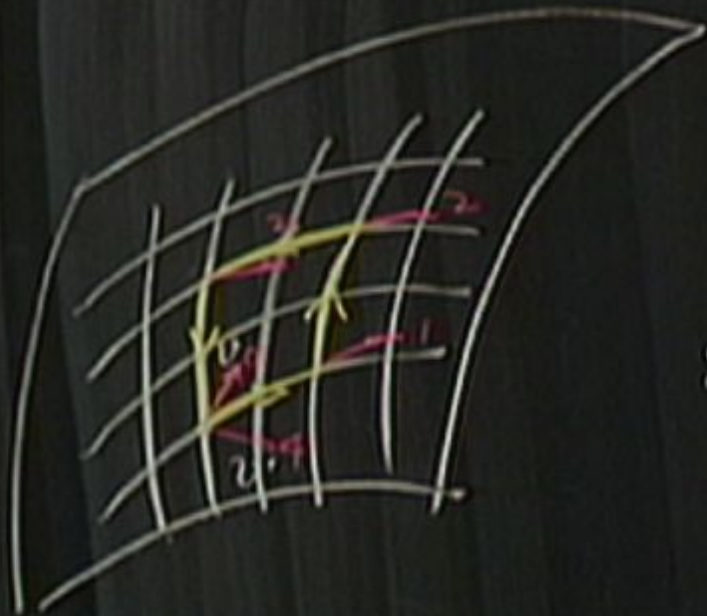
$$\frac{d^2 x^i}{dt^2} + \sum_{j,k} \Gamma_{jk}^i(x) \frac{dx^j}{dt} \frac{dx^k}{dt} = 0$$

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

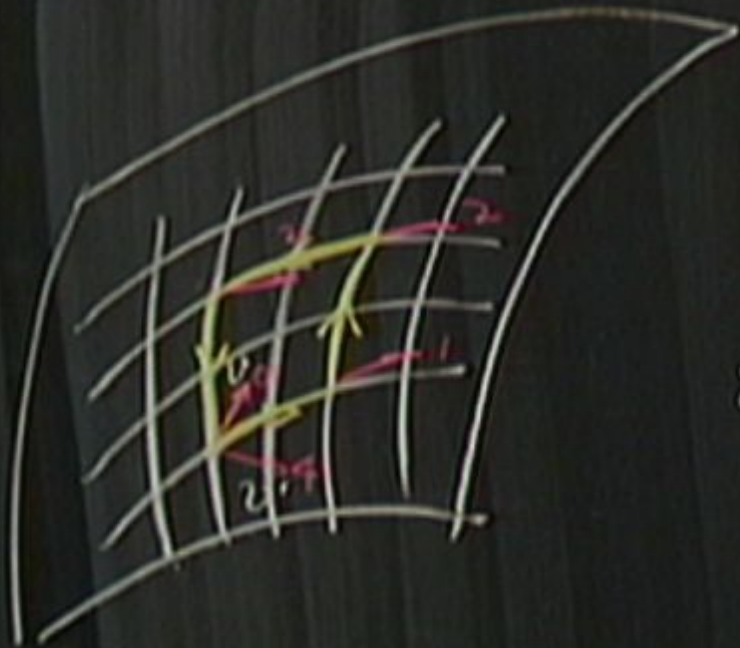
$$\Gamma_{jk}^i = \frac{1}{2} g^{il} (g_{je,k} + g_{ke,j} - g_{jk,e})$$





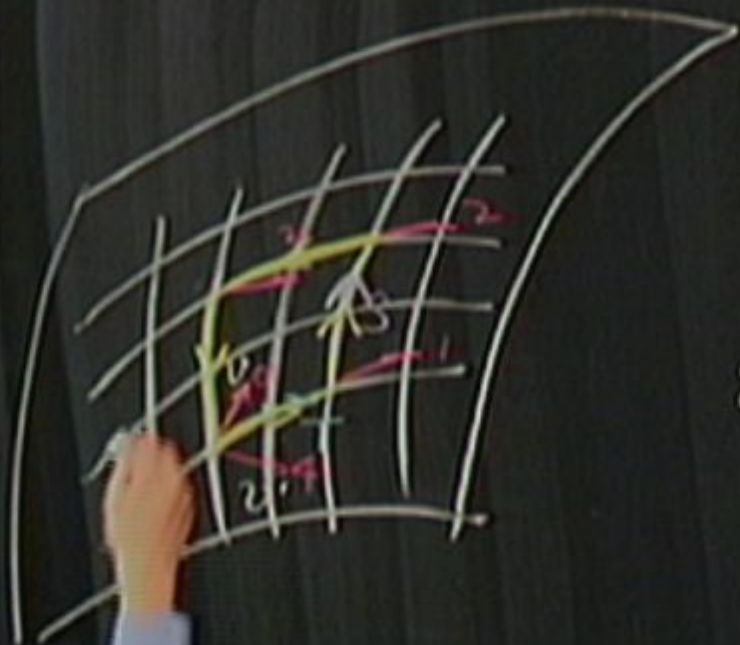


$$\delta v^a = \gamma'^a v^a$$



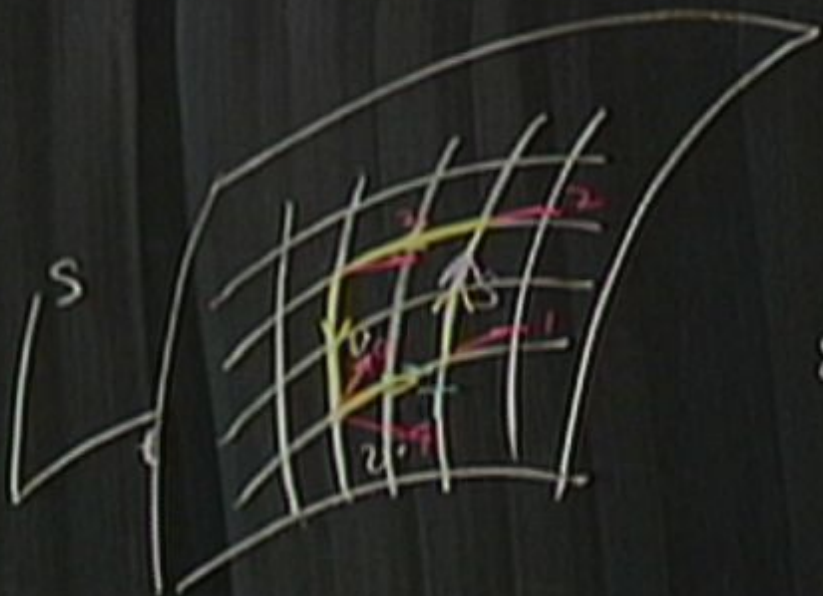
$$\begin{aligned}\delta v^a &= v'^a - v^a \\ &= R_{bcd}{}^a T^b S^c v^d \Delta s \Delta t\end{aligned}$$

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



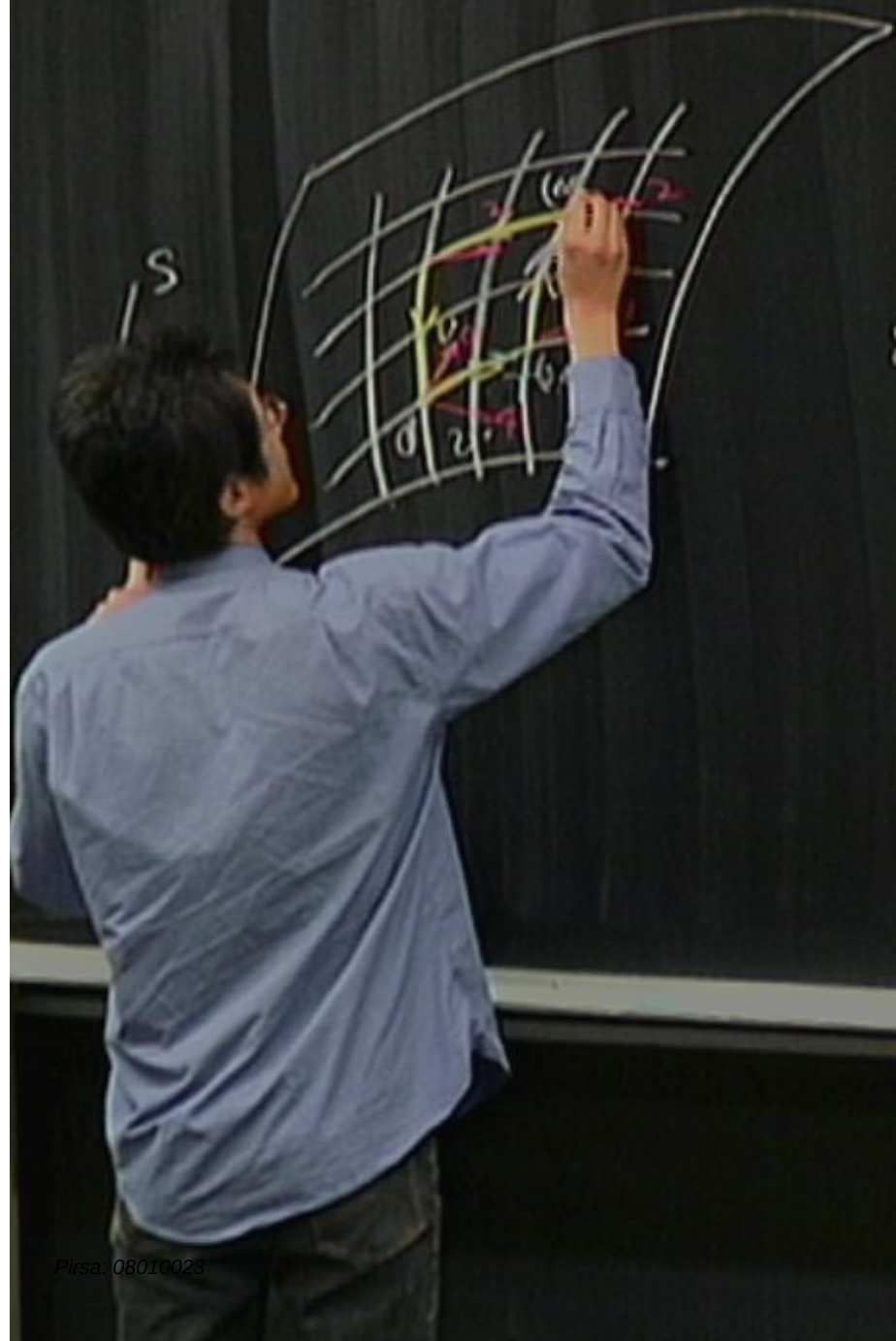
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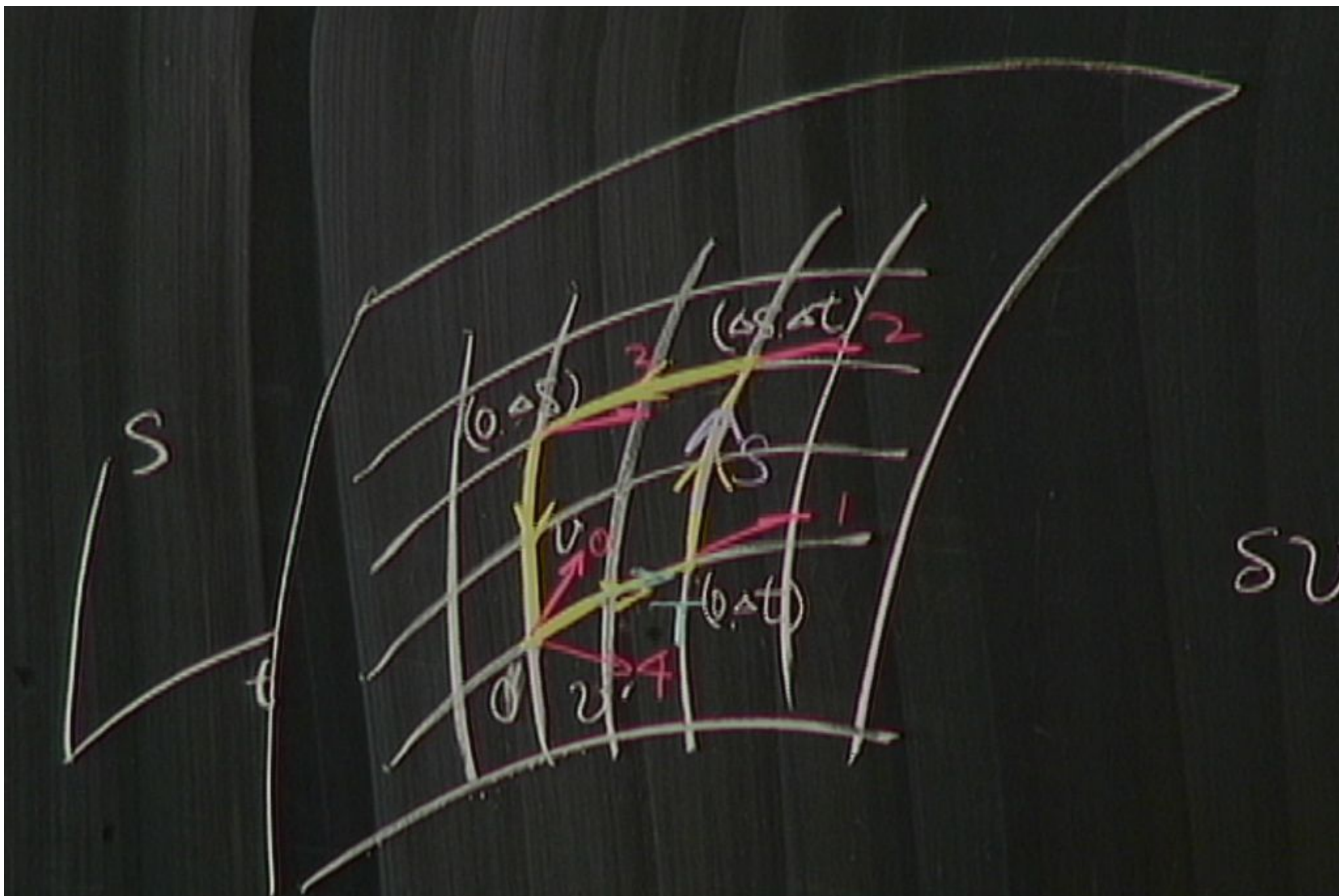
+ higher order
in $(\Delta S, \Delta t)$

