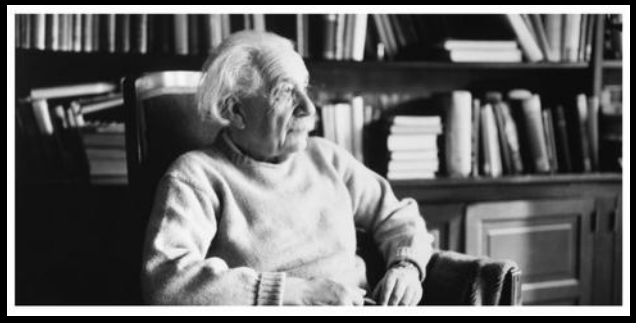
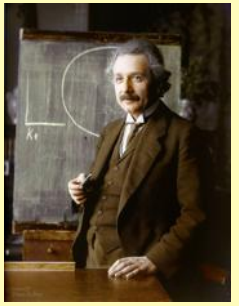
Our Strange Universe



Albert Einstein



• published *4 papers* at *age 26*, during his ***Annus Mirabilis (1905)***

• ***Brownian Motion***
• ***Special Relativity***
• ***$E = mc^2$***
• ***Photoelectric Effect*** ⇒ ***Nobel, 1921***

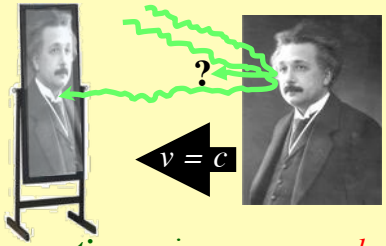
• only comparable achievement: ***Newton***, 1665-66
• ***calculus***, ***Gravitation***, ***theory of colour***

• ***Einstein*** spent last 30 years of his life trying to ***unify gravity & electromagnetic force***

On Common Sense…

• a 16 year old ***Einstein*** asked his uncle:

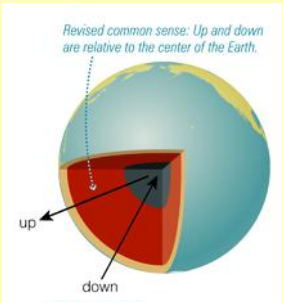
"If I were in a train car moving at the speed of light & I looked into a mirror, what would I see?"



• such ***bizarre questions*** arise *near speed of light* and our ***common sense*** is (often) *little help*

• many scenarios *conflict* with "***common sense***"

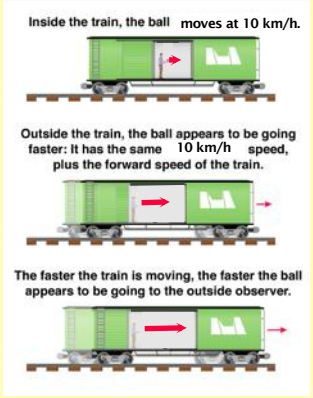
• ***common sense*** is based on ***everyday*** *experiences*
• but motion *at speed of light* is **not** "*everyday*"



(eg) *Things fall* ***down****, so why don't Australians fall off the Earth, since they are "down under"?*

• our common sense notions of "up" and "down" change over time & become more sophisticated…

It's Relative…



• *throw a ball* at *10 km/h*

Q: *Compared to what?*

• hop on *train moving at 100 km/h* and *throw ball* at *10 km/h* ***"forward"***

CLICKER: *How fast is the ball moving?*
(a) 10 km/h (b) 90 km/h (c) 100 km/h (d) 110 km/h

Q: *Which speed is* ***actually*** *right?*

• measurements **must** be made *relative* to *some* ***frame of reference*** ***eg.*** *the Earth*

(eg) *Speed limits* ***assume a reference frame****; but don't try to argue a* ***speeding ticket*** *on this point, though (it annoys the cops :-)*

• ***Einstein***: there are *no* ***preferred*** *reference frames*

Q: *Are you "at rest" right now? Relative to…?*

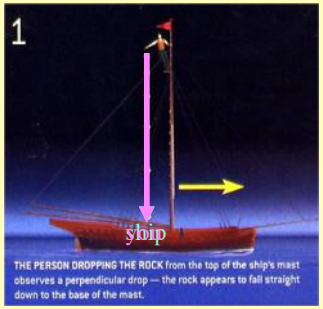
(eg) *Passing on highway or "creeping" at a light…*

