Singular Lorentz Transformations and Pure Radiation Fields

Kevin Maguire

April 22, 2014

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5. The Fractional Linear Transformation
6. Infinitesimal Lorentz Transformation
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Introduction: Lorentz Transformations

- A Lorentz transformation is defined by the preservation of the quadratic form

$$x'^2+y'^2+z'^2-t'^2 = x^2+y^2+z^2-t^2,$$

  in the transformation $(x,y,z,t) \to (x',y',z',t')$
- Take the Proper Orthochronous Lorentz Transformations(POLTs) which form the restricted Lorentz group $SO^+(1,3)$
- In general lorentz transformations have two invariant null directions

- –Proper is det 1 . preserves the orientation of spacial axes, preserves handedness
- –orthochronous means time is always positive and the direction of time is preserve
- –Think of the standard Lornetz transformation, always two null directions at $x \pm$

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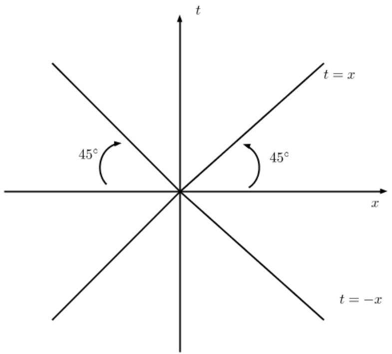

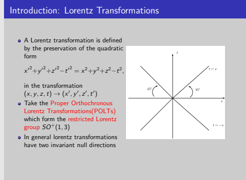

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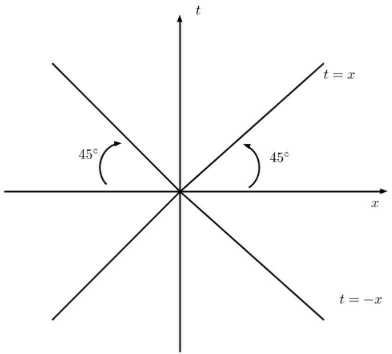

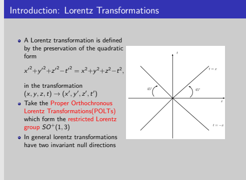

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- derive a strange minkowskian line element
- making a complicated transformation that keeps a single null geodesic fixed look trivial

Strange Minkowskian Line Element

- Start with the Schwarzschild solution

$$\epsilon \mathrm{d}s^2 = \left(1 - \frac{2m}{r}\right)^{-1} \mathrm{d}r^2 + r^2(\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\phi^2) - \left(1 - \frac{2m}{r}\right) \mathrm{d}t^2.$$

- Make the Eddington-Finkelstein coordinate transformation [2]

$$u = t - r - 2m \ln(r - 2m).$$

- Make further coordinate transformations to obtain

$$\epsilon \mathrm{d}s^2 = \frac{r^2}{\cosh^2 \mu\xi}(\mathrm{d}\xi^2 + \mathrm{d}\eta^2) - 2\mathrm{d}u\mathrm{d}r - \left(\mu^2 - \frac{2k}{r}\right) \mathrm{d}u^2.$$

- Taking the limit as the energy, $\mu \to 0$ gives The Kasner Solution

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- Then with $m = 0$ the strange Minkowskian line element is obtained

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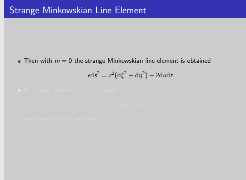

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LTs that leave one null invariant direction are constructed

Singular Lorentz Transformation

- Define an arbitrary complex parameter $\zeta := \xi + i\eta$, to get the new line element[3]
$$\epsilon ds^2 = r^2 d\zeta d\bar{\zeta} - 2dudr.$$
- The transformation $\zeta \to \zeta + w$, where $w \in \mathbb{C}$ is then trivial and leaves the single null geodesic $r = 0$ invariant.
- In Cartesian coordinates this transformation becomes

$$\begin{aligned} x' + iy' &= x + iy + w(t - z), \\ z' - t' &= -r = z - t, \\ z' + t' &= z + t + w(x - iy) + w(x + iy) + w\bar{w}(t - z). \end{aligned}$$

- Addition of complex numbers is commutative, and w has two parameters, so the singular Lorentz transformations form a 2-parameter abelian subgroup of the Lorentz group

- This is what we want, An LT which leaves one null invariant.
- The use in the previous coord transforms was to make this transformation look trivial
- So this is what the seemingly trivial transformation looks like in cartesians
- Again its clear that $r = 0$ keeps one direction fixed, as then z=t
- but it doesn't work both ways, not all 2 parameter abelian subgroups are singular lorentz transformations

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- shown here that there is a 2 to 1 correspondence between SL(2,C) and POLTs

$SL(2,\mathbb{C})$ Matrices of the POLT

- There is a one to one correspondence between points in Minkowskian space-time and Hermitian matrices
- Contruct the following matrix

$$A = \begin{pmatrix} t-z & x+iy \\ x-iy & t+z \end{pmatrix},$$

- This is useful as its determinant is the Lorentz quadratic form modulo a sign

$$\det(A(\vec{x})) = t^2 - x^2 - y^2 - z^2.$$

- Construct the transformation $A(\vec{x}') = UA(\vec{x})U^\dagger$, where

$$U = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix},$$

is an element of $SL(2,\mathbb{C})$

- Complex Hermitian matrices have 4 independant components, so the element of such a matrix can be used to represent points in Minkowskian space-time.
- where $\alpha, \beta, \gamma, \delta$ are complex its an element of the special linear group. This mean it has determinant 1. **write it on the board**

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- Thus the general relations

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Example: Singular Lorentz transformation

- Take the singular Lorentz transformation from earlier

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\begin{aligned}
t' - z' &= t - z, \\
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- Equate coefficients on the RHS of this equation with the RHS of the general relations on the previous slide to obtain

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\begin{aligned}
\alpha &= \pm 1, & \beta &= 0, \\
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- So there are always two possible choices of U

$$U = \pm \begin{pmatrix} 1 & 0 \\ \bar{w} & 1 \end{pmatrix}$$

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Layout

1. Introduction: Lorentz Transformations
2. Strange Minkowskian Line Element
3. Singular Lorentz transformation
4. $SL(2, \mathbb{C})$ Matrices of the Lorentz Transformation
5. The Fractional Linear Transformation
6. Infinitesimal Lorentz Transformation
7. Pure Radiation conditions

Layout
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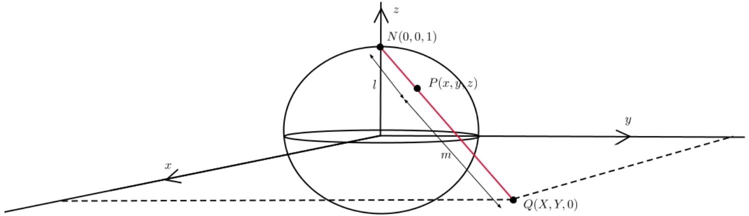
5. The Fractional Linear Transformation

- Connect Minkoswkian space to the 2-sphere by stereographic projection, so we ca use points on a 2 sphere to think about LTs

Fractional Linear Transformation: Stereographic Projection

- Use Stereographic Projection to map $\mathbb{S}^2$ to the extended complex plane, $\hat{\mathbb{C}} = \mathbb{C} \cup \{\infty\}$



- The algebraic relation for a unit vector is

$$(x, y, z) = \left(\frac{\bar{\zeta} + \zeta}{\bar{\zeta}\zeta + 1}, i\frac{\bar{\zeta} - \zeta}{\bar{\zeta}\zeta + 1}, \frac{\bar{\zeta}\zeta - 1}{\bar{\zeta}\zeta + 1}\right),$$

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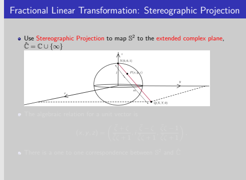

- As we know, stereographic projection doesn't map the point N at the top of the circle, so thats why we map N to infinity and need to consider the extended complex plane
- It can also be written in terms of θ and ϕ

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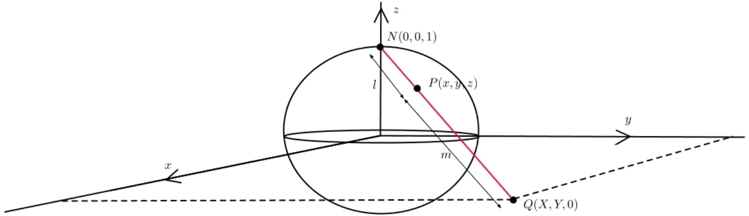

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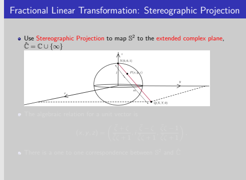

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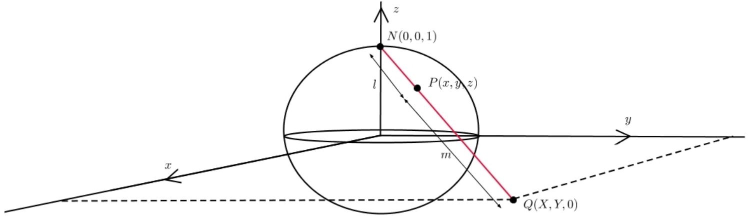

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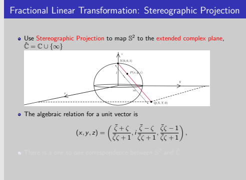

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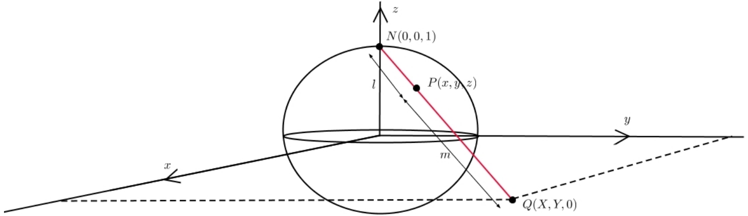

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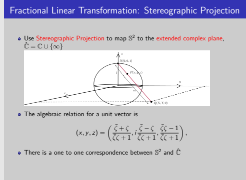

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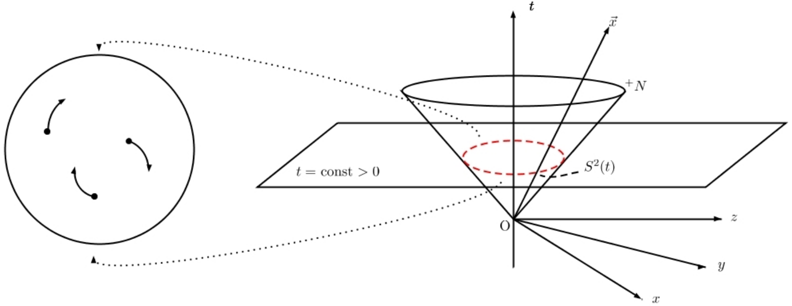
- Extend this to Minkowskian space-time[1]



- $(x, y, z, t) \leftrightarrow \mathbb{S}^2 \leftrightarrow \hat{\mathbb{C}}$
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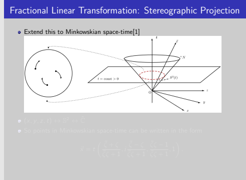

- all the points on the 2 sphere are generators of the future null cone in Minkowskia space time
- Can denote an LT by moving three arbitrary points along the surface of the spher as the generators have dimension two, so to match the dim of the LT (it's 6) we need three of them
- Extra coord is becasue we take time into account now, now ζ has two parameters so x is in terms of two parameters, t just defines the direction

Fractional Linear Transformation: Stereographic Projection

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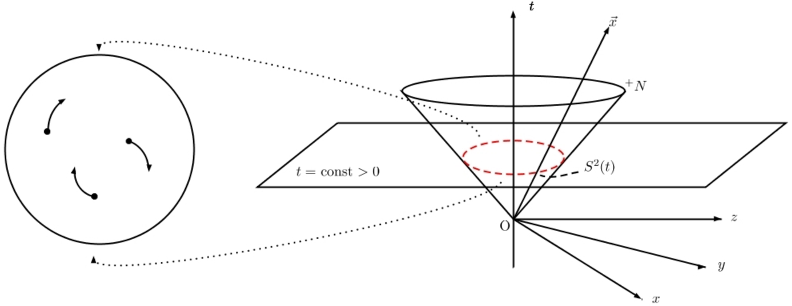

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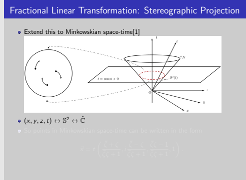

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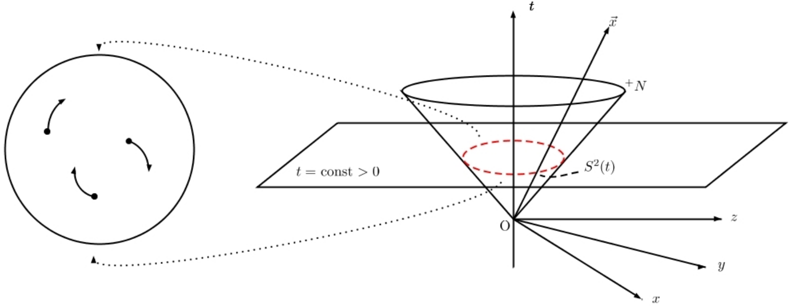

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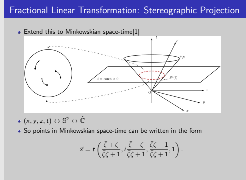

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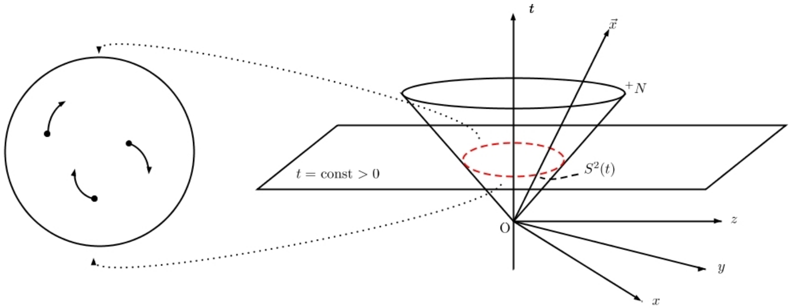
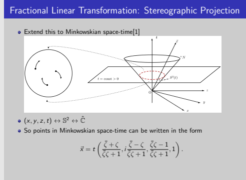


- $(x, y, z, t) \leftrightarrow \mathbb{S}^2 \leftrightarrow \hat{\mathbb{C}}$
- So points in Minkowskian space-time can be written in the form

$$\vec{x} = t\left(\frac{\bar{\zeta}+\zeta}{\bar{\zeta}\zeta+1}, i\frac{\bar{\zeta}-\zeta}{\bar{\zeta}\zeta+1}, \frac{\bar{\zeta}\zeta-1}{\bar{\zeta}\zeta+1}, 1\right).$$



- all the points on the 2 sphere are generators of the future null cone in Minkowskia space time
- Can denote an LT by moving three arbitrary points along the surface of the spher as the generators have dimension two, so to match the dim of the LT (it's 6) we need three of them
- Extra coord is becasue we take time into account now, now ζ has two parameters so x is in terms of two parameters, t just defines the direction

Fractional Linear Transformation

- Make the transformation $\zeta \to \zeta'$ by constructing the matrix $A(\vec{x})$ and determining the matrix U.

$$A(\vec{x}) = \begin{pmatrix} \frac{2t}{\zeta\bar{\zeta}+1} & \frac{2t\zeta}{\zeta\bar{\zeta}+1} \\ \\ \frac{2t\bar{\zeta}}{\zeta\bar{\zeta}+1} & \frac{2t\zeta\bar{\zeta}}{\zeta\bar{\zeta}+1} \end{pmatrix} = c_0 \begin{pmatrix} 1 & \zeta \\ \bar{\zeta} & \bar{\zeta}\zeta \end{pmatrix},$$

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- Solve for ζ' to get the fractional linear transformation

$$\zeta' = \frac{(\bar{\gamma} + \bar{\delta}\zeta)}{(\bar{\alpha} + \bar{\beta}\zeta)},$$

- There is a one to one correspondence between POLTs and fractional linear transformations

- These are null directions
- Refer to eqn (27) which should be on the board
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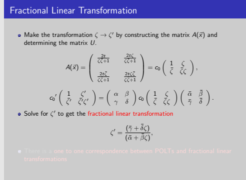

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Layout

Singular Lorentz Transformations and Pure Radiation Fields

2014-04-22

└─Layout

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5. The Fractional Linear Transformation
6. Infinitesimal Lorentz Transformation

- temp

Infinitesimal Lorentz Transformation

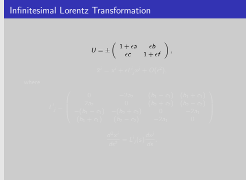
$$U = \pm \begin{pmatrix} 1+\epsilon a & \epsilon b \\ \epsilon c & 1+\epsilon f \end{pmatrix},$$

$$\bar{x}^i = x^i + \epsilon L^i{}_j x^j + O(\epsilon^2),$$

where

$$L^i{}_j = \begin{pmatrix} 0 & -2a_2 & (b_1 - c_1) & (b_1 + c_1) \\ 2a_2 & 0 & (b_2 + c_2) & (b_2 - c_2) \\ -(b_1 - c_1) & -(b_2 + c_2) & 0 & -2a_1 \\ (b_1 + c_1) & (b_2 - c_2) & -2a_1 & 0 \end{pmatrix}$$

$$\frac{d^2 x^i}{ds^2} = L^i{}_j(s) \frac{dx^j}{ds}.$$



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Infinitesimal Lorentz Transformation: Lorentz Force

- Can rewrite this equation in terms of the particles 3-velocity $\vec{u}$, in component form

$$\frac{d}{dt}(\gamma(u)u^{(1)}) = -2a_2 u^{(2)} + (b_1 - c_1)u^{(3)} + b_1 + c_1,$$
$$\frac{d}{dt}(\gamma(u)u^{(2)}) = 2a_2 u^{(1)} + (b_2 + c_2)u^{(3)} + b_2 - c_2,$$
$$\frac{d}{dt}(\gamma(u)u^{(3)}) = -(b_1 - c_1)u^{(1)} - (b_2 + c_2)u^{(2)} - 2a_1,$$
$$\frac{d\gamma(u)}{dt} = (b_1 + c_1)u^{(1)} + (b_2 - c_2)u^{(2)} - 2a_1 u^{(3)}.$$

- Define the 3-vectors

$$\vec{P} = (b_1 + c_1, b_2 - c_2, -2a_1),$$
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Infinitesimal Lorentz Transformation: Lorentz Force

- Writing the equations in terms of these

$$\frac{d}{dt}(\gamma(u)\vec{u}) = \vec{P} + \vec{u} \times \vec{Q},$$

- This is the same form as the Lorentz force
- Make the Identification

$$\vec{P} = \frac{q}{m}\vec{E}, \qquad \vec{Q} = \frac{q}{m}\vec{B}, \tag{1}$$

- To be compatible with special relativity the Lorentz force must depend on $\vec{u}$ in this way. So the Lorentz force is a special case of a charged particle moving along a world line in minkowskian space-time generated by an infinitesimal Lorentz transformation.

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Pure Radiation Conditions

- The fractional linear transformation of the infinitesimal transformation is

$$\zeta' = \frac{\zeta + \epsilon(\bar{c} - \bar{a}\zeta) + O(\epsilon^2)}{1 + \epsilon(\bar{a} + \bar{b}\zeta) + O(\epsilon^2)}.$$

- Fixed points of the system are given by $\zeta = \zeta'$ and correspond to null directions
- With this condition solve the fractional linear transformation for ζ

$$\bar{\beta}\zeta^2 + (\bar{\alpha} - \bar{\delta})\zeta - \bar{\gamma} = 0.$$

- A quadratic means it has two roots in general
- Interested in the singular root case so take the descriminant equal to zero to get

$$a^2 + bc = 0.$$

refer to this as the quadratic condition.

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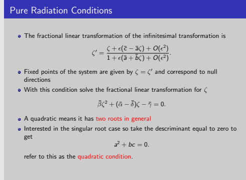

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Pure Radiation Conditions

- The a and b are related to $\vec{E}$ and $\vec{B}$ through the Lorentz force as

$$a_1 = -\frac{1}{2}E^3, \qquad b_2 = \frac{1}{2}(E^2 + B^1), \qquad c_1 = \frac{1}{2}(E^1 + B^2),$$
$$a_2 = -\frac{1}{2}B^3, \qquad b_1 = \frac{1}{2}(E^1 - B^2), \qquad c_2 = \frac{1}{2}(B^1 - E^2).$$

- Then the real and imaginary parts of the quadratic condition give us the relations

$$|\vec{E}|^2 = |\vec{B}|^2,$$
$$\vec{E} \cdot \vec{B} = 0.$$

- These are the familiar pure radiation conditions. Thus if the world line of a charged particle is generated by an infinitesimal Lorentz transformation then the particle is moving in a pure radiation EM field.

- q/m factors suppresed for convenience

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Layout

add in the contents

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- MAny other things can be shown, I will finally show one small lemma of this resul

References

1 J.L. Synge - “Relativity: The Special Theory” - North Holland Publishing Company (1965)
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