

Title: 13/14 PSI - Relativity - Lecture 3

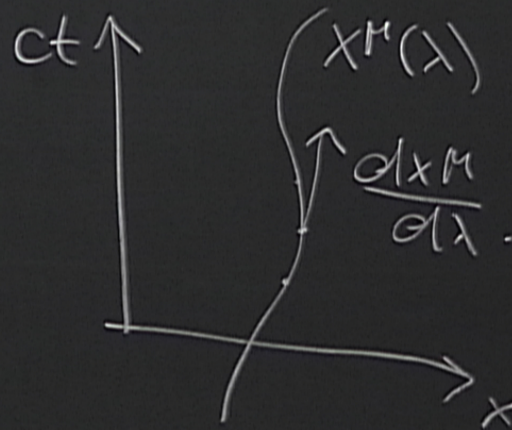
Date: Sep 11, 2013 09:00 AM

URL: <http://pirsa.org/13090013>

Abstract:

C) RELATIVISTIC MECHANICS

• PARTICLE MOTION



WORLDLINE

λ .. PARAMETER

$\frac{dx^\mu}{d\lambda}$... PARAMETRIC 4-VELOCITY

$$ds^2 = \eta_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda} d\lambda^2 > 0 \quad \text{SPACELIKE}$$

$$ds^2 = \eta_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda} d\lambda^2 \begin{cases} > 0 \\ = 0 \end{cases} \begin{array}{l} \text{SPACELIKE (TACHYON)} \\ \text{NULL (LIGHTLIKE)} \end{array}$$

$$ds^2 = \eta_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda} d\lambda^2$$

> 0 SPACELIKE (TACHYON)
 $= 0$ NULL (LIGHTLIKE)
 < 0 TIMELIKE (PHYSICAL MASSIVE PARTS)

CS

WORLDLINE

PARAMETER

PARAMETRIC 4-VELOCITY

$$ds^2 = \eta_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda} d\lambda^2$$

> 0

$= 0$

< 0

SPACELIKE (T)

NULL (LIGHT)

TIMELIKE (PH)
HAS

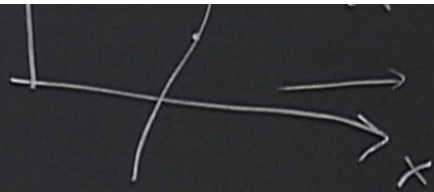
• FOR TIMELIKE CURVES DEFINE

$$cd\tau = \sqrt{-\eta_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau} d\tau^2}$$

$$ds^2 = \eta_{\mu\nu} \frac{dx^\mu}{dx} \frac{dx^\nu}{dx} dx^2 \begin{cases} > 0 & \text{SPACELIKE (TACHYON)} \\ = 0 & \text{NULL (LIGHTLIKE)} \\ < 0 & \text{TIMELIKE (PHYSICAL MASSIVE PARTS)} \end{cases}$$

• FOR TIMELIKE CURVES DEFINE

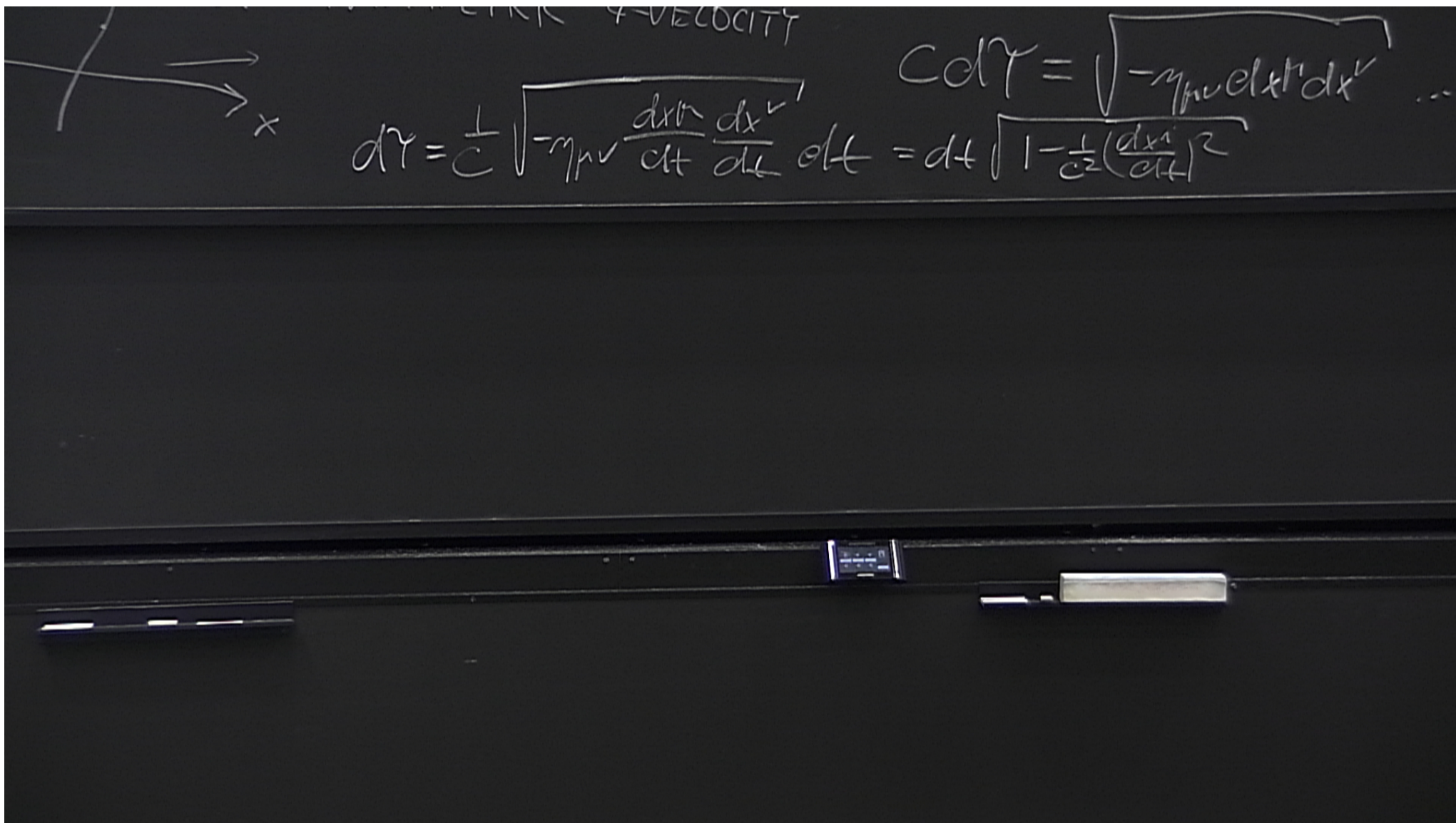
$$cd\tau = \sqrt{-\eta_{\mu\nu} dx^\mu dx^\nu} \dots \text{LI, } \tau \dots \text{PROPER TIME}$$



4-VELOCITY

$$d\tau = \frac{1}{c} \sqrt{-\eta_{\mu\nu} \frac{dx^\mu}{dt} \frac{dx^\nu}{dt}} dt$$

$$cd\tau = \sqrt{\dots}$$



$$ds^2 = \eta_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda} d\lambda^2 \begin{cases} > 0 & \text{SPACELIKE (TACHYON)} \\ = 0 & \text{NULL (LIGHTLIKE)} \\ < 0 & \text{TIMELIKE (PHYSICAL MASSIVE PARTS)} \end{cases}$$

• FOR TIMELIKE CURVES DEFINE

$$cd\tau = \sqrt{-\eta_{\mu\nu} dx^\mu dx^\nu} \quad \dots \text{LI, } \tau \dots \text{PROPER TIME}$$

$$d\tau = dt \sqrt{1 - \frac{1}{c^2} \left(\frac{dx^i}{dt} \right)^2} = dt \sqrt{1 - v^2/c^2} = dt/\gamma$$



$$d\tau = \frac{1}{c} \sqrt{-\eta_{\mu\nu} \frac{dx^\mu}{dt} \frac{dx^\nu}{dt}} dt = dt \sqrt{1 - \frac{v^2}{c^2}}$$

• 4-VELOCITY $u^\mu = \frac{dx^\mu}{d\tau} = \frac{dx^\mu}{dt} \frac{dt}{d\tau} = \gamma (c, \vec{v})$

$$\Rightarrow u^\mu u_\mu = -c^2$$

• PARTICLE MASS DEPENDS ON THE VELOCITY

$$m = \gamma m_0 \quad \text{--- REST MASS}$$



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$$= g(c, \vec{v}) \quad \bullet \text{ 4-MOMENTUM. } p^\mu = m_0 u^\mu = (\gamma m_0 c, \gamma m_0 \vec{v})$$

CITY
S (ZEE)

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$$= \left(\frac{E}{c}, \vec{p} \right)$$

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CALCULATE

$$p^2 = p^\mu p_\mu =$$

CITY

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CALCULATE ^{REST}

$$p^2 = p^\mu p_\mu \stackrel{\text{REST}}{=} -m_0^2 c^2$$

CITY

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CALCULATE

$$p^2 = p^\mu p_\mu \stackrel{\text{REST}}{=} -m_0^2 c^2 \stackrel{\text{OTHER}}{=} -\frac{E^2}{c^2} + |\vec{p}|^2$$

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S (ZEE)

$$E = c \sqrt{\vec{p}^2 + m_0^2 c^2} = m_0 c^2 \sqrt{1 + \left(\frac{\vec{p}}{m_0 c}\right)^2}$$

$$\approx m_0 c^2 \left(1 + \frac{1}{2} \frac{\vec{p}^2}{m_0^2 c^2} \right) = \underbrace{m_0 c^2}_{\text{RESF}} + \underbrace{\frac{\vec{p}^2}{2 m_0}}_{\text{KE}}$$

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$m_0 = 0$ $E = c |\vec{p}|$

• DYNAMICS : NEWTON LAW

4-FORCE

$$F^\mu = \frac{dp^\mu}{d\tau}$$

E.G. $F^\mu = q F^{\mu\nu} v_\nu$.. LORENTZ

$\frac{d\gamma}{d\tau}$

E.G. $F^\mu = q F^{\mu\nu} u_\nu$... LORENTZ

• $F \cdot u = \eta_{\mu\nu} F^\mu u^\nu = \eta_{\mu\nu} u^\nu \frac{dp^\mu}{d\tau}$

4-FORCE

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$$m_0 = 0$$

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E.G. $F^\mu = q F^{\mu\nu} u_\nu$. LORENTZ

$$\bullet F \cdot u = \eta_{\mu\nu} F^\mu u^\nu = \eta_{\mu\nu} u^\nu \frac{dp^\mu}{d\tau} = \eta_{\mu\nu} u^\nu \frac{dm_0}{d\tau} u^\mu + \eta_{\mu\nu} u^\nu \frac{d\vec{p}}{d\tau} \cdot \vec{u}$$

$$E = c \sqrt{\vec{p}^2 + m_0^2 c^2} = m_0 c^2 \sqrt{1 + \left(\frac{p}{m_0 c}\right)^2}$$

$$\approx m_0 c^2 \left(1 + \frac{1}{2} \frac{\vec{p}^2}{m_0^2 c^2} \right) = \underbrace{m_0 c^2}_{\text{REST}} + \underbrace{\frac{\vec{p}^2}{2 m_0}}_{\text{KE}}$$

$$\underline{m_0 = 0} \quad \boxed{E = c |\vec{p}|}$$

$$\frac{d}{d\tau} (m^\mu m_\mu) = (-c^2)' = 0$$

$$\frac{dm_0}{d\tau} u^\mu + \underbrace{\eta_{\mu\nu} u^\mu \frac{du^\nu}{d\tau}}_{=0} m_0$$

(ϵE)

$$E = c \sqrt{\vec{p}^2 + m_0^2 c^2} = m_0 c^2 \sqrt{1 + \left(\frac{p}{m_0 c}\right)^2}$$

$$\approx m_0 c^2 \left(1 + \frac{1}{2} \frac{\vec{p}^2}{m_0^2 c^2} \right) = \underbrace{m_0 c^2}_{\text{REST}} + \underbrace{\frac{\vec{p}^2}{2 m_0}}_{\text{KE}}$$

$m_0 = 0$ $E = c |\vec{p}|$

$$\frac{d}{d\tau} (m^\mu m_\mu) = (-c^2)' = 0$$

RENTZ

$$\frac{dp^\mu}{d\tau} = \underbrace{\eta_{\mu\nu} m^\nu}_{-c^2} \frac{dm_0}{d\tau} + \underbrace{\eta_{\mu\nu} m^\nu}_{\cancel{0}} \frac{dm_0}{d\tau} = -c^2 \frac{dm_0}{d\tau}$$

E.G. $F^\mu = q F^{\mu\nu} u_\nu$.. LORENTZ

• $F \cdot u = \eta_{\mu\nu} F^\mu u^\nu = \eta_{\mu\nu} u^\nu \frac{dp^\mu}{d\tau} = \underbrace{\eta_{\mu\nu} u^\nu}_{-c^2} \frac{dm_0}{d\tau} u^\mu + \underbrace{\eta_{\mu\nu} u^\nu}_{-c^2} \frac{d\mathbf{p}}{d\tau}$

$F \cdot u \Rightarrow m_0$ CHANGES

NOT THE CASE OF EM: $F \cdot u = q \underbrace{\eta_{\mu\nu} u^\nu}_{-c^2} F^\mu$

E.G. $F^\mu = q F^{\mu\nu} u_\nu$.. LORENTZ

• $F \cdot u = \eta_{\mu\nu} F^\mu u^\nu = \eta_{\mu\nu} u^\nu \frac{dp^\mu}{d\tau} = \underbrace{\eta_{\mu\nu} u^\nu}_{-c^2} \underbrace{\frac{dm_0}{d\tau}}_{=0} u^\mu + \underbrace{\eta_{\mu\nu} u^\nu}_{=0}$

~~$F \cdot u$~~ $\Rightarrow$ no CHANGES

NOT THE CASE OF EM: $F \cdot u = q \eta_{\mu\nu} u^\nu F^\mu = 0$

2) FIRST LOOK AT GR

a) CONCEPTUAL PATH TO THE THEORY

i) FIELD THEORY FOR GRAVITY

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i) FIELD THEORY FOR GRAVITY

$$F_g = G \frac{m_1 m_2}{r^2}$$

ELIMINATE INSTANTANEOUS ACTION AT A DISTANCE.

2) FIRST LOOK AT GR

a) CONCEPTUAL PATH TO THE THEORY

i) FIELD THEORY FOR GRAVITY

$$F_g = G \frac{m_1 m_2}{r^2} \quad \Leftrightarrow \quad F_e = k \frac{q_1 q_2}{r^2}$$

ELIMINATE INSTANTANEOUS ACTION AT A DISTANCE.

ii) RELATIVITY OF MOTION

SPACE AS - ABSOLUTE .. NEWTON

$$\frac{q^2}{r^2}$$

A DISTANCE.

ii) RELATIVITY OF MOTION

SPACE AS $\left\{ \begin{array}{l} \text{ABSOLUTE} \dots \text{NEWTON} \\ \text{RELATION} \dots \text{ARISTOTEL, DESCARTES} \dots \end{array} \right.$

$\frac{92}{1^2}$

A DISTANCE,

11) RELATIVITY OF MOTION

SPACE AS $\left\{ \begin{array}{l} \text{ABSOLUTE} \dots \text{NEWTON} \\ \text{RELATION} \dots \text{ARISTOTEL, DESCARTES} \dots \end{array} \right.$

MOTION $\left\{ \begin{array}{l} \text{ABSOLUTE} \\ \text{RELATIVE} \dots \text{GOING FROM CONTINUITY OF} \\ \text{ONE OBJECT TO —||— OF ANOTHER} \\ \text{OBJECT.} \end{array} \right.$

$\frac{92}{12}$

A DISTANCE.

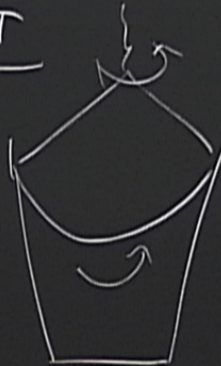
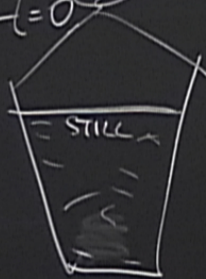
NEWTON'S BUCKET

$t=0$



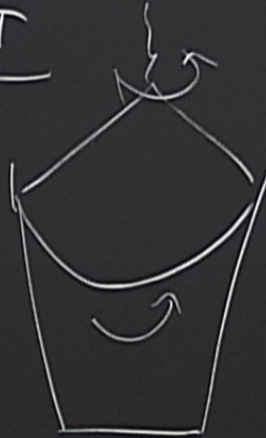
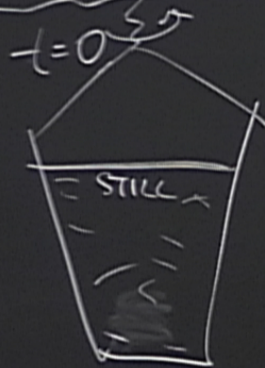
• NEWTON'S BUCKET

$t=0$



CONCAVITY IS DUE TO THE ROTATION OF THE WATER
ROTATION W.R.T WHAT?

NEWTON'S BUCKET



CONCAVITY IS DUE TO THE ROTATION OF THE
ROTATION W.R.T WHAT?

DESCARTES: BUCKET ↙
NEWTON: ABSOLUTE SPACE

$$T_g = G \frac{M}{r^2} \quad \leftrightarrow \quad F_c = k \frac{v^2}{r^2}$$

MOTION - ABSOLUTE
 RELATIVE ... GOING FROM CONTINUITY
 ONE OBJECT TO —||— OF ANOTHER

ELIMINATE INSTANTANEOUS ACTION AT A DISTANCE.

NEWTON'S BUCKET

CONCAVITY IS DUE TO THE ROTATION OF THE WATER

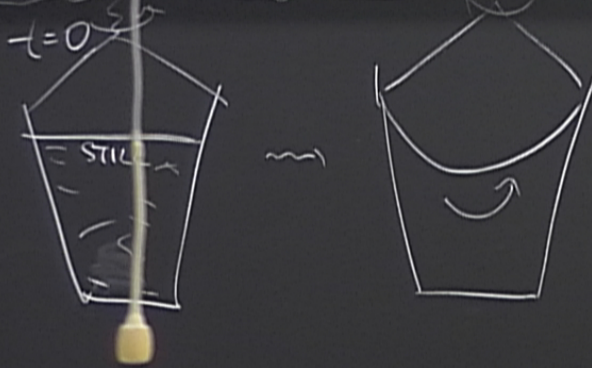
ROTATION W.R.T WHAT?

DESCARTES: BUCKET

NEWTON: ABSOLUTE SPACE .. PROOF

MACH: THE FULL MATTER CONTENT OF THE UNIVERSE
 INERTIA CAUSED BY DISTANT STARS

EINSTEIN: LOCAL PHYS. QUANTITY - GRAVITATIONAL FIELD



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② WHY SHOULD BE NEWTONIAN ACCELERATION DEFINED W.R.T. THE GRAV. FIELD? ②

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b) PRINCIPLE OF EQUIVALENCE

OBSERVATION: ALL BODIES IN A GIVEN GRAV. FIELD EXPERIENCE THE SAME ACCELERATION.

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$$F = m_I a = m_g g$$

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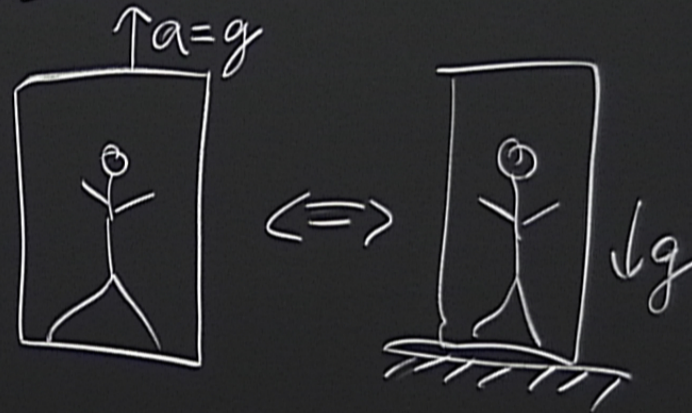
PRINCIPLE OF EQUIVALENCE

$$(m_I = m_g, \text{ (EXPERIMENT) }) \Rightarrow \boxed{a = g}$$

• E

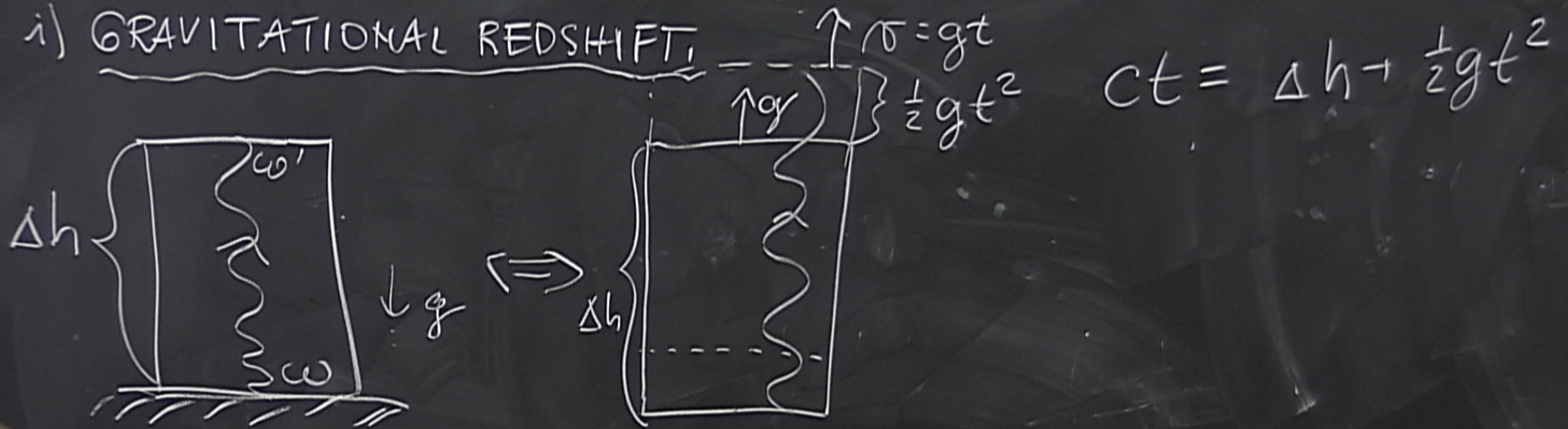
$$m_I = m_g \text{ (EXPERIMENT)} \Rightarrow \boxed{a=g}$$

• EINSTEIN'S ELEVATOR



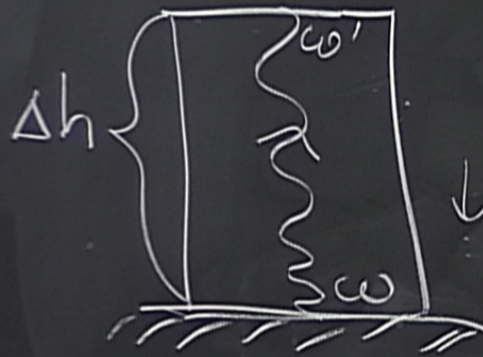
CONSEQUENCES:

i) GRAVITATIONAL REDSHIFT,

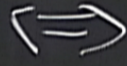


CONSEQUENCES:

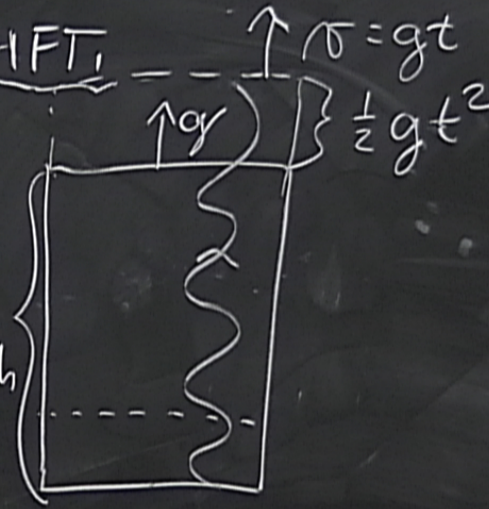
i) GRAVITATIONAL REDSHIFT,



$\downarrow g$



Δh



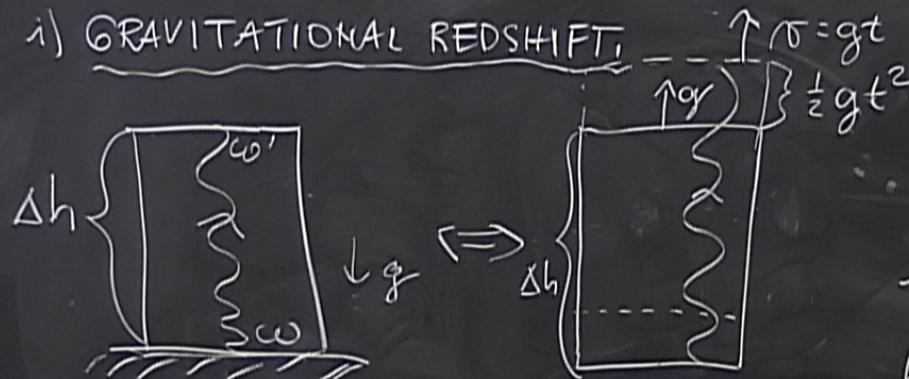
$$ct = \Delta h + \frac{1}{2}gt^2$$

$$r = gt \approx g \cdot \frac{\Delta h}{c}$$

E.G. $F^{\mu} = \dots F^{\mu\nu}$

CONSEQUENCES:

1) GRAVITATIONAL REDSHIFT



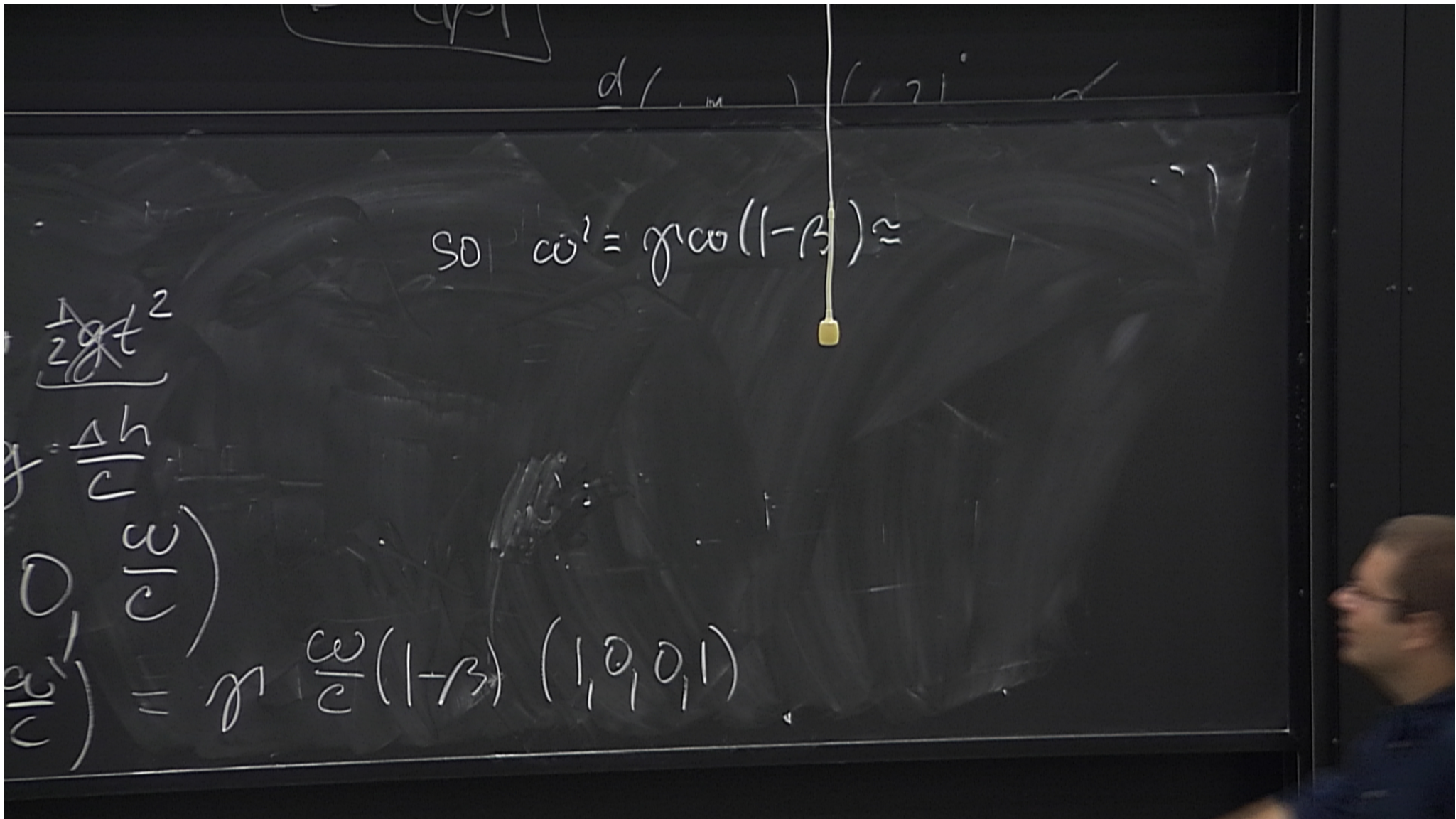
$$ct = \Delta h + \frac{1}{2}gt^2$$

$$v = gt = g \frac{\Delta h}{c}$$

$$R^{\mu} = \left(\frac{\omega}{c}, 0, 0, \frac{\omega}{c} \right)$$

$$R^{\mu'} = \left(\frac{\omega'}{c}, 0, 0, \frac{\omega'}{c} \right) = \gamma \frac{\omega}{c} (1 - \beta) (1, 0, 0, 1)$$

SO $\omega' =$



$$\text{SO } \omega' = \gamma \omega (1 - \beta) \approx \omega (1 - \beta) \\ \approx \omega \left(1 - \frac{\Delta h g}{c^2} \right)$$

$$\frac{1}{2} g t^2$$

$$g = \frac{\Delta h}{c}$$

$$\left(\frac{\omega}{c} \right)$$

$$\left(\frac{\omega'}{c} \right) = \gamma \frac{\omega}{c} (1 - \beta) (1, 0, 0, 1)$$

$$\text{SO } \omega' = \gamma \omega (1 - \beta) \approx \omega (1 - \beta) \\ \approx \omega \left(1 - \frac{\Delta h g}{c^2} \right)$$

GRAV. REDSHIFT

$$z = \frac{\omega' - \omega}{\omega}$$

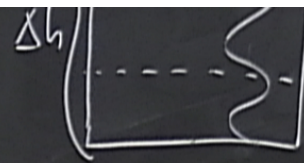
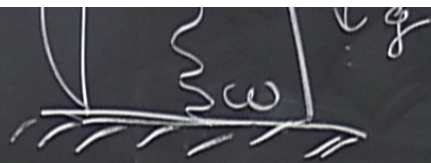
$$\frac{\omega'}{c} = \gamma \frac{\omega}{c} (1 - \beta) \begin{pmatrix} 1 & 0 & 0 & 1 \end{pmatrix}$$

$$\text{SO } \omega' = \gamma \omega (1 - \beta) \approx \omega (1 - \beta) \\ \approx \omega \left(1 - \frac{\Delta h g}{c^2} \right)$$

GRAV. REDSHIFT

$$\left(z = \frac{\omega' - \omega}{\omega} \approx \frac{\omega'}{\omega} - 1 = - \frac{\Delta h g}{c^2} < 0 \right)$$

$$\left(\frac{\omega'}{c} \right) = \gamma \frac{\omega}{c} (1 - \beta) \begin{pmatrix} 1 & 0 & 0 & 1 \end{pmatrix}$$



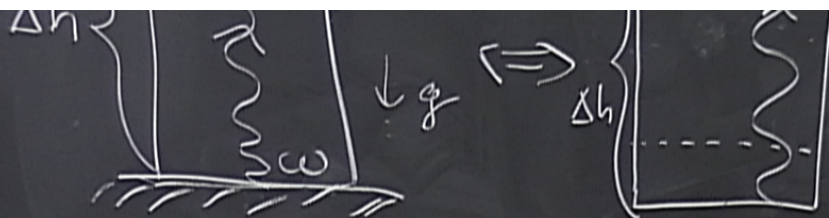
$$k^\mu = \left(\frac{\omega}{c}, 0, 0, 0 \right)$$

$$k'^\mu = \left(\frac{\omega'}{c}, 0, 0, 0 \right)$$

$$F \cdot u = \eta_{\mu\nu} F^\mu_{\mu} u^\nu = \eta_{\mu\nu} u^\nu \frac{dp^\mu}{dx} = \left(\eta_{\mu\nu} u^\nu \right) \frac{d(m_0 c)}{dx} \left(\eta_{\mu\nu} u^\nu \right)$$

PHOTONS ARE "REDDER" UP THERE.

EXPERIMENT.



$$k^\mu = \left(\frac{\omega}{c}, 0, 0, \frac{\omega}{c} \right) \quad (z = \Delta h)$$

$$k'^\mu = \left(\frac{\omega'}{c}, 0, 0, \frac{\omega'}{c} \right) = \gamma \frac{\omega}{c} (1 - \frac{v}{c})$$

$$F \cdot u = \eta_{\mu\nu} F^\mu M^\nu = \eta_{\mu\nu} u^\nu \frac{dp^\mu}{d\tau} = \left(\eta_{\mu\nu} u^\nu \frac{dmo}{d\tau} \right) \frac{p^\mu}{m} + \left(\eta_{\mu\nu} u^\nu \frac{d\pi^\mu}{d\tau} \right)$$

PHOTONS ARE "REDDER" UP THERE.

• EXPERIMENT. TOWER & FLASH LIGHT. ... POUND & REBKA, (1960)

$$\Delta h = 22.6 \text{ m}$$

$$z = \frac{2.3 \times 10^2}{(3 \times 10^8 / c)} \approx 2.5 \times 10^{-15}$$

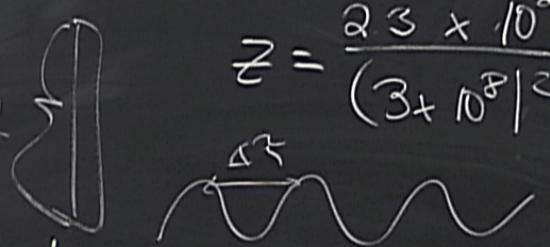
$$\Delta h \left\{ \begin{array}{c} \uparrow \\ \downarrow \end{array} \right\} \Leftrightarrow \Delta h \left\{ \begin{array}{c} \uparrow \\ \downarrow \end{array} \right\} \quad k^\mu = \left(\frac{\omega}{c}, 0, 0, \frac{\omega}{c} \right) \quad (z =$$

PHOTONS ARE "REDDER" UP THERE

• EXPERIMENT TOWER & FLASH LIGHT. ... POUND & REBKA, (1960)

$$\Delta h = 22.6 \text{ m} \quad z = \frac{23 \times 10^2}{(3 \times 10^8)^2} \approx 2.5 \times 10^{-15}$$

$\Delta \gamma \propto \frac{1}{\omega}$



$$m_I = m_g \text{ (EXPERIMENT)} \Rightarrow a = g$$

ii) BENDING OF LIGHT

