Chapter 10: Special Relativity

Einstein's revolutionary demolition of the classical notions of absolute space and time and motion, as well as a radically new insight into mass & energy.

"Common sense consists of those layers of prejudice laid down in the mind before the age of eighteen."

Albert Einstein

Does it matter in your life? Name some examples…..

Key to understanding: keep an open mind (mental flexibility), drop preconceptions about *time/space/motion/mass & energy*

1st part of the "modern" physics revolution of the early 20th century. Difficulty: far removed from our normal experiences, NOT the math

Fascinating history & legends/folklore related to Einstein…makes great reading.

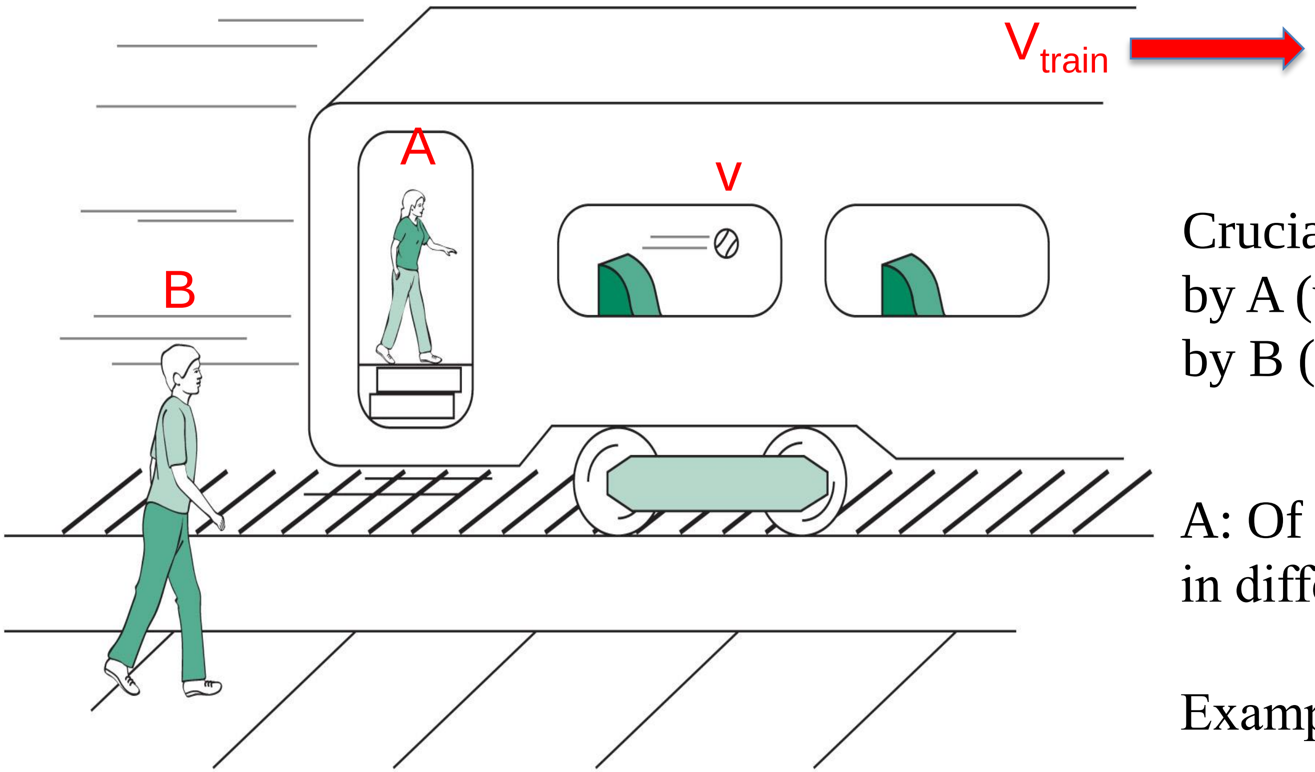
Foundations of S. R. are 2 postulates or principles:

1) Principle of Relativity: Laws of Physics are the same for every *non*-accelerated observer. (not that surprising, makes sense)

2) Constancy of c – i.e. independent of motion of source and/or observer. (quite surprising!)

Start with the non-strange: relativity principle in the context of **relative motion**. Need the important concept of **reference frame**.

Think back: what does v = 20 km/hr mean?



Crucial question: is v measured by A (v_A) same as v measured by B (v_B)?

A: Of course not – they measure in different "reference frames"!

Examples…..