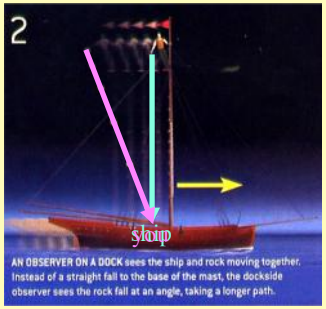
Q: *Which direction is "left"?*

(eg) *Watch me toss a ball… describe the motion.*

DEMO: *rolling cart shooting a projectile*

(eg) *Watch a ball fall from the mast of a ship*





• ***boat at rest***: *agree* on ***distance*** ball travels

• ***boat moving***: *disagree* on ***distance*** ball travels

• but ***speed = distance/time***

Q: *Who measures a* ***longer*** *travel distance?*

Q: *Who measures a* ***faster*** *speed? Why?*

(eg) *Replace ball with a* ***beam of light****; if as above, we'd each measure a* ***different speed of light***

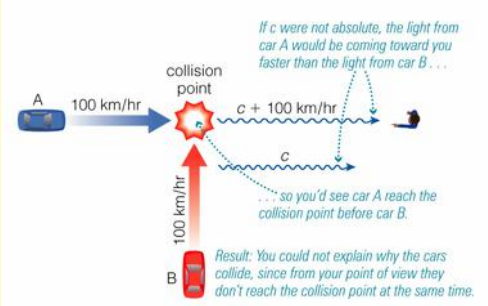
• ***Maxwell*** (1864): unified ***electricity*** & ***magnetism***
• ***light***: a *wave* with ***constant*** *speed ~1 billion km/h*

• ***speed = distance/time*** = ***constant*** (for ***light***)

• a *constant speed of light* **forces** our notions of ***distance*** & ***time*** to become "*flexible*" ("***relative***")

• since ***speed of light is a constant for everyone, distance & time measurements vary*** when viewed from *one frame moving with respect to another*

(eg) *Thought experiments show a* ***constant*** *"c" agrees with observations of* ***cause & effect***



Special Relativity (1905)

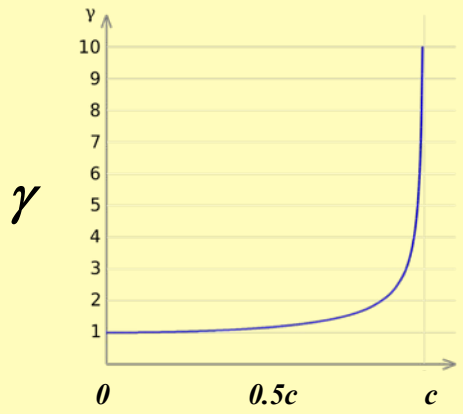
• ***Einstein assumed*** that:
• ***laws of nature are the same*** for everyone
• ***light*** has ***same speed in all reference frames***

• ***"special"*** – applies ***only*** to constant motion
• ***"relativity"*** since ***measurements only make sense when we know what they are measured relative to***

• ***Lorentz factor, γ***
⇒ ***strength*** of ***relativistic effects***

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$$

(eg) *typically* $v << c$, so $\gamma \sim 1$

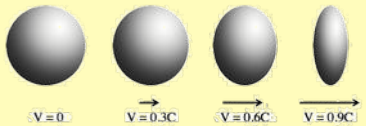


(eg) The ***Lorentz Factor*** γ is *usually* ~ 1

Speed of Light (***c***): *"it's not a suggestion, it's the law"*

• *observers can* ***disagree*** *about* ***L*** *&* ***t but not c***

(1) ***length contraction***: *length decreases* along direction of motion *as speed increases*



(2) ***time dilation***: *time slows as speed increases*

(3) *mass increases as speed increases*

$$L = L_o/\gamma \qquad \Delta t = \gamma \Delta t_o \qquad m = \gamma m_o$$

DVD: *Cosmos - "Relativity"*

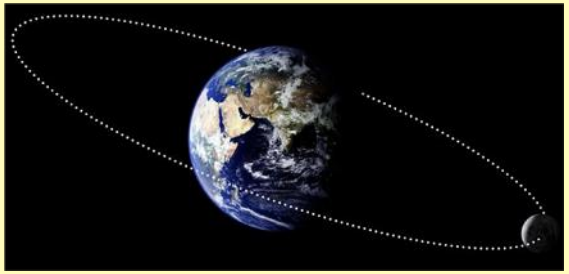
CLICKER: *compared to* ***before*** *they boarded, someone traveling at 0.5c on a spaceship would*
(a) feel heavier
(b) feel time passing more slowly
(c) feel like they were thinner
(d) notice no difference

Q: *what would someone on Earth say about them?*

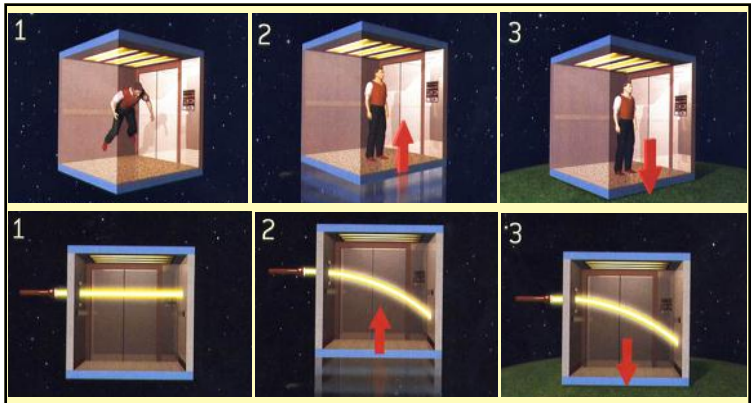
(eg) *relativistic effects* can make deep space travel reasonable: 500 ly trip @ 0.999 c ~ 45 y round trip

General Relativity (1915)

• ***SR only*** applies to ***constant motion***; ***GR applies*** in ***all cases, including accelerated motion***



• ***Einstein*** was ***trying*** to work with ***accelerations***, but discovered a ***new*** way to think about ***gravity***

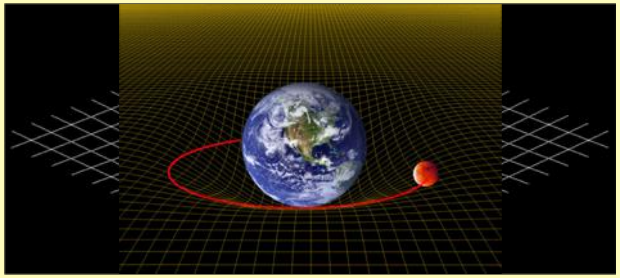


• ***cannot*** distinguish between case 2 & 3!

• ***equivalence principle****: effects of gravity* are ***exactly equivalent*** to *effects of an acceleration*

• ***Einstein*** envisioned a *4-D* "***spacetime***": *(x, y, z, t)*

• *curvature of* ***spacetime*** ("*shape*") depends on *distribution of matter & energy* within the space



• *curvature* ***creates*** what we ***feel*** as ***gravity***

"Matter tells space how to curve, and curved space tells matter how to move." - John Wheeler

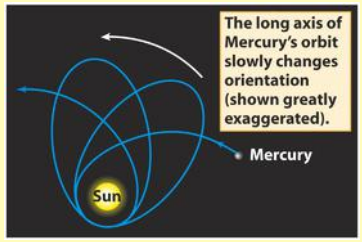
CLICKER: *Since light is massless, Newton predicted that a beam of light passing near an object with a* ***strong*** *gravitational field would*

(a) gain mass
(b) begin to orbit around the object
(c) continue to travel in a straight line
(d) slow down

Testing Relativity

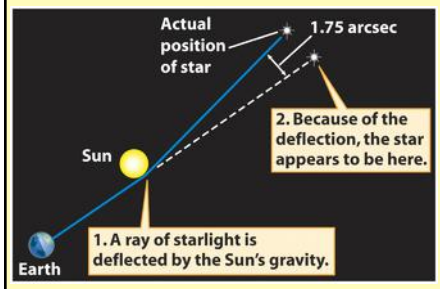
- if you **cannot test it** *it is* ***not*** *science*
- ***very few tests*** early on for relativity
- 3 types of tests exist:
  1) ***direct*** predictions made by relativity
  2) ***new, unpredicted effects***
  3) ***inadvertent*** tests

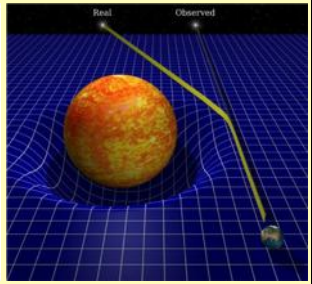
Perihelion of Mercury



- *Newton* calculated Mercury's perihelion as advancing ***531" per century*** due to other planets
- actually ***574" per century***; *Einstein* showed extra "pull" entirely due to *relativistic effects*