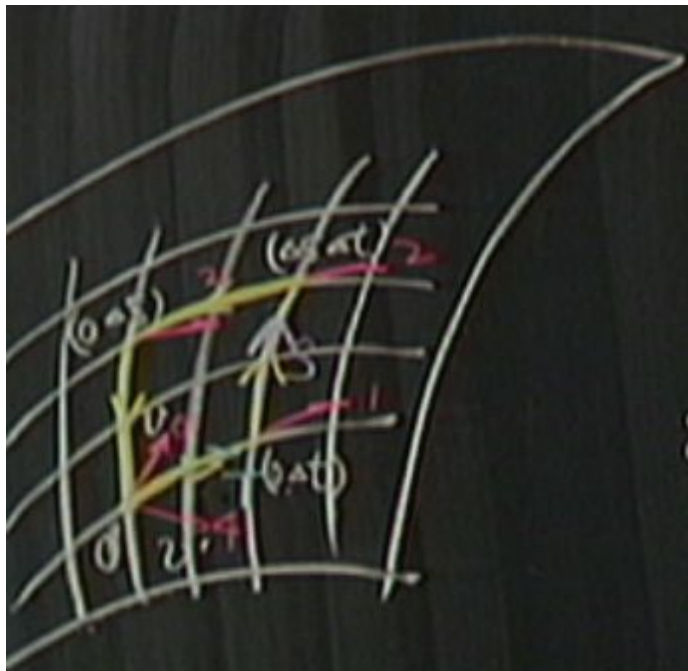


$$\delta v^a = v'^a - v^a$$

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

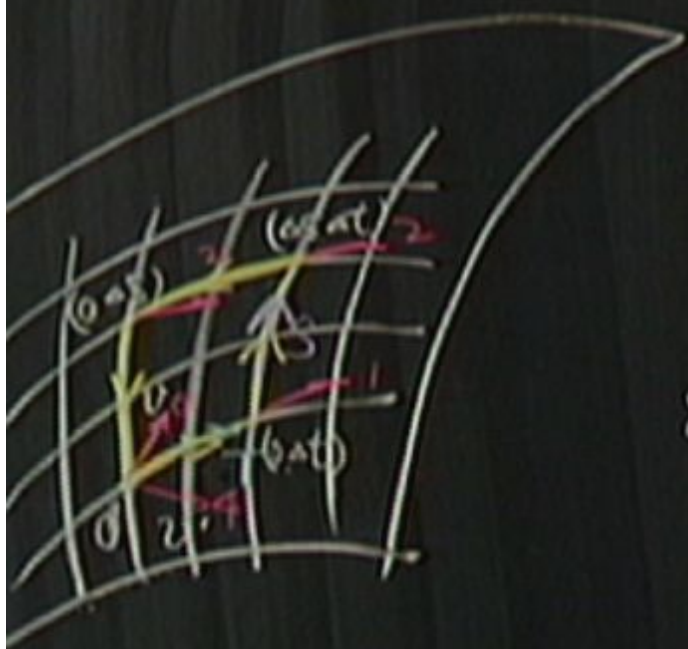
+ higher order
in $(\Delta S, \Delta t)$





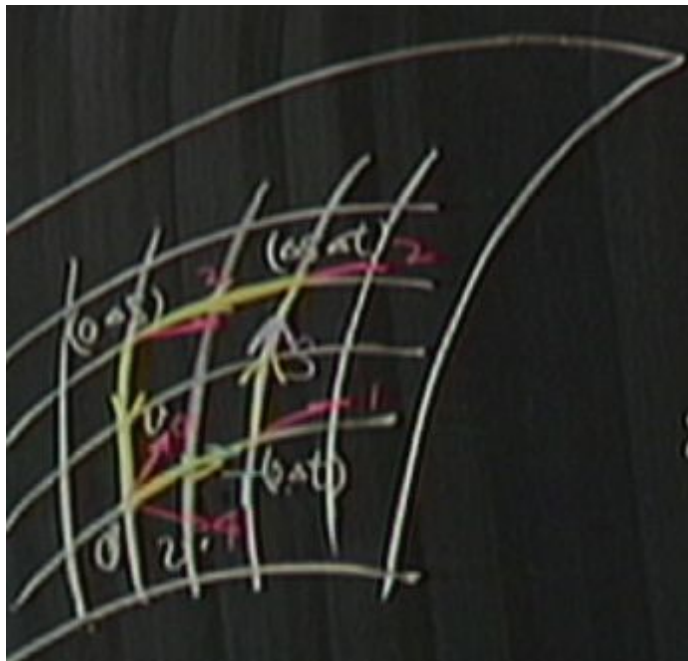
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+ higher order
in $(\Delta s, \Delta t)$



$$\begin{aligned}\delta v^a &= v'^a - v^a \\ &= \boxed{R_{bcd}{}^a} T^b S^c v^d \Delta s \Delta t\end{aligned}$$

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



$$\begin{aligned}\delta v^a &= v'^a - v^a \\ &= \boxed{R_{bcd}{}^a} T^b S^c v^d \Delta s \Delta t\end{aligned}$$

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

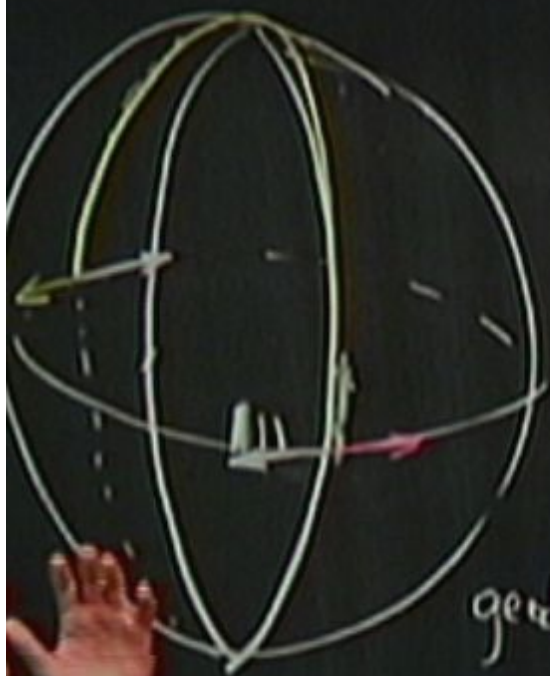
$$\nabla^2 \phi = -4\pi G_N \rho$$

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$$g_{\mu\nu}$$

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

$$g_{\mu\nu}$$



$$x^i(t)$$

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

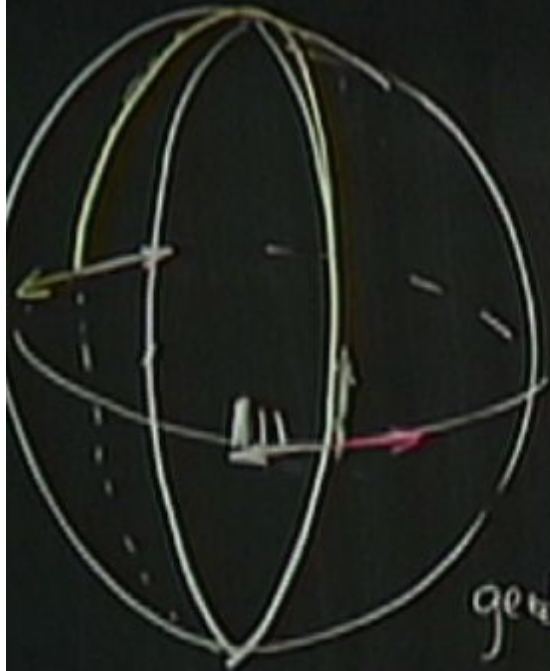
minimal length.

geodesic

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

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

$$\Gamma_{jk}^i = \frac{1}{2} \frac{\partial g_{il}}{\partial x^k} (g_{je,k} + g_{ke,j} - g_{jk,e})$$



$$x^i(t)$$

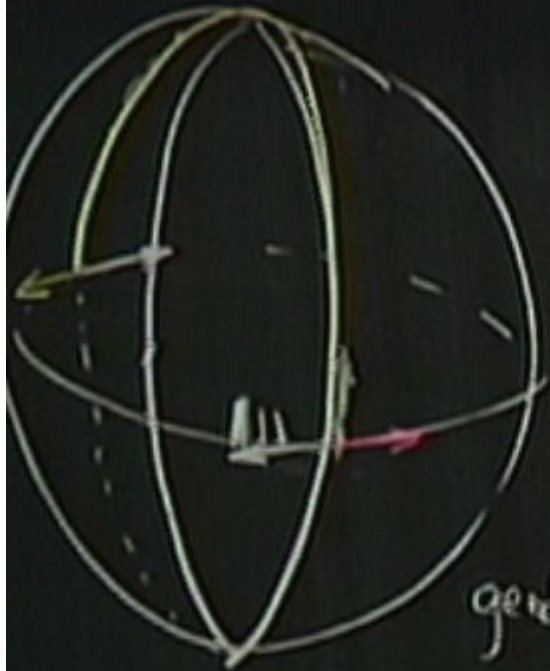
$$S(A, B) = \int_{t_A}^{t_B} dt \sqrt{g_{ij} \frac{dx^i}{dt} \frac{dx^j}{dt}}$$

minimal length.

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

$$\Gamma^i_{jk} = \frac{1}{2} g^{il} \left(\frac{\partial g_{lj}}{\partial x^k} + \frac{\partial g_{lk}}{\partial x^j} - \frac{\partial g_{jk}}{\partial x^l} \right)$$

$$g_{kl,j} - g_{jk,l}$$



$$x^i(t)$$

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

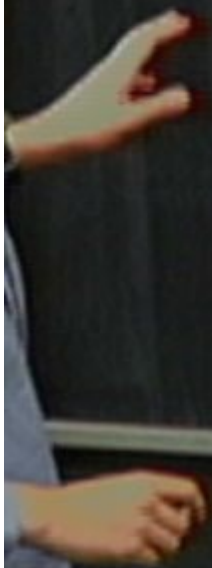
minimal length

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

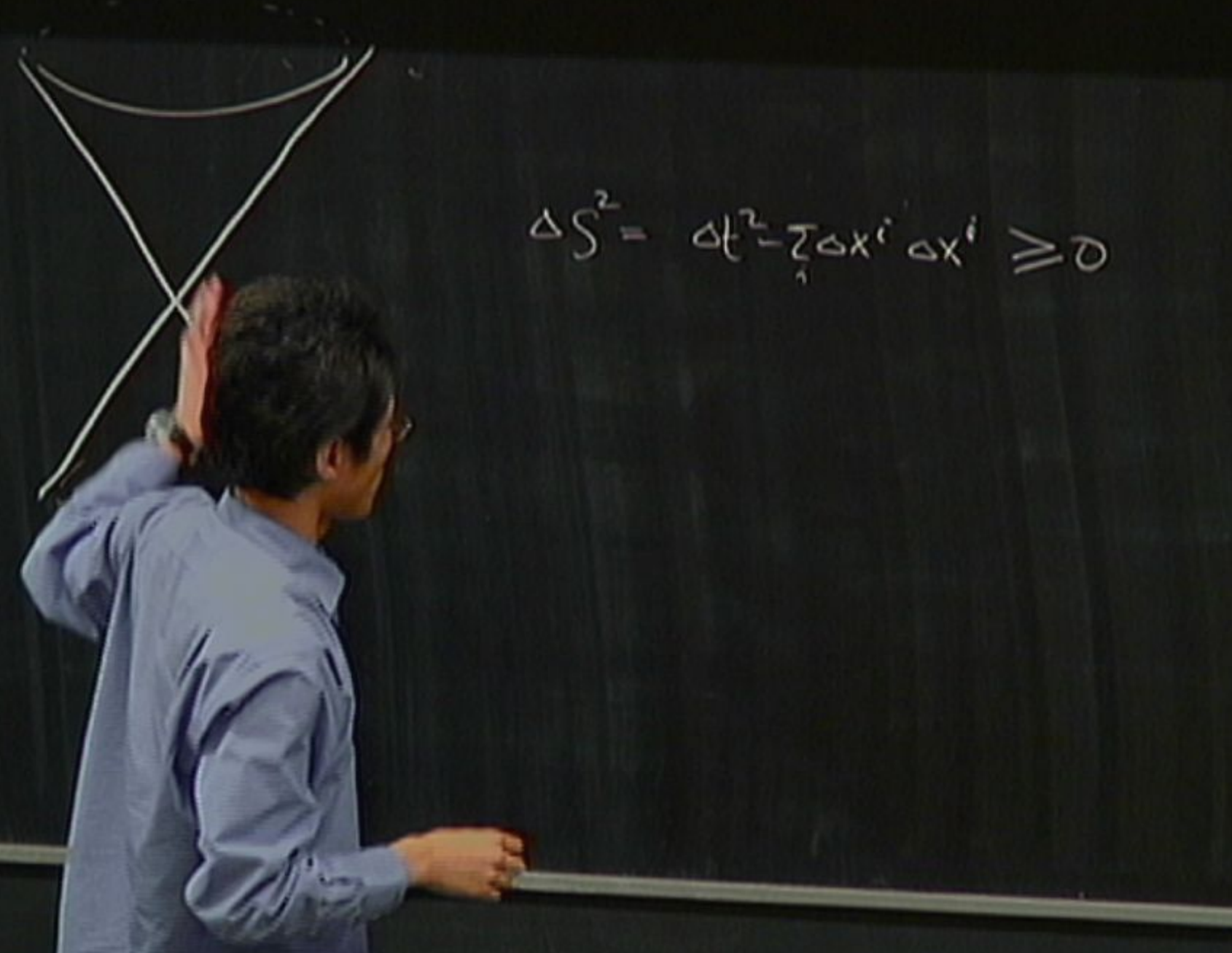
$$x^i = a^i t + b^i$$

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

$$\Gamma_{jk}^i = \frac{1}{2} g^{il} \left(\frac{\partial g_{jl}}{\partial x^k} + \frac{\partial g_{kl}}{\partial x^j} - \frac{\partial g_{jk}}{\partial x^l} \right)$$






$$\Delta S^2 = \Delta t^2 - \sum_i \Delta x_i^2 \geq 0$$



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$$x^i(t)$$

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

minimal length.

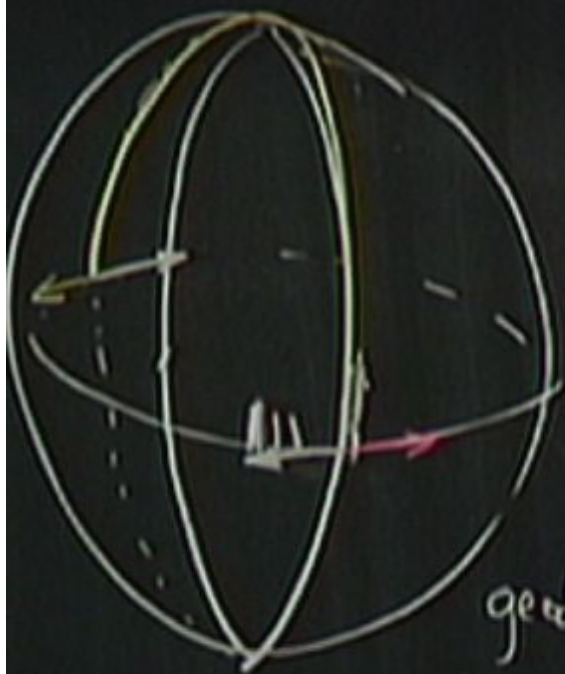
$$\begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix}$$

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

geodesic

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

$$g_{j\ell,k} + g_{k\ell,j} - g_{ik,\ell}$$



geodesic

$$x^i(t)$$

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

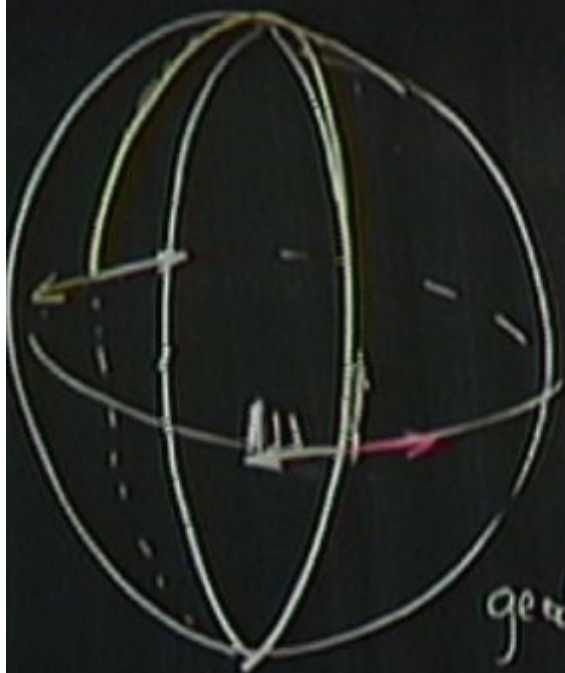
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geodesic

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

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

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

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

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

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

$$T_{\mu\nu}$$

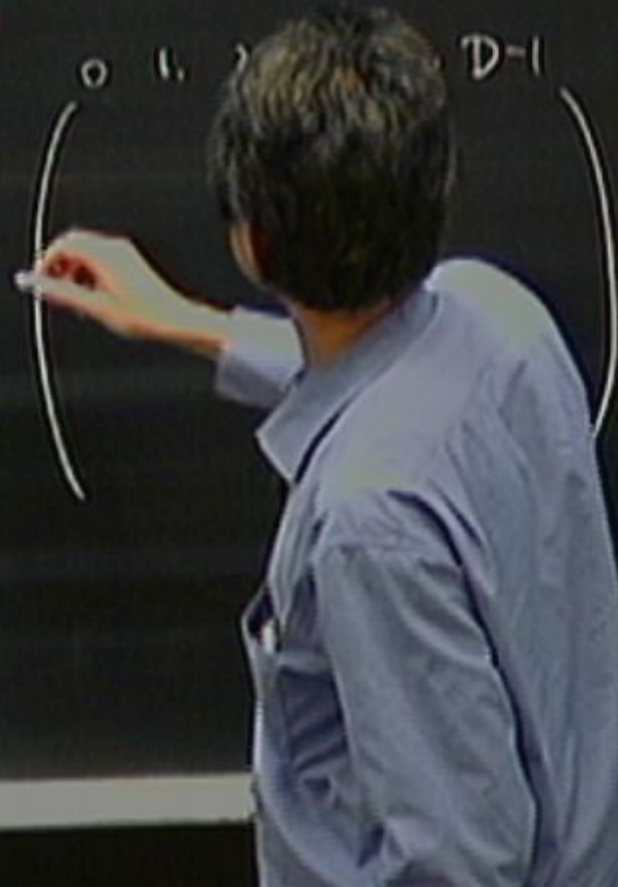
$$\nabla^2 \phi = -4\pi G_N \rho$$

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

$D = \text{dim of spacetime}$
 $(1, D-1)$

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

$$T_{\mu\nu}$$



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

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

$D = \text{dim of spacetime}$
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$$\underline{g_{\mu\nu}}$$

$$T_{\mu\nu}$$

$$\rho^{1, 2, \dots}$$

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

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$$T_{\mu\nu}$$

$$\rho_{\quad 1, 2, \dots}$$

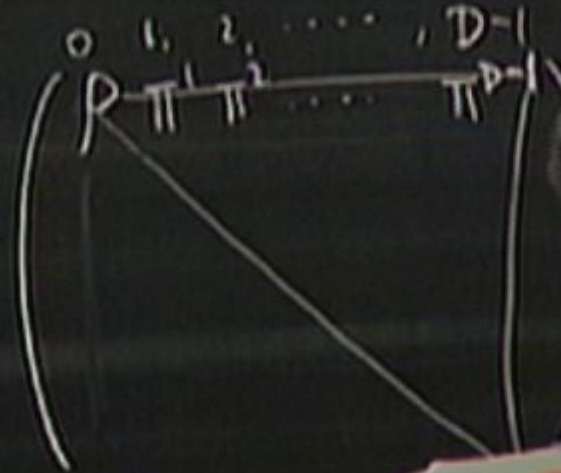
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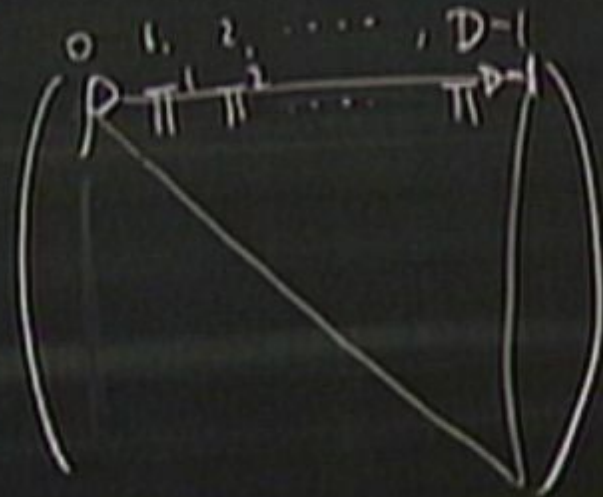
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$D = \text{dim of spacetime}$
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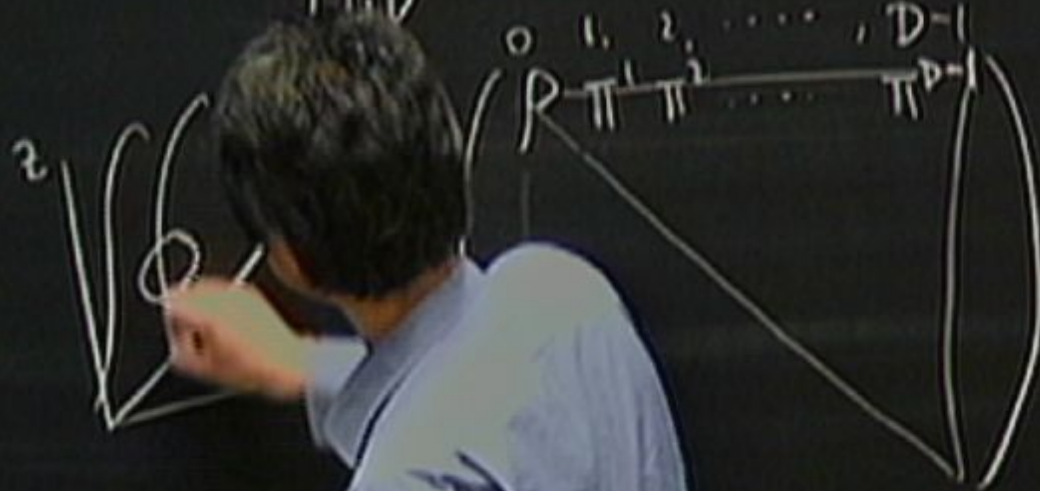
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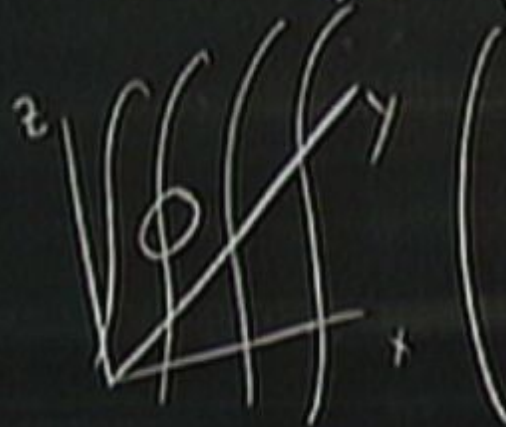
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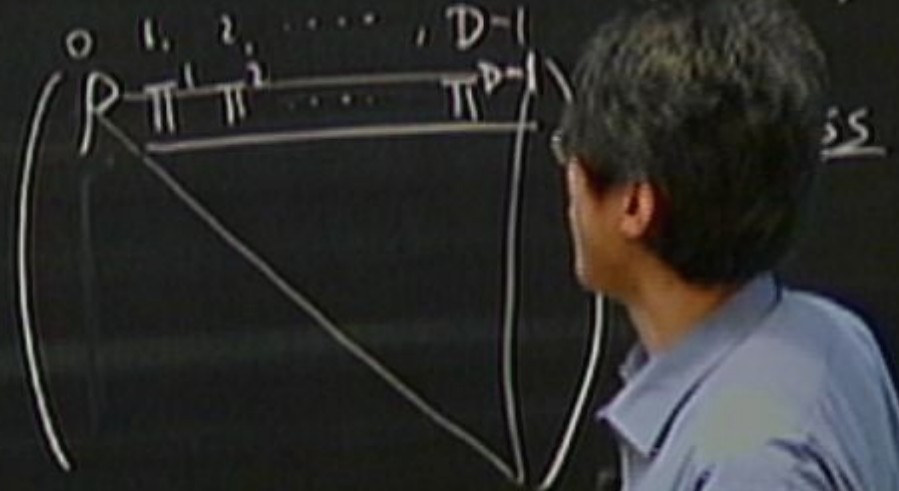
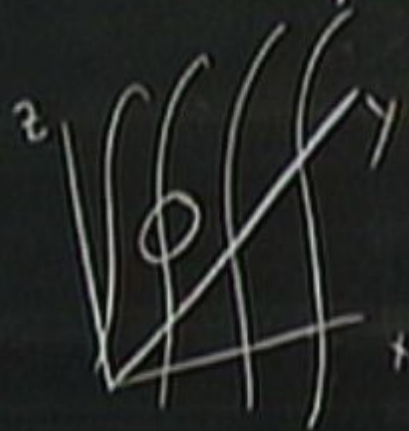
$$\nabla^2 \phi = -4\pi G_N \rho$$

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

$D = \text{dim of spacetime}$
 $(1, D-1)$

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

$$T_{\mu\nu}$$



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

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

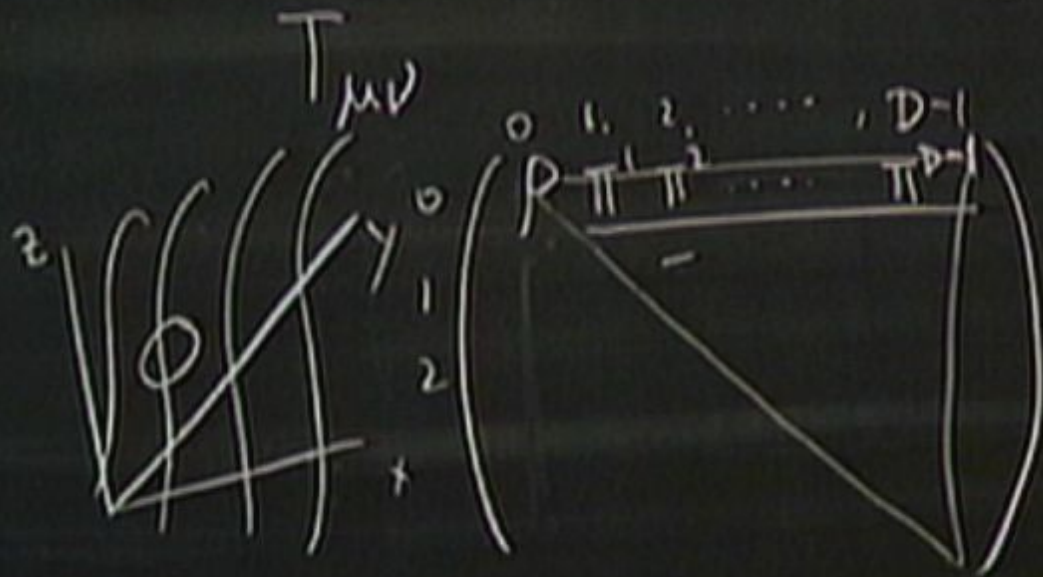
$D = \text{dim of spacetime}$
 $(1, D-1)$

