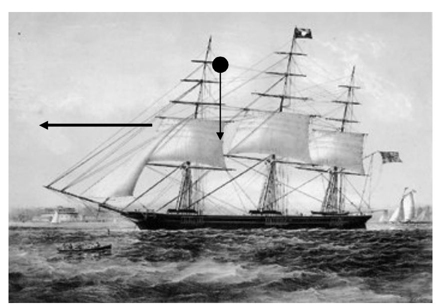
Relativity

- **Principle of relativity**
  - **not a new idea!**
- **Basic concepts of special relativity**
  - **…an idea whose time had come…**
- **Basic concepts of general relativity**
  - **a genuinely new idea**
- **Implications for cosmology**

Relativity



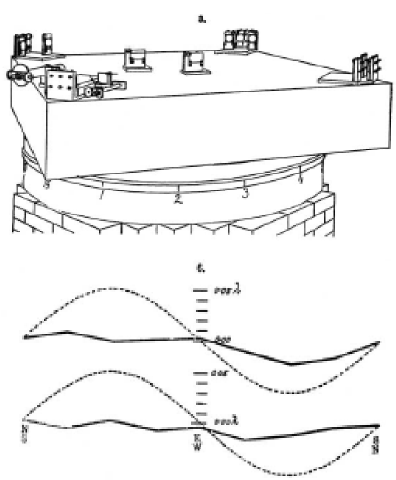
- **"If the Earth moves, why don't we get left behind?"**
- **Relativity of motion (Galileo)**
  - **velocities are measured relative to given frame**
  - **moving observer only sees velocity *difference***
  - **no absolute state of rest (cf. Newton's first law)**
  - **uniformly moving observer *equivalent* to static**

Relativity

- **Principle of relativity**
  - **physical laws hold for all observers in inertial frames**
    - inertial frame = one in rest or uniform motion
  - **consider observer B moving at v_x relative to A**
    - $x_B = x_A - v_x t$
    - $y_B = y_A$; $z_B = z_A$; $t_B = t_A$
    - $V_B = dx_B/dt_B = V_A - v_x$
    - $a_B = dV_B/dt_B = a_A$
- **Using this**
  - **Newton's laws of motion**
    - OK, same acceleration
  - **Newton's law of gravity**
    - OK, same acceleration
  - **Maxwell's equations of electromagnetism**
    - $c = 1/\sqrt{\mu_0 \varepsilon_0}$ – not frame dependent
    - but c = speed of light – frame dependent
    - problem!

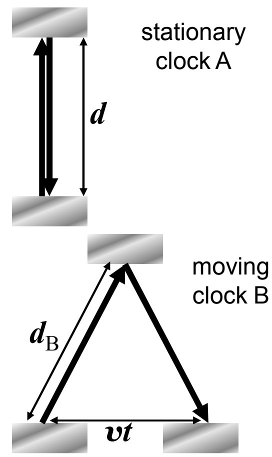
Michelson-Morley experiment

- **interferometer measures phase shift between two arms**
  - **if motion of Earth affects value of *c*, expect time-dependent shift**
  - **no significant shift found**



Basics of special relativity

- **Assume speed of light constant in all inertial frames**
  - **"Einstein clock" in which light reflects from parallel mirrors**
  - **time between clicks $t_A = 2d/c$**
  - **time between clicks $t_B = 2d_B/c$**
    - but $d_B = \sqrt{(d^2 + ¼v^2t_B^2)}$
    - so $t_A^2 = t_B^2(1 - \beta^2)$ where $\beta = v/c$
    - moving clock seen to tick more slowly, by factor $\gamma = (1 - \beta^2)^{-1/2}$
  - **note: if we sit on clock B, we see clock A tick more slowly**

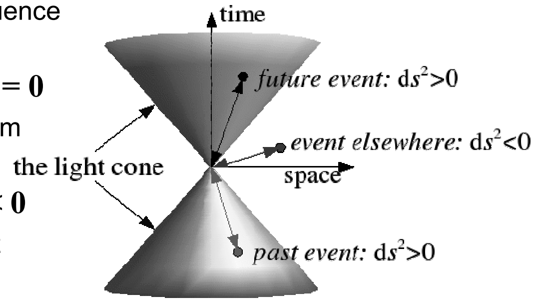


Basics of special relativity

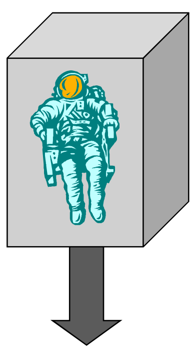
- **Lorentz transformation**
  - $x_B = \gamma(x_A - \beta ct_A)$; $y_B = y_A$; $z_B = z_A$; $ct_B = \gamma(ct_A - \beta x_A)$
    - mixes up space and time coordinates ➔ spacetime
    - time dilation: moving clocks tick more slowly
    - Lorentz contraction: moving object appears shorter
    - all inertial observers see same speed of light c
  - **spacetime interval $ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$ same for all inertial observers**
  - **same for energy and momentum: $E_B = \gamma(E_A - \beta cp_{xA})$; $cp_{xB} = \gamma(cp_{xA} - \beta E_A)$; $cp_{yB} = cp_{yA}$; $cp_{zB} = cp_{zA}$;**
    - interval here is invariant mass $m^2c^4 = E^2 - c^2p^2$