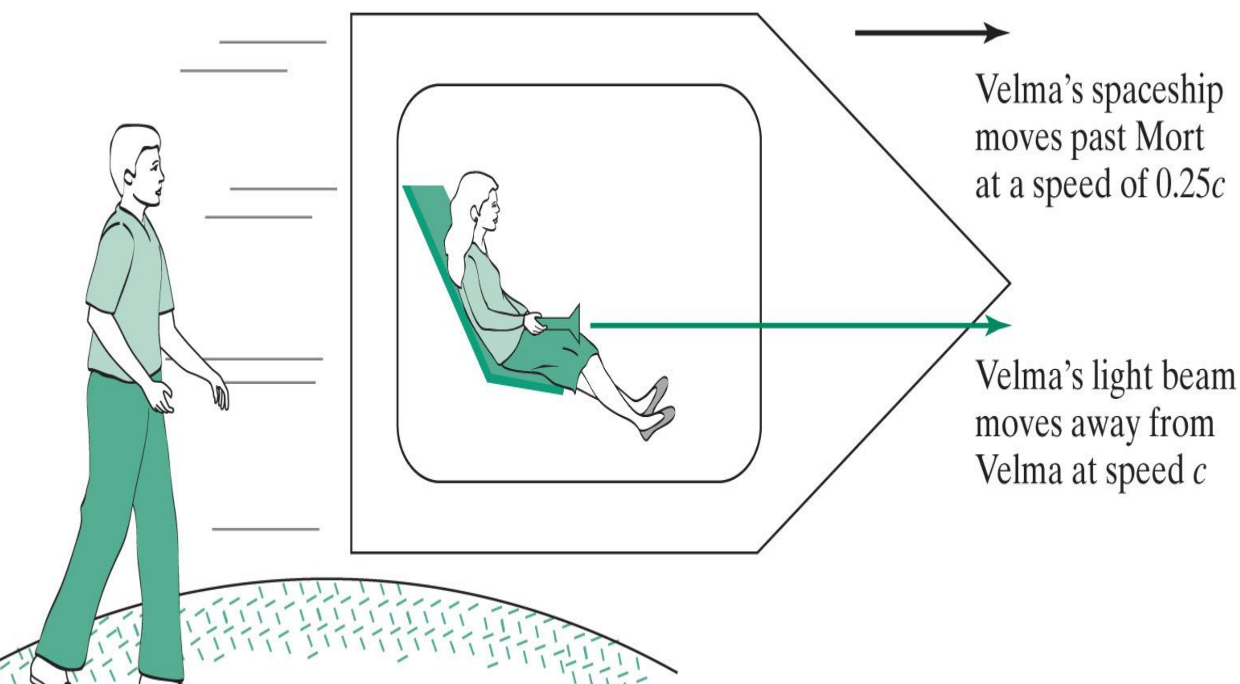
CONCEPT CHECK 1 Velma's normal ball-throwing speed is 20 m/s. She is in a train moving eastward at 70 m/s and throws a ball toward the rear of the train. The velocity of the ball relative to Velma is (a) 50 m/s eastward; (b) 50 m/s westward; (c) 20 m/s eastward; (d) 20 m/s westward; (e) 70 m/s eastward; (f) 70 m/s westward.

CONCEPT CHECK 2 In the preceding question, the velocity of the ball relative to Mort, who is standing beside the tracks, is (a) 50 m/s eastward; (b) 50 m/s westward; (c) 20 m/s eastward; (d) 20 m/s westward; (e) 70 m/s eastward; (f) 70 m/s westward.

<u>Quiz # 77</u>: Velma bikes <u>northward</u> at 4 m/s. Mort, standing by the side of the road, throws a ball <u>northward</u> at 10 m/s. <u>Relative to Velma</u>, the ball's speed & direction is
(a) 6 m/s north   (b) 6 m/s south   (c) 14 m/s north
(d) 14 m/s south (e) 10 m/s north

<u>Quiz # 78:</u> Same question, but Mort throws <u>southward</u> at 10 m/s.
(a) through (e) same as above

All this referred to as <u>**Galilean**</u> <u>**Relativity**</u> – very sensible, but turns out to be "ever so slightly incorrect". As v approaches c, it becomes extremely incorrect!



The Principle of Relativity

Every nonaccelerated observer observes the same laws of nature. In other words, no experiment performed within a sealed room moving at an unchanging velocity can tell you whether you are standing still or moving.

Smoothly flying, <u>UN</u>-accelerated airplane:
Does coffee pour straight downward?
Window shades are down: can you tell whether you're flying or not?
In fact can you do *any* physics experiment that would answer the above?
What if the plane were accelerating?

→ Clearly a plausible & sensible principle.

Something to keep in mind in this context:
All motion is relative, there is no "absolute" motion.