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

$$T_{\mu\nu}$$

stress

$$T_{xy}$$



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

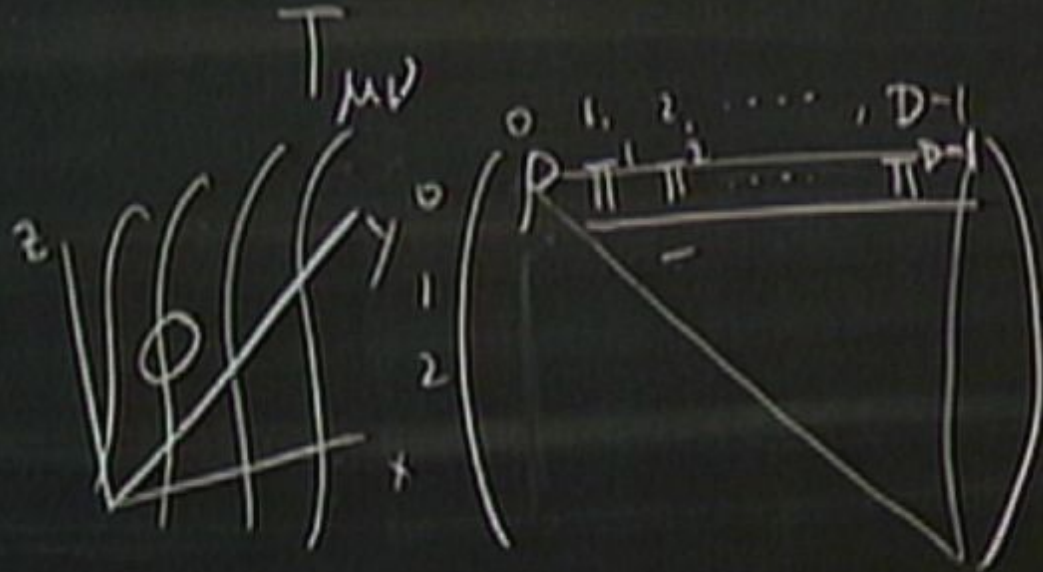
$$\underline{x^0 = t}$$

$D = \text{dim of spacetime}$
 $(1, D-1)$

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

$$T_{xy}$$

$$T_{\mu\nu}$$



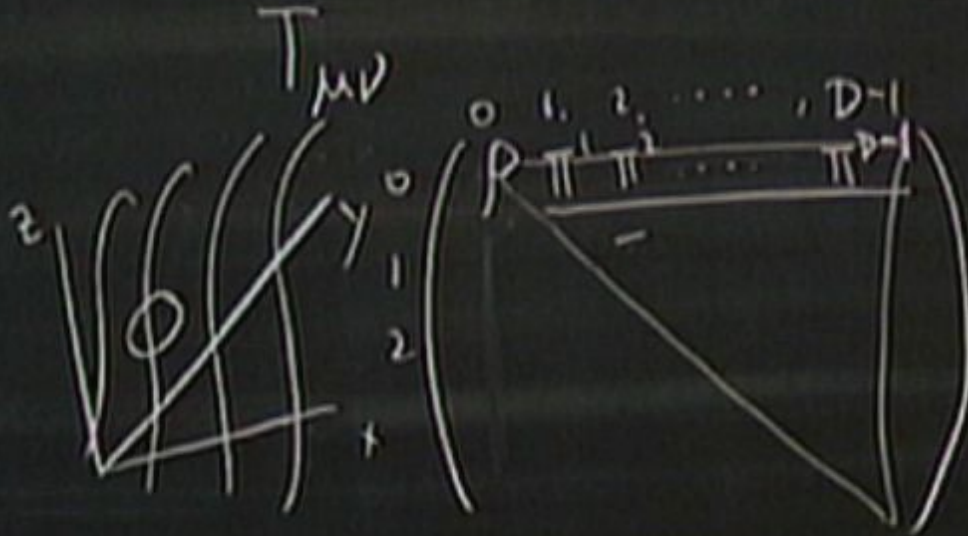
stress

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

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

$$D = \text{dim of spacetime}$$

stress

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


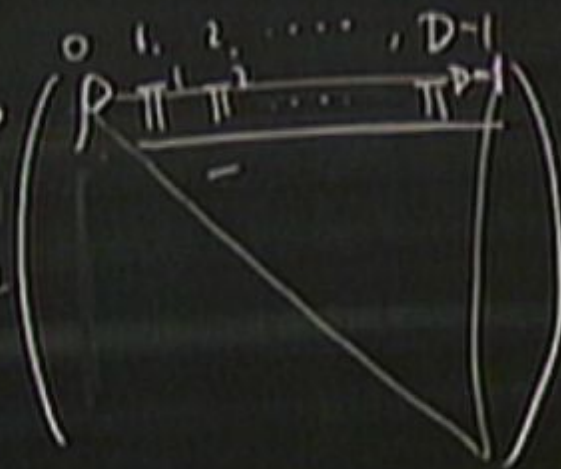
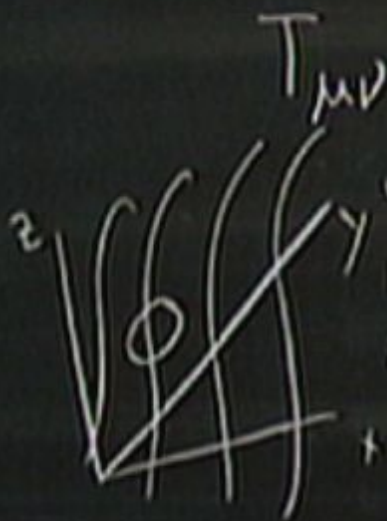
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 $(1, D-1)$

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

$$T_{xy}$$



stress

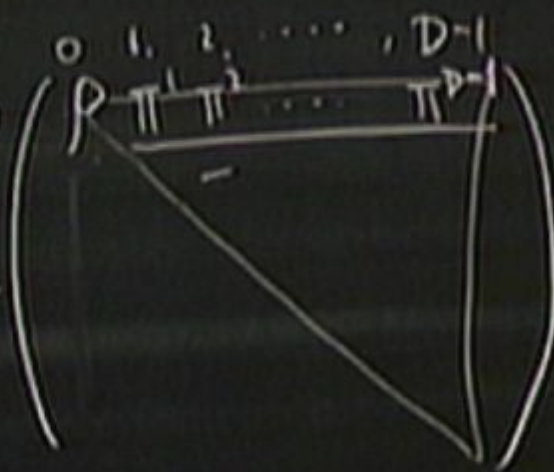
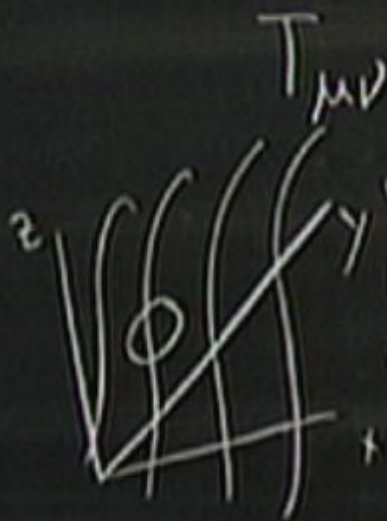
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$D = \text{dim of spacetime}$
 $(1, D-1)$

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

$$T_{\lambda\rho}$$

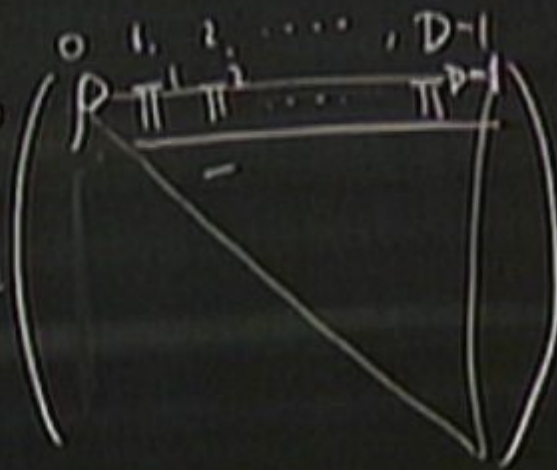
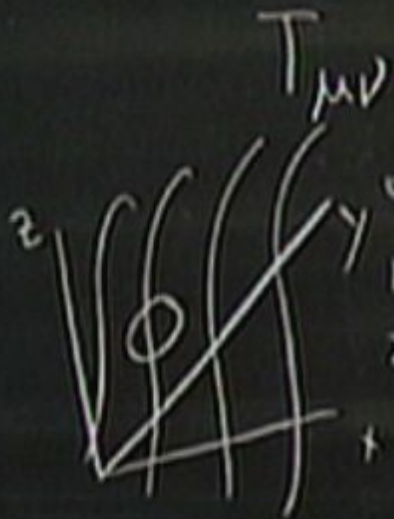
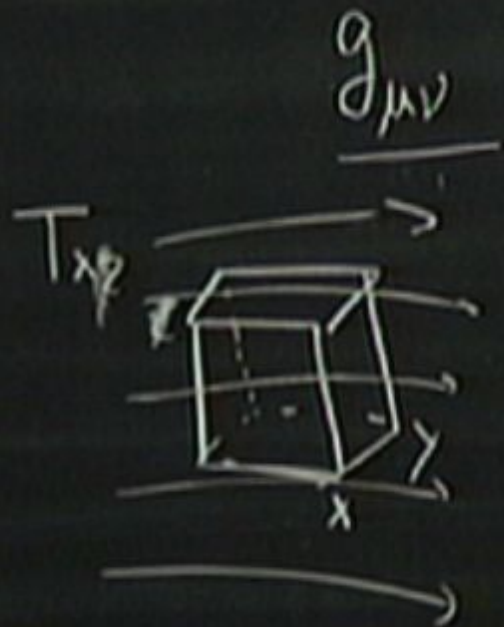


stress

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

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

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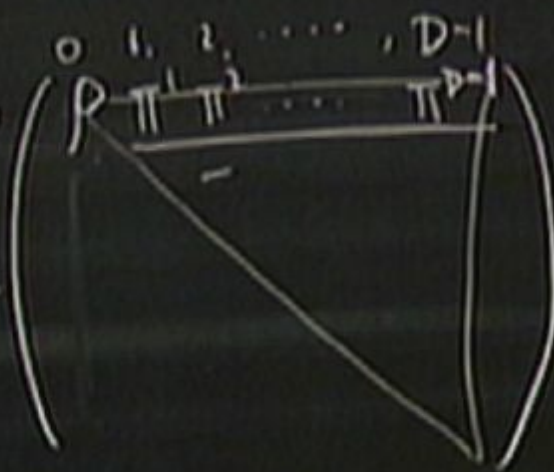
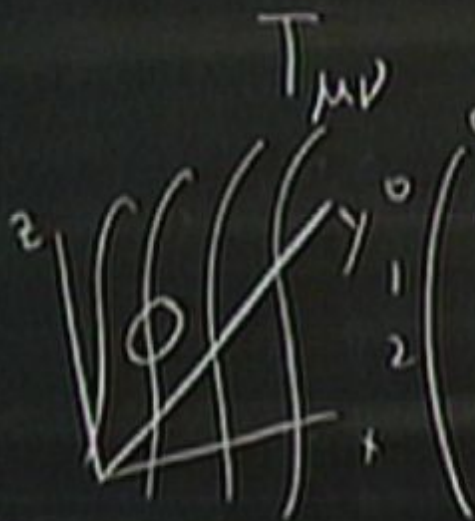
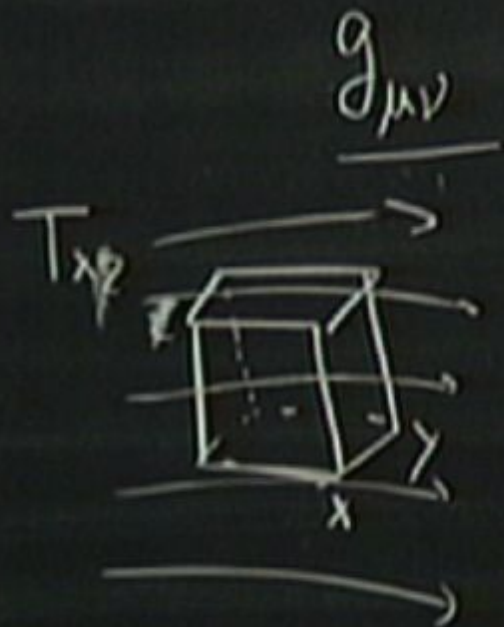