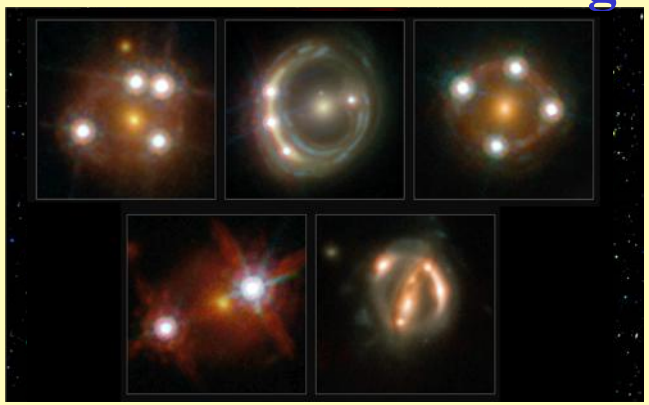
Bending of massless light





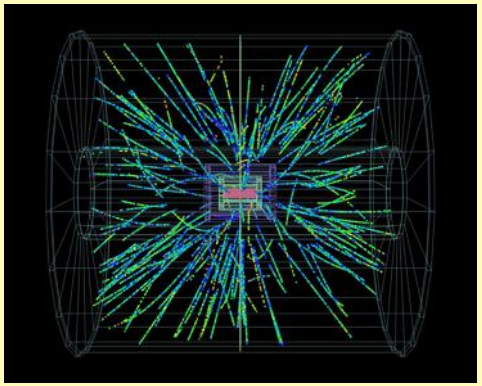
- *stellar positions* recorded 6 months earlier vs. positions viewed during 1919 ***total solar eclipse***

Gravitational Lensing



• *inhomogeneous, asymmetric galaxy* bends light of a ***quasar*** (8 Gly away) to form ***four images (A-D)***

Relativistic Mass



• calculations of *collisional energies in particle accelerators* require ***relativistic mass corrections***

Time Dilation

• ***atomic clocks*** keep time to *better than a second over a million years*

• synchronized ***atomic clocks*** measured *nanosecond discrepancies* after being flown at 600 km/h (1971)

• *repeated* in 1996 on London-Washington flights & confirmed predictions *to better than* ± 5%

GPS Satellites

• ***GPS satellites*** orbit at altitude of ~ *20,000 km*
• speed ~ *14,000 km/h*
• ***GR*** & ***SR*** predict that *clocks in high gravity* & *moving clocks run slow*
• *relativistic effect*: +45μs, -7μs discrepancy per day
• 1970's: engineers included *relativistic corrections* in the software but were not sure if needed
• if corrections ***not*** used, get *km size errors* per day!

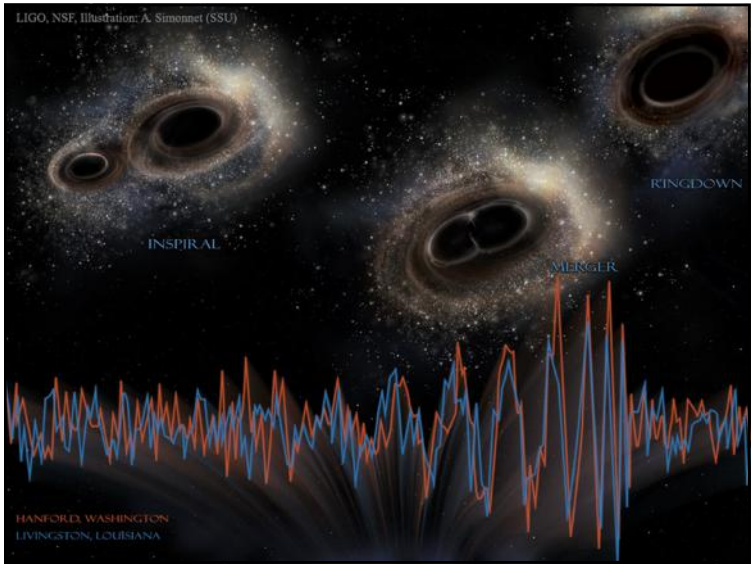
Gravity Waves

• ***Einstein*** predicted massive moving objects cause *waves in spacetime*, much like your hand in water

• first detection in **Sept, 2015** ***(eg)*** **LIGO** or Laser Interferometer Gravitational Wave Observatory

• distortions ***smaller*** than *size of an atom* over 4 km long "arms"

(eg) binary pulsars: orbiting ***neutron stars*** lose energy as gravity waves



Review: Relativity

• ***speed of light must be the same*** for ***all*** observers

• ***Special Relativity*** holds for uniform motion

• SR predicts ***time dilation, length contraction***

• ***General Relativity*** adds accelerating systems

• ***matter*** & ***energy*** "curve" *4-D spacetime*