

# Lecture 3 Special Relativity (2)

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Lucas

## Invariance of the Laws of Nature

Laws take the same form in every reference frame. Definition of a straight line for example is the « shortest distance between two points » does not reference a coordinate system. Apply the Pythagorean Theorem at the infinitesimal level.

$$ds = \sqrt{dx^2 + dy^2}$$

The distance between two points is

$$s = \int ds = \int dx \sqrt{1 + \left(\frac{dy}{dx}\right)^2}$$

find the curve that minimizes the distance  $s$ . Find quantities which are invariant under coordinate transformations The vector  $(dx, dy)$  for example is not invariant under a rotation, but  $ds^2$  is invariant. For example, a vector (tensor) rotation (transformation):

$$A_s = A_x \cos \theta - A_y \sin \theta$$

$$A_y = A_x \sin \theta + A_y \cos \theta$$

Compare to a Lorentz transformation:

$$x' = x \cosh \omega - T \sinh \omega$$

$$T' = -x \sinh \omega + T \cosh \omega$$

$$y' = y$$

$$z' = z$$

The invariant combination is

$$d\tau^2 = T^2 - x^2 - y^2 - z^2$$

Time  $T$  does not change under a spatial rotation. All 4-vectors transform as indicated under a Lorentz transformation. How to construct quantities which are scalar invariants with respect to a Lorentz transformation? Consider the contravariant 4-vector

$$dx^\mu = (dT, dx, dy, dz)$$

Construct the covariant vector by reversing the sign of the time coordinate.

$$dx_\mu = (-dT, dx, dy, dz)$$

Note that the product between these two vectors is invariant. Use the summation convention.

$$d\tau^2 = dx^\mu dx_\mu = -dT^2 + dx^2 + dy^2 + dz^2$$

In general, given the contravariant vector  $A^\mu$  and the covariant vector  $B_\mu$ , then  $A^\mu B_\mu$  is invariant by construction under the Lorentz Transformation.

$$A^\mu B_\mu = -A_T B_T + A_x B_x + A_y B_y + A_z B_z$$

The inertial reference frame implies Cartesian coordinates and that Newton's Laws are satisfied.

### Transformation rule

If  $A^\mu$  is a 4-vector and  $B_\mu$  has unknown transformation properties, then if  $A^\mu B_\mu$  is a scalar then  $B_\mu$  is a 4-vector.

### Field Theory

Fields in nature: \* Higgs field is a scalar. \* 4-vector electromagnetic field is a 4-vector. \* Energy and momentum are parts of a 4-vector. \* Temperature field in a room is a scalar field. Lagrangians must be scalars. The partial derivative of a scalar is a covariant 4 -vector.

$$\frac{\partial \phi}{\partial x^{2x}} = \phi$$

The quantity  $dx^\mu$  is a contravariant vector, so then

$$\frac{\partial \phi}{\partial x^\alpha} dx^\alpha$$

should be a scalar. Identify this expression as the total derivative.

$$\frac{\partial \phi}{\partial x^\mu} dx^\mu = d\phi$$

The right hand side is scalar, therefore the left hand side is a scalar, therefore

$$\frac{\partial \phi}{\partial x^x}$$

is a covariant 4 -vector. Invent  $\phi_\mu$  by changing the sign of the time component.

$$\begin{aligned}\phi_{\mu\mu} &= \left( \frac{\partial \phi}{\partial t}, \frac{\partial \phi}{\partial x}, \frac{\partial \phi}{\partial y}, \frac{\partial \phi}{\partial z} \right) \\ \phi_{\mu\mu} &= \left( -\frac{\partial \phi}{\partial t}, \frac{\partial \phi}{\partial x}, \frac{\partial \phi}{\partial y}, \frac{\partial \phi}{\partial z} \right)\end{aligned}$$

then  $\phi_{\mu\mu} \phi^\mu$  is a scalar.

$$\phi_{\mu\mu} \phi^\mu \left( -\left( \frac{\partial \phi}{\partial t} \right)^2, \left( \frac{\partial \phi}{\partial x} \right)^2, \left( \frac{\partial \phi}{\partial y} \right)^2, \left( \frac{\partial \phi}{\partial z} \right)^2 \right)$$

### The four-dimensional Lagrangian

Generalize the action from

$$\text{Action} = \int dt \mathcal{L}$$

to a four-dimensional integration.

$$\text{Action} = \int dx dt L \quad \text{Integrate over spacetime.}$$

Return to the vibrating string problem.

$$L = \frac{\dot{\phi}^2}{2} - \frac{c^2(\partial_x \phi)^2}{2}$$

The Lagrangian  $L$  is a scalar which implies Lorentz invariant equations of motion.

$$\text{Action} = \int dx^4 \left[ \dot{\phi}_i^2 - \dot{\phi}_x^2 - \dot{\phi}_y^2 - \dot{\phi}_z^2 \right]$$

or

$$\text{Action} = \int dx^4 \left[ \dot{\phi}^\mu \dot{\phi}_{j\mu} \right]$$

Minimize the action. Start with minimizing a little region... to be continued.