The light cone

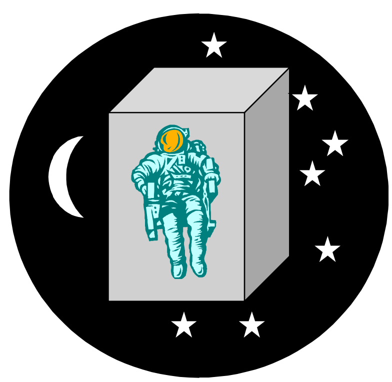
- **For any observer, spacetime is divided into:**
  - **the observer's past: d$s^2 > 0$, $t < 0$**
    - these events can influence observer
  - **the observer's future: d$s^2 > 0$, $t > 0$**
    - observer can influence these events
  - **the light cone: d$s^2 = 0$**
    - path of light to/from observer
  - **"elsewhere": d$s^2 < 0$**
    - no causal contact



Basics of general relativity



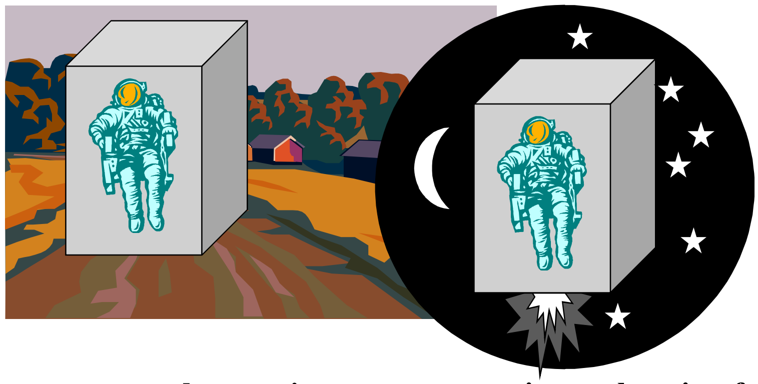
astronaut in freefall



astronaut in inertial frame

frame falling freely in a gravitational field "looks like" inertial frame

Basics of general relativity

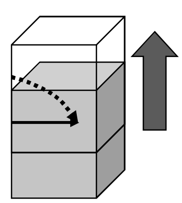


astronaut under gravity   astronaut in accelerating frame

gravity looks like acceleration
(gravity appears to be a "kinematic force")

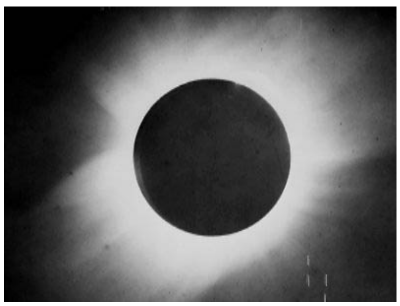
Basics of general relativity

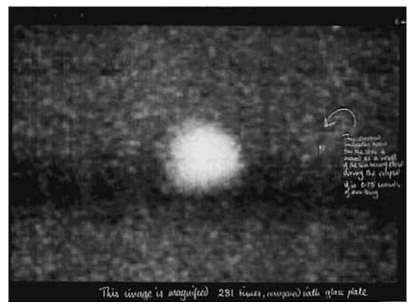
- **(Weak) Principle of Equivalence**
  - **gravitational acceleration same for all bodies**
    - as with kinematic forces such as centrifugal force
  - **gravitational mass ∝ inertial mass**
    - experimentally verified to high accuracy
  - **gravitational field locally indistinguishable from acceleration**
    - light bends in gravitational field
    - but light takes shortest possible path between two points (Fermat)
    - spacetime must be curved by gravity



Light bent by gravity

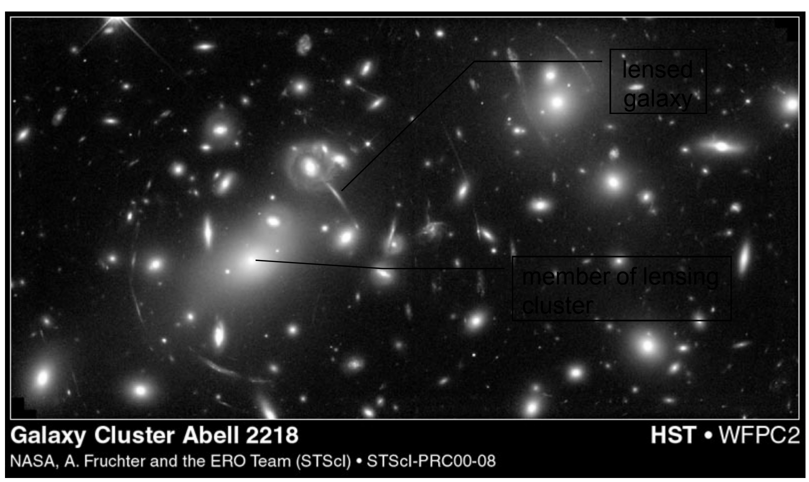
- **First test of general relativity, 1919**
  - **Sir Arthur Eddington photographs stars near Sun during total eclipse, Sobral, Brazil**
  - **results appear to support Einstein (but large error bars!)**





photos from National Maritime Museum, Greenwich

Light bent by gravity



Conclusions

- **If we assume**
  - **physical laws same for all inertial observers**
    - i.e. speed of light same for all inertial observers
  - **gravity behaves like a kinematic (or fictitious) force**
    - i.e. gravitational mass = inertial mass
- **then we conclude**
  - **absolute space and time replaced by observer-dependent spacetime**
  - **light trajectories are bent in gravitational field**
  - **gravitational field creates a curved spacetime**