stress

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

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

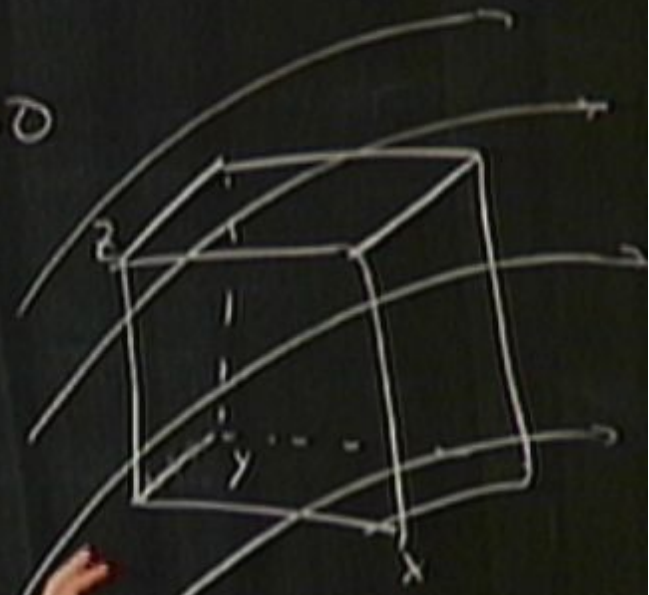
$D = \text{dim of spacetime}$
 $(1, D-1)$



stress



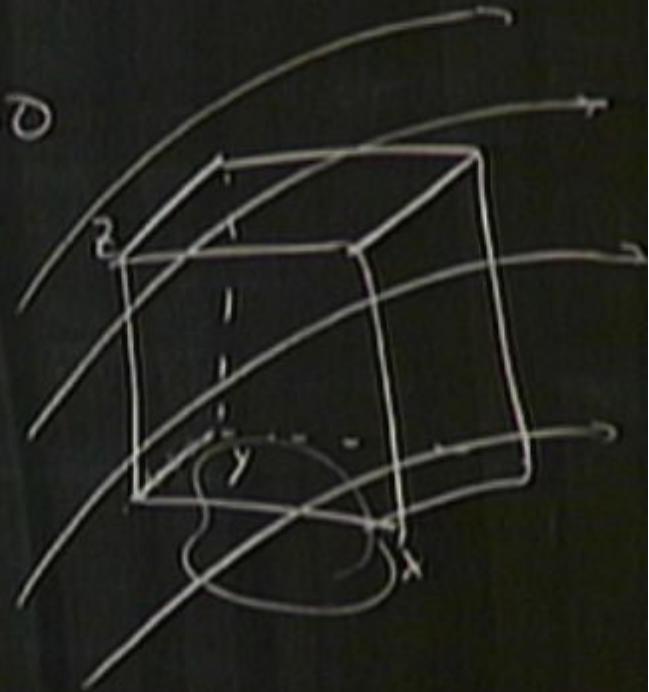
$$\Delta S^2 = \Delta t^2 - \sum_i \Delta x_i^2 \geq 0$$





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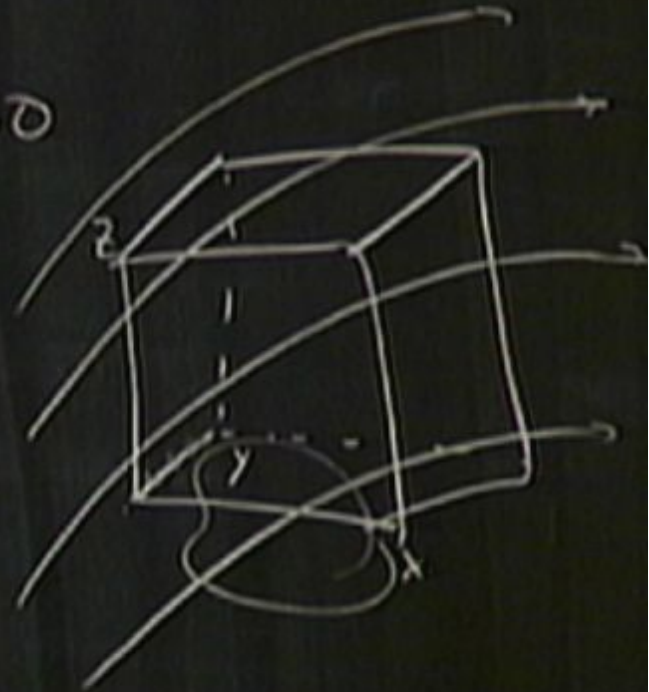
T_{xz}



$$\Delta S^2 = \Delta t^2 - \sum_i \Delta x_i^2 \geq 0$$

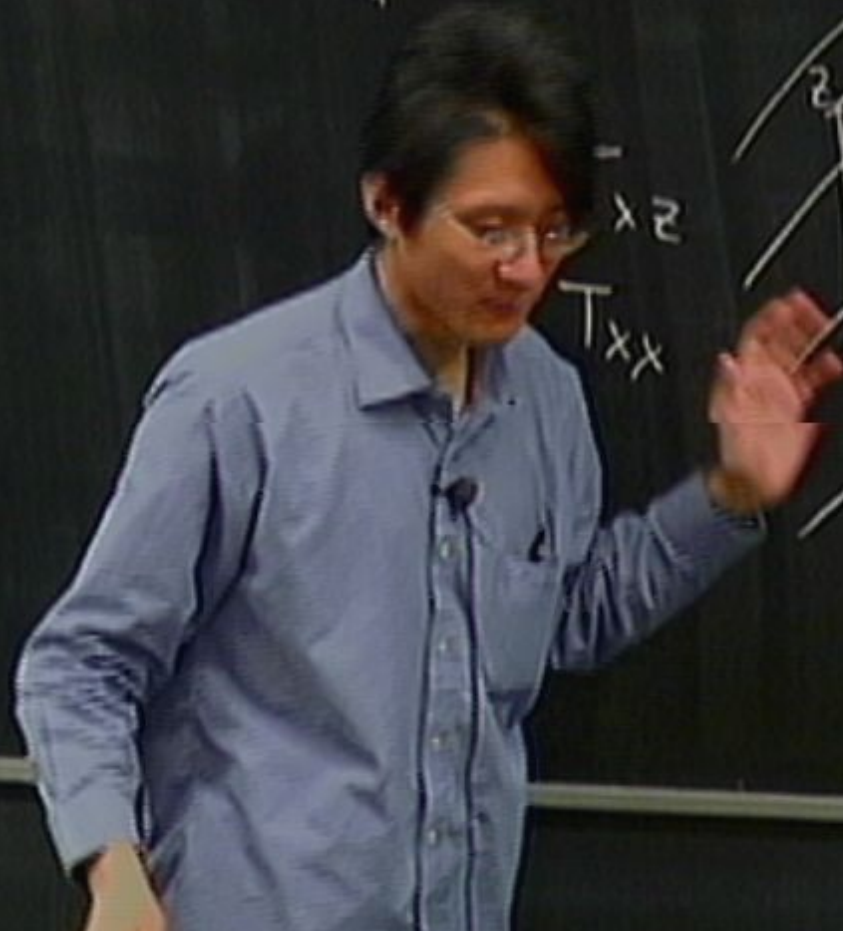
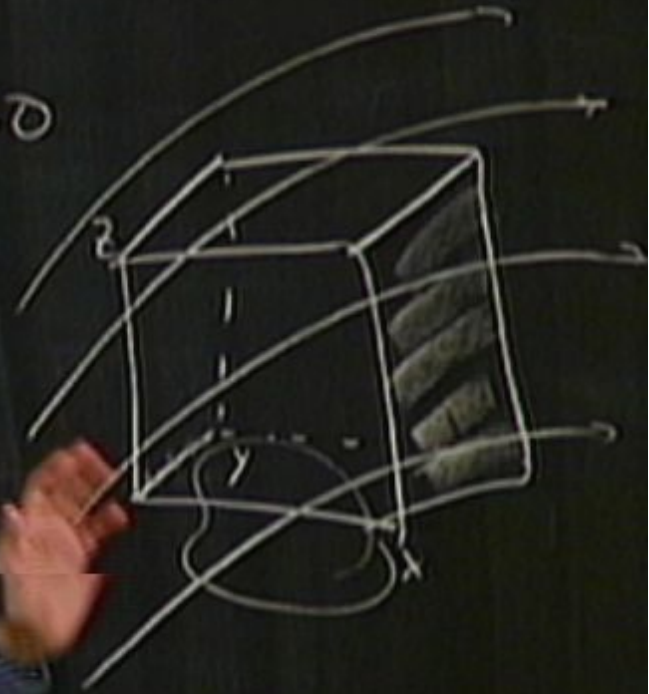
T_{xz}

T_{xx}





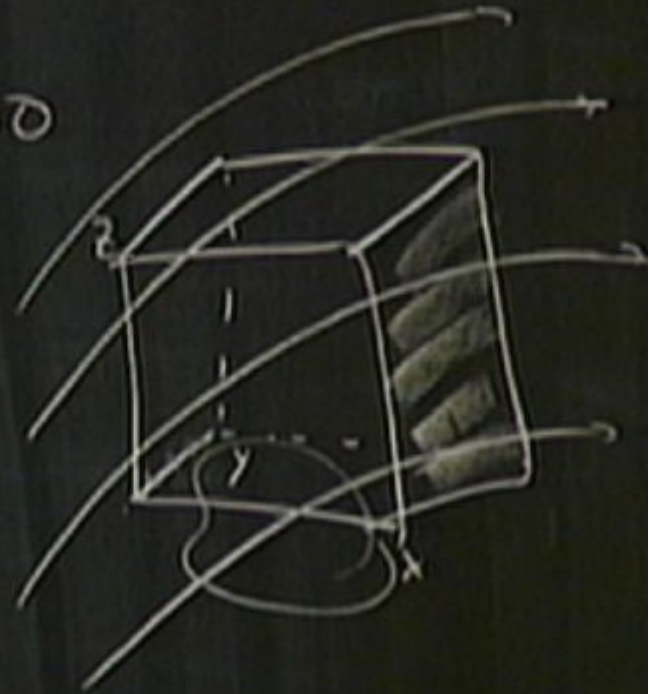
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T_{xz}

T_{xx}





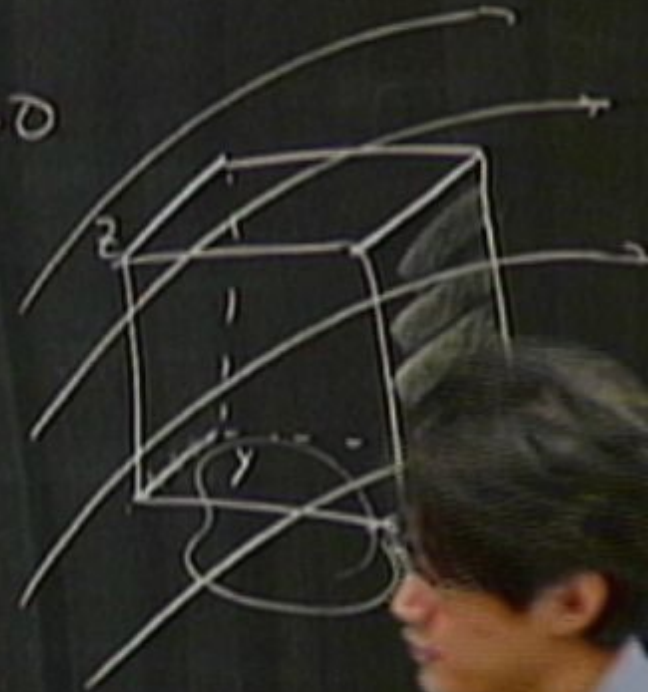
$$\Delta S^2 = \Delta t^2 - \sum_i \Delta x^i \Delta x^i \geq 0$$

T_{xz}

T_{xx}

T_{yy}

T_{zz}



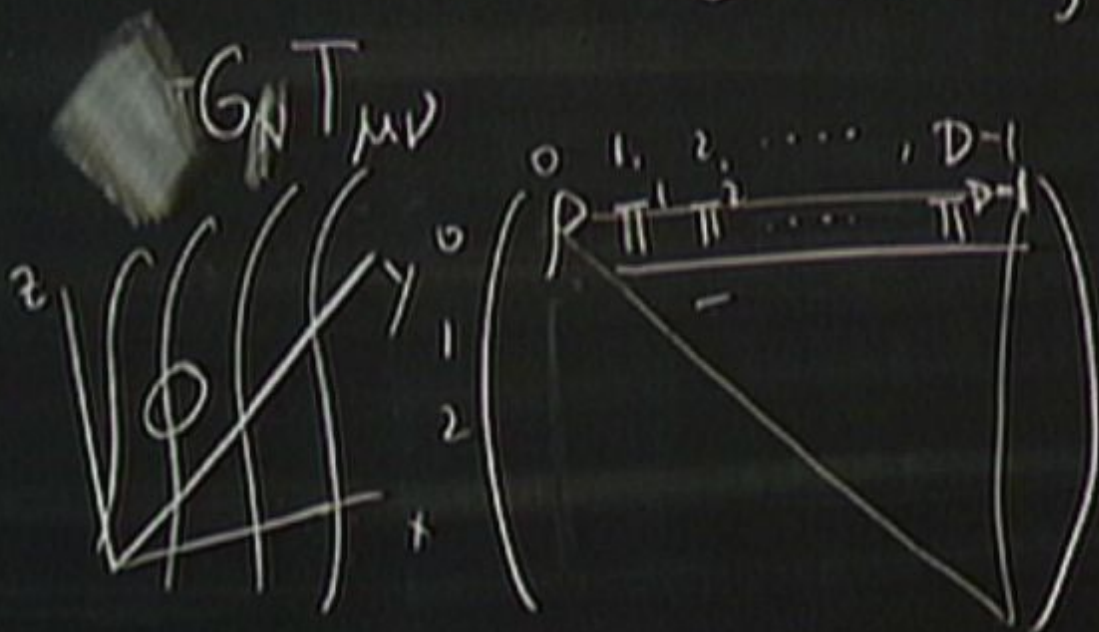
$$\nabla^2 \phi = -4\pi G_N \rho$$

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

$D = \text{dim of spacetime}$
 $(1, D-1)$

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

$$-G_N T_{\mu\nu}$$



stress

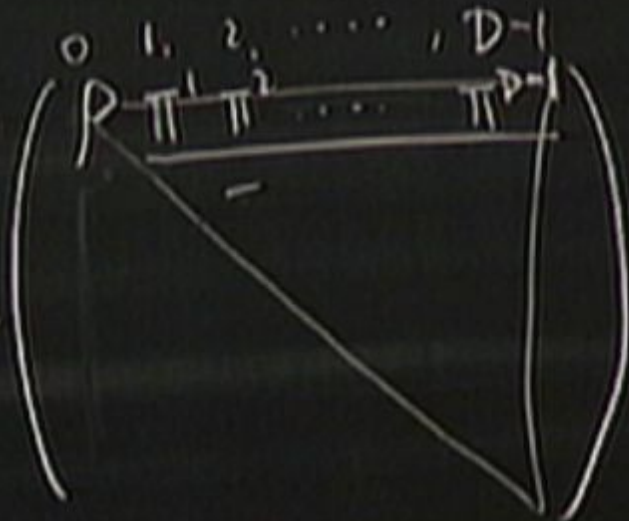
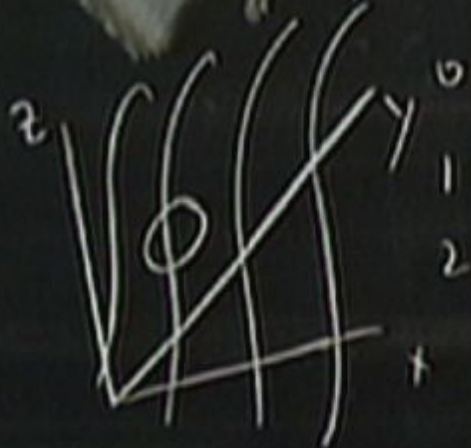
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$$\underline{x^0 = t}$$

$D = \text{dim of spacetime}$
 $(1, D-1)$

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

$$c\pi G_N T_{\mu\nu}$$



stress

R_{bcd}^a



R_{bcd}^a

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

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

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

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

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

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

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

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

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

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

$$\tilde{A} = \sum_b A_{ab}{}^{cd}{}_b$$

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

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

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

$$\tilde{A}_a{}^{cd} = \sum_b A_{ab}{}^{cd}$$

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

$$C_{ab}{}^{def}{}^{cg}{}^h = A_{ab}{}^c B_{def}{}^{gh}$$

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

$$\tilde{A}_a{}^{cd} = \sum_b A_{ab}{}^{cd}{}^b$$

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

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

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

$$\tilde{A}_a{}^{bcd} = \sum_b A_{ab}{}^{cd}$$

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

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

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

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

$$\tilde{A}_a{}^{cd} = \sum_b A_{ab}{}^{cd}$$

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

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

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

$$\tilde{A}_a{}^{cd} = \sum_b A_{ab}{}^{cd}$$

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

Ricci Tensor

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

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

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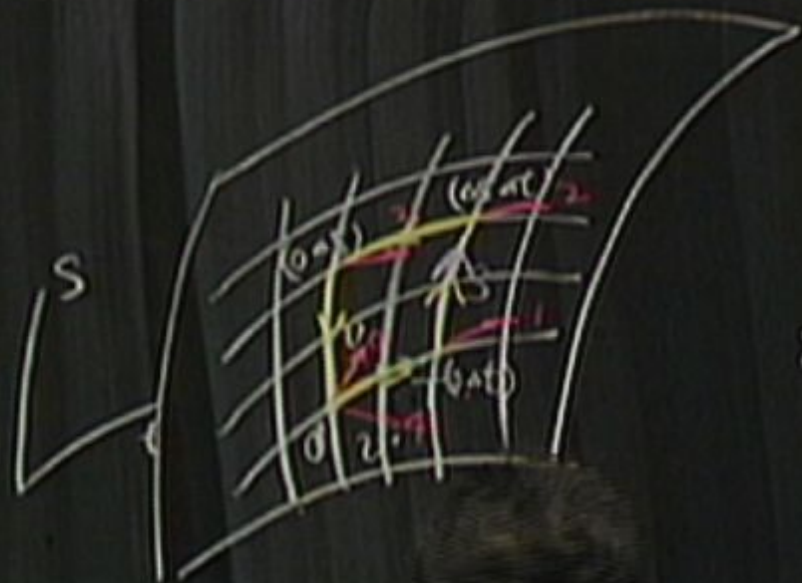
$$C_{ab\,def}{}^{gh} = A_{ab}{}^c B_{def}{}^{gh}$$

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Ricci Tensor



$$R_{ijk}^{\ell} = \partial_j \Gamma_{ik}^{\ell} - \partial_i \Gamma_{jk}^{\ell} + \sum_m (\Gamma_{ik}^m \Gamma_{mj}^{\ell} - \Gamma_{jk}^m \Gamma_{im}^{\ell})$$

$$\begin{aligned} \delta v^a &= v^{;a} v^a \\ &= \boxed{R_{bcd}^a} T^b S^c v^d \Delta s \Delta t \end{aligned}$$

+ higher order

Riemann curvature tensor $(\Delta s, \Delta t)$

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

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

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$$\tilde{A}_a{}^{cd} = \sum_b A_{ab}{}^{cd}$$

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Ricci Tensor

$$R_{ab} = 8\pi G_{\mu} T_{ab}$$

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

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

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

$$\nabla_b T_{ab} = 0$$

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

Ricci Tensor

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Ricci Tensor

$$\tilde{A}_a{}^{cd} = \sum_b A_{ab}{}^{cd}$$

$$\underline{R_{ab}} = 8\pi G_{\mu\nu} T_{ab}$$

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

Ricci scalar

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

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

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

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

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

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

$G_{\mu\nu} = 0$

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

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

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

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

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

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

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

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

$$A^\mu = 0$$

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

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

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

$$A^\mu = 0$$

$$\partial_\mu \bar{Y}_{\mu\nu} = 0$$

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

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

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

$$A^\mu = 0$$

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

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

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

Einstein Equ

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

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

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

$$A^\cdot = 0$$

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

$$\partial^\mu \partial_\mu \gamma_{\rho\sigma} = 0$$

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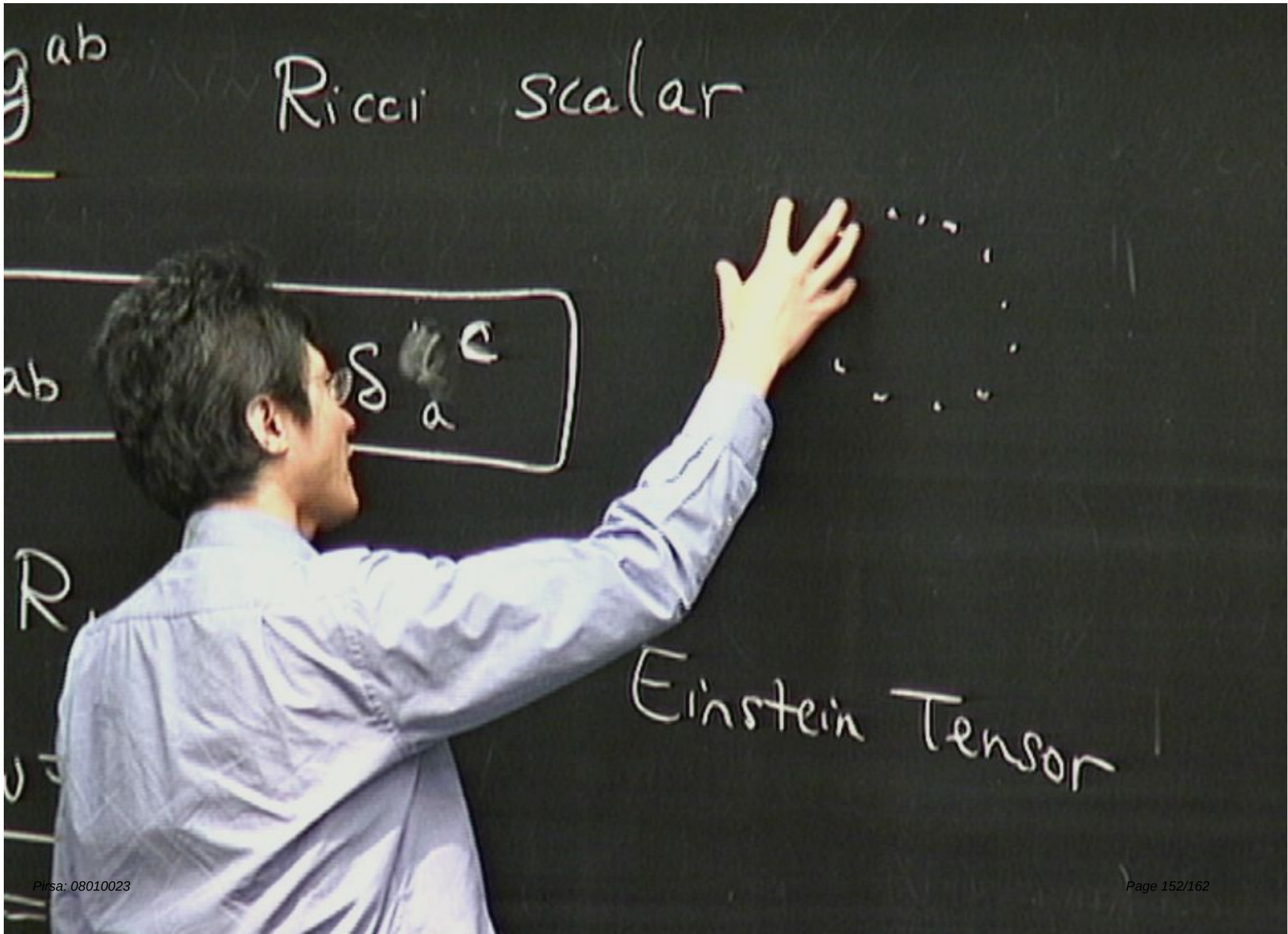
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$\bar{\gamma}_{\mu\nu} = \gamma_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} \gamma^\rho{}_\rho$

$5 - 3 = 2$



g^{ab}

Ricci scalar

$$g^{bc} = \delta_a^c$$



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

Einstein Tensor

$$= 0$$

$$= 8\pi G T$$

g^{ab}

Ricci scalar

$$g^{bc} = \delta_a^c$$



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

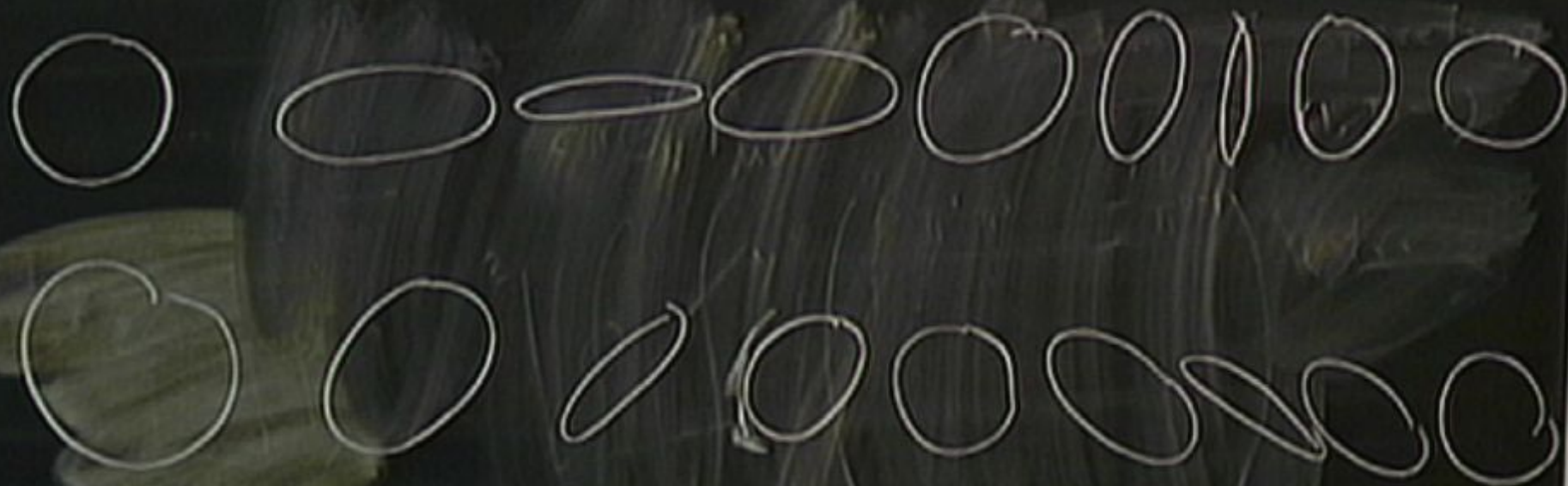
Einstein Tensor

$$= 0$$

$$= 8\pi G T$$

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

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



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

$A^- = 0$

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

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Einstein Equ

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

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

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

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

$A^\mu = 0$

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

$5 - 3 = 2$

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

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

$$\phi = g_{00}$$



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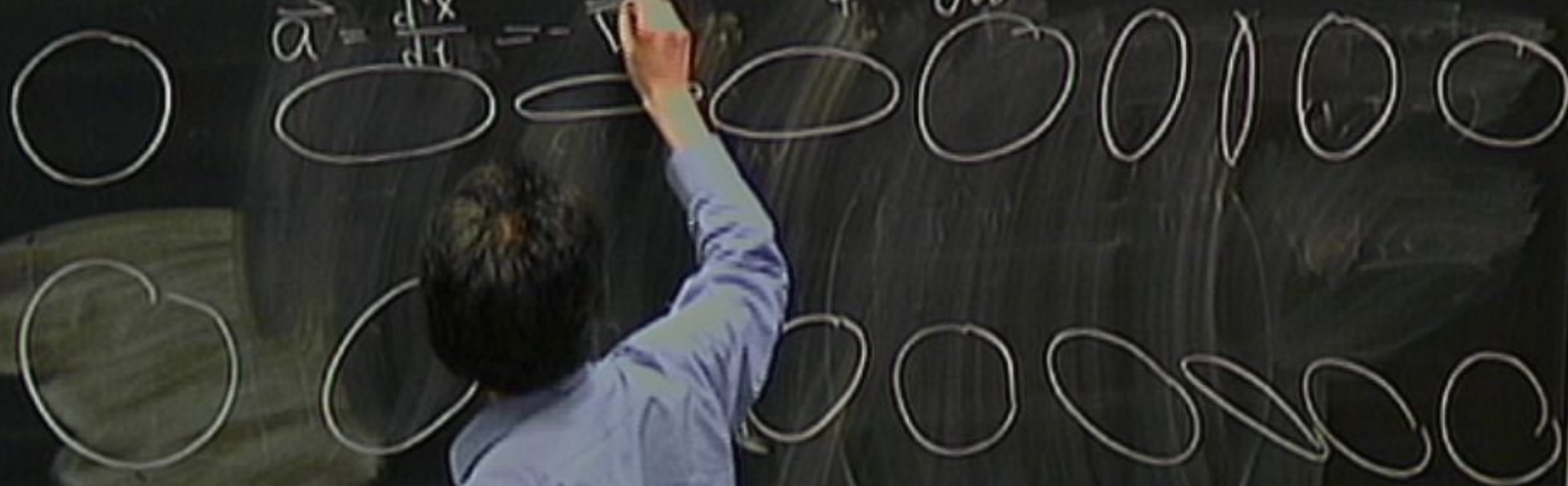


$$\nabla^2 \phi = -4\pi G_N \rho$$

$$\underline{x^2 = t}$$

$$\phi = g_{00}$$

$$\vec{a} = \frac{d^2 \vec{x}}{dt^2} = -\nabla \phi$$

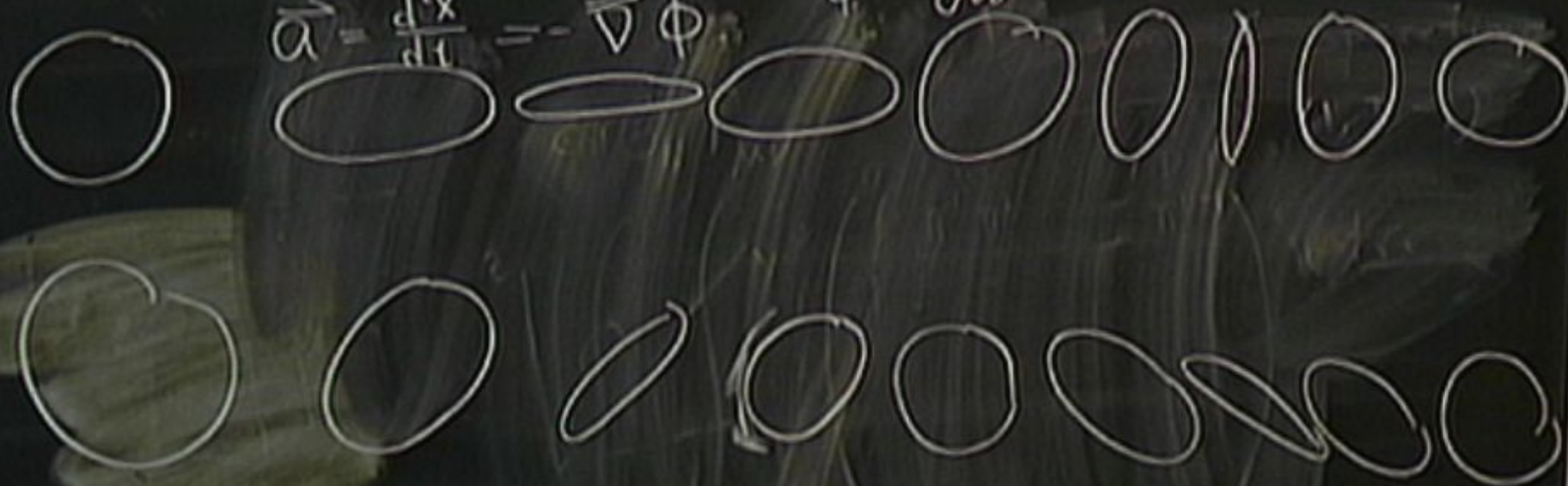


$$\nabla^2 \phi = -4\pi G_N \rho$$

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

$$\vec{a} = \frac{d^2 \vec{x}}{dt^2} = -\vec{\nabla} \phi$$

$$\phi = g_{00}$$



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

$$\vec{a} = \frac{d^2 \vec{x}}{dt^2} = -\vec{\nabla} \phi$$

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

