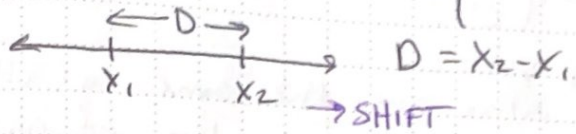


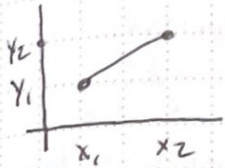
Dr. David Kaplan: HS Relativity + other things

Physicists are addicted to Geometry

Length



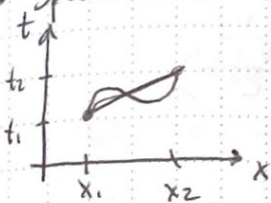
D is invariant under shift



D is invariant under shift of origin + rotations

Pythag gives length

Space Time



Events happen @ time t and space x

$\bar{v} = \frac{\Delta x}{\Delta t} = \text{slope}$  - straight line  $\rightarrow$  constant velocity

$F = ma = m \frac{dv}{dt}$  if car is driving @ constant speed

$F = m \frac{d(v+v_0)}{dt} = m \frac{dv}{dt}$

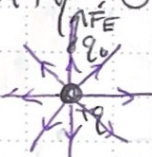


$v \rightarrow v - v_0$  Galilean Invariance

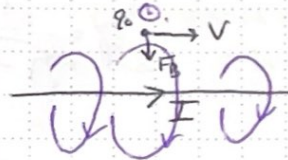
Special Relativity: Origin Story

Electromagnetism

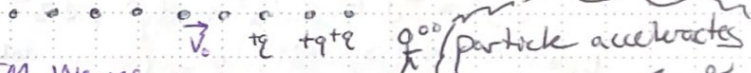
$\vec{F}_E = q_0 \vec{E}$



$\vec{F}_B = q_0 \vec{v} \times \vec{B}$



string of charges



Maxwell says light are EM waves

$v = c = 3 \times 10^8 \text{ m/s}$

only 1 observer can measure correctly



Test for Ether



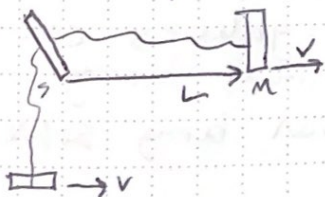
$\frac{c}{v} - (v + c)?$

Mickelson - Morley

Beam-splitter pattern



due to interference



$t = \left( \frac{L + \Delta L}{c} \right)$

$t_{hor} = \frac{L}{c} + \frac{v t_{hor}}{c} = \frac{2cL}{c^2 - v^2}$

$t_{vert} = \frac{2L}{c}$

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$f \equiv$  frequency of light  $f_{\text{thor}} - f_{\text{tvet}}$   
 $\frac{2Lf}{c} \cdot \left(\frac{v^2}{c^2}\right)$   $v$  is speed of Earth through Ether  $3 \times 10^4 \text{ m/s}$

Einstein's Proposition

- ① Laws of nature are the same in all inertial frames
- ② Speed of light =  $c$  is a law of nature

light from rocket  $t_{\text{man}} = \frac{D}{c}$   $t_{\text{Rocket}} = \frac{D}{c + v}$

- Loss of simultaneity
- Length contraction
- Time dilation
- velocity addition

Geometry of Spacetime

$$\frac{v_1 + v_2}{\left(1 + \frac{v_1 v_2}{c^2}\right)}$$

$\frac{t}{x} = \frac{1}{c}$   $ct = x$   $0 = x^2 - (ct)^2$

Interval

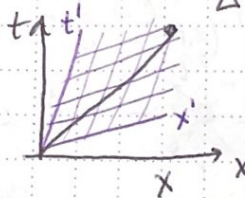
$$I = (\Delta x)^2 - c^2(\Delta t)^2$$

$$= (\Delta x')^2 - c^2(\Delta t')^2$$

$$\Delta t' = \gamma \Delta t - \frac{v \Delta x}{c^2}$$

$$\Delta x' = -v \gamma \Delta t + \gamma \Delta x$$

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



Einstein Tensor  $g_{\mu\nu}$  how space is curved  $\rightarrow$   $G_{\mu\nu} = 8\pi G T_{\mu\nu}$  matter or energy tensor

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2 = (dt \ dx \ dy \ dz) \begin{pmatrix} -1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}$$

Uniform matter  $ds^2 = -dt^2 + a^2(dx^2 + dy^2 + dz^2)$

$$ds^2 = -g_{00}(t) dt^2 + g_{xx}(t)(dx^2 + dy^2 + dz^2)$$

$$(\sqrt{g_{00}(t)} dt)^2 = dT^2$$

$$ds^2 = -dT^2 + g_{xx}(T)(dx^2 + dy^2 + dz^2)$$

$\rightarrow a^2$  Two galaxies can expand without moving  
 ~ leads to Mercury's precision being solved

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# Expansion of universe

$$\dot{a} = \frac{d}{dt} a \quad \ddot{a} = \frac{d^2}{dt^2} a$$

$$G^{tt} \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho$$

energy density

$$G^{xx} = G^{yy} = G^{zz} = 0$$

$$\frac{\ddot{a}}{a} + \frac{1}{2} \left(\frac{\dot{a}}{a}\right)^2 = -4\pi G_N P$$

↑ acceleration      ↑ velocity

Hubble constant      Pressure

$$T^{\mu\nu} \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

Equations of motion for universe?

Einstein looks at static universe / expand contracting

if velocity is zero Pressure needs to be zero too, but Energy density is related to pressure so add cosmological constant

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho + \underbrace{\Lambda}_{\text{pressure}} \text{ cosmological constant}$$

possible that the cosmological constant is variable in time, if so it cannot be listed in the form above as constant

$$G^{ij} = 8\pi G_N T^{ij}$$

$$G^{00} = 8\pi G_N T^{00}$$

Hamiltonian

$$\frac{\ddot{a}}{a} + \frac{1}{2} \left(\frac{\dot{a}}{a}\right)^2 = -4\pi G_N P$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho + \text{constant}$$

$$H = 0$$

$i \frac{d}{dt} \Psi = 0$  universe does nothing no fun

must be true due to Quantum mechanics

Research suggests this is not correct

$$\langle H \rangle = \text{const}(x)$$

dark

First derivative functions could get added a constant and it does not matter when dealing with the Hamiltonian

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