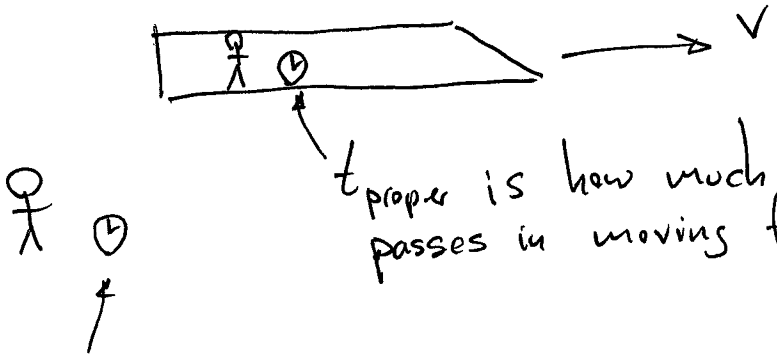
LAST TIME:

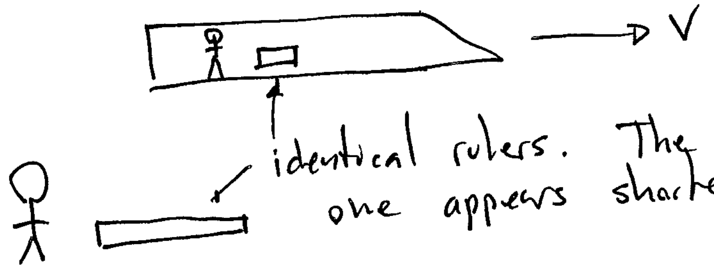
Time Dilation: $t_{obs} = \gamma\, t_{proper}$



t_{proper} is how much time passes in moving frame.

t_{obs} is how much time we measure

Length Contraction: $D_{moving} = \dfrac{D_{at\ rest}}{\gamma}$

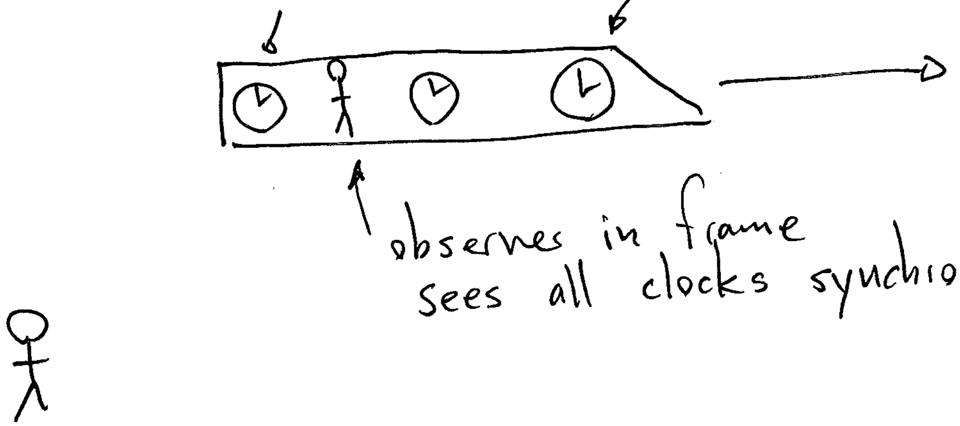


identical rulers. The moving one appears shorter.

Simultaneity:

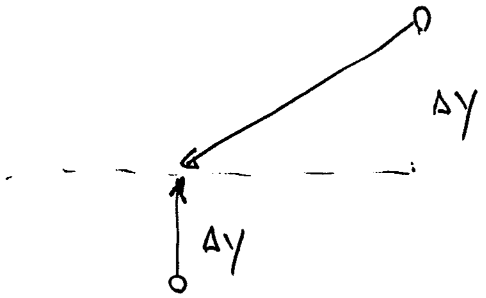
later times

earlier times



observer in frame sees all clocks synchronized.

Relativistic momentum:



$$p_y = m\frac{\Delta y}{\Delta t_{proper}}$$

$$= m\gamma\frac{\Delta y}{\Delta t_{obs}}$$

$$= m\gamma\, v_y$$

velocity of ball in our frame using our time.

So $\vec{p} = \gamma m \vec{v}$

For the slanted path v_{red} is larger. So,

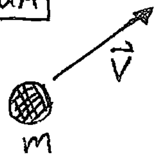
$$p_y = m\gamma v_y$$

this has v^2 in it, so it gets bigger, making up the lost momentum.

Large velocities: momentum + energy still conserved (Noether)

BUT: need to correct our formulae:

MOMENTUM



$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$\boxed{\vec{p} = \gamma m \vec{v}}$$

CLICKER

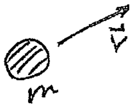
much less than

PROPERTIES: $\vec{p} \to m\vec{v}$ $\quad |\vec{v}| \ll c$

$|\vec{p}| \to \infty$ for $|\vec{v}| \to c$

sum of $\vec{p}$ for all objects same before + after any collision.

ENERGY



Total relativistic energy of an isolated object:

$$\boxed{E = \gamma m c^2}$$

WORKSHEET #1, #2...

Small $\vec{v}$: $$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} = mc^2\left(1 + \frac{1}{2}\frac{v^2}{c^2} + \dots\right)$$

$$= \underset{\substack{\uparrow \\ \text{mass} \\ \times\, c^2}}{mc^2} + \underset{\substack{\uparrow \\ \text{non-relativistic} \\ \text{kinetic energy}}}{\frac{1}{2}mv^2} + \dots$$

small velocities: - mass always conserved

- kinetic energy only conserved in elastic collisions

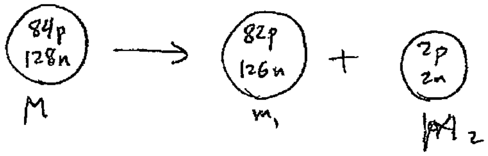
relativity: $$E = \underset{\substack{\nearrow \\ \text{MASS ENERGY}}}{mc^2} + \underset{\substack{\nwarrow \\ \text{RELATIVISTIC KINETIC ENERGY}}}{(\gamma - 1)mc^2}$$ $\nearrow$ combo conserved in ALL processes

BUT: can convert mass ⟷ kinetic energy.

CLICKER

e.g. nuclear reactions

$$^{212}Po \rightarrow {}^{208}Pb + \alpha$$

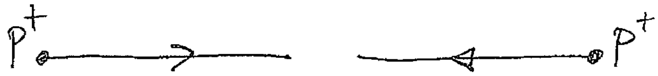


$M > m_1 + m_2$

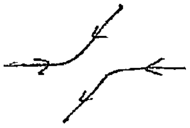
$(\Delta M)c^2 \approx 1.4 \times 10^{-12} J$ → goes into kinetic energy of products.

→ enormous if multiplied by Avogadro's number.

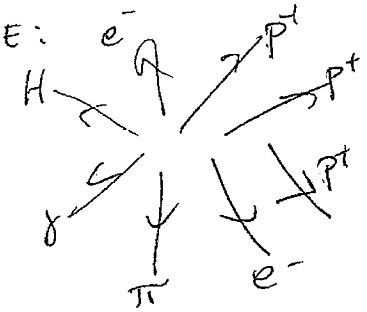
Another example: particle collisions



low E: scattering



large E:



Can produce new particles from kinetic energy!

LHC: each proton has $E \approx 7000$ times its rest energy

– could produce 14000 protons/antiprotons!