(By the way, un-accelerated ref. frames often called "inertial" frames.)

The Principle of the Constancy of Lightspeed

The speed of light (and of other electromagnetic radiation) in empty space is the same for all nonaccelerated observers, regardless of the motion of the light source or of the observer.

Seems crazy, but……it's a consequence of the relativity principle and Maxwell's E & M equations, which, after all, have c *directly* built into them.

Einstein's firm belief: relativity principle should/**must** apply to E & M (meaning not just to mechanics).

(Various "cute Gedanken (thought) – experiments" attributed to Einstein)

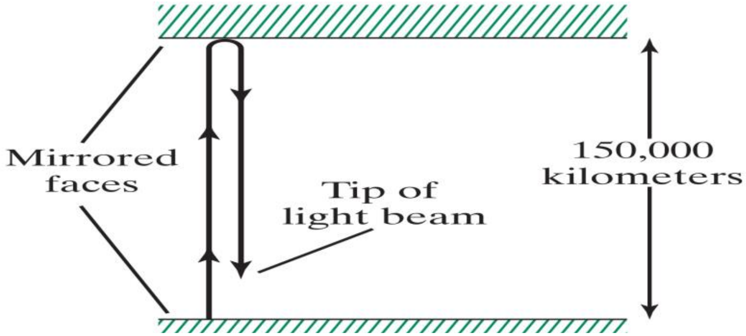
In the end, it's an *experimental fact, i.e. "because nature says so*".

Experiment briefly described on p. 233/234: $\pi^0 \rightarrow 2\gamma$

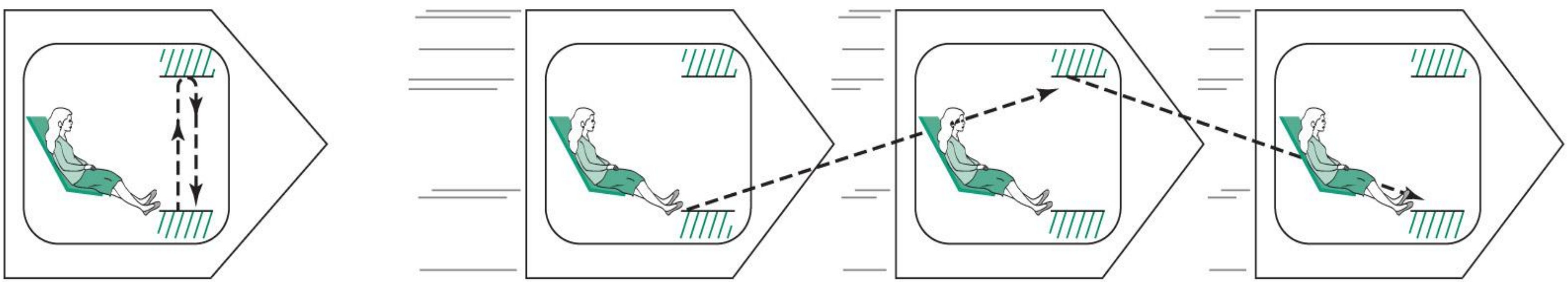
(γ = photon, the particle/quantum of light or of e & m radiation)

The 2 principles have dramatic (at high speed!) consequences: **Relativity** (to the observer) **of Time & Space** – so-called time dilation and length contraction

Start with time measurement → need a clock → following Einstein, let’s use a (simple!) light clock:

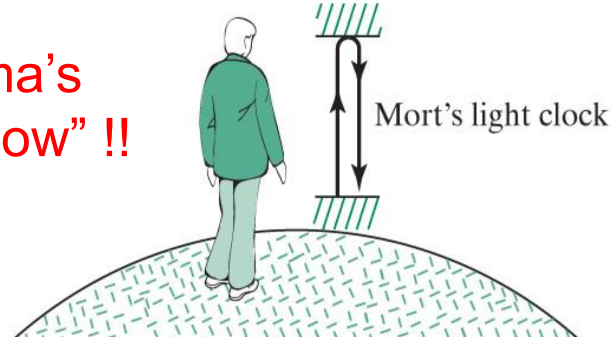


→ Mort’s observation: because of constant c



(a) (b)

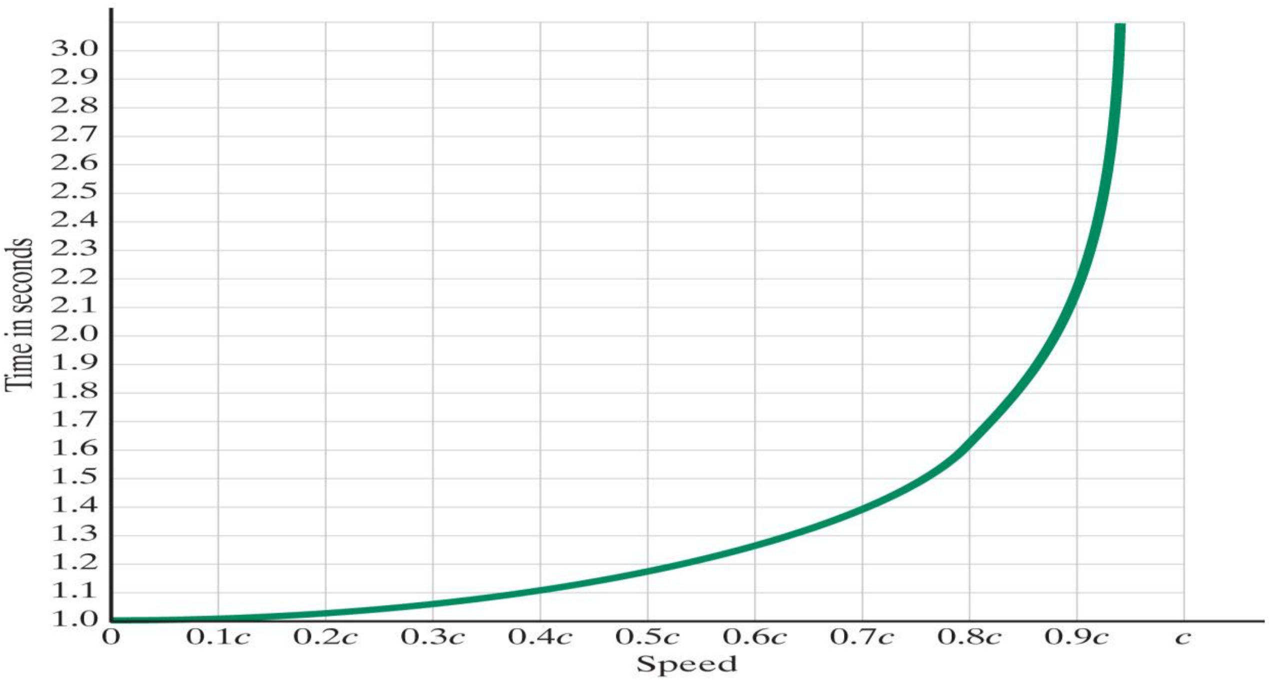
more time elapses between Velma’s ticks, i.e. “moving clock runs slow” !!



So, M & V measure different time intervals for the same event.
→ ***Time is relative to the observer.***

Crucial: Velma observes the same, i.e. more time elapses between Mort's clock ticks – according to her, his (moving) clock runs slow! That's relativity for you: both are right – both observations are correct – there is NO "universal time", only M's time & V's time & every other possible observer's time.

How big an effect? A: $\gamma = 1/\sqrt{(1 - v^2/c^2)}$



Time dilation:
$T = \gamma T_0$, where T_0 is the "proper" time, i.e. time in the clock's rest frame.

→ Let's derive this gamma ("Lorentz") factor!

Table 10.1

The relativity of time: some quantitative predictions

To give you a feel for these speeds: 0.3 km/s is a typical subsonic jet plane speed, 3 km/s is twice the speed of a high-powered rifle bullet, at 3000 km/s you could cross the United States in 1 second, and at 30,000 km/s you could circle the globe in 1 second. Clearly, relativistic effects are small until the speed becomes very large!

Relative speed (km/s)	Relative speed as a fraction of lightspeed (*c*)	Duration of one "tick" on a moving clock, as measured by an observer past whom the clock is moving (*s*)
0.3	10^{-6}	1.000 000 000 000 5
3	10^{-5}	1.000 000 000 5
30	10^{-4}	1.000 000 005
300	0.001	1.000 000 5
3000	0.01	1.000 05
30,000	0.1	1.005
75,000	0.25	1.03
150,000	0.5	1.15
225,000	0.75	1.5
270,000	0.9	2.3
297,000	0.99	7.1
299,700	0.999	22.4

Quiz # 79: Mort & Velma have identical 10-minute clocks. Velma passes Mort at 75% of c. Predict what Mort measures for *his* and *Velma's clock*.

(a) 10 min & 10 min (b) 10 min & 15 min (c) 10.5 min & 10 min

(d) 10 min & 10.5 min (e) 15 min & 10 min

OK, Professor, how do we know that time dilation has *anything* to do with reality, i.e. with observables, with experiments?

Ah, particle physics comes to the rescue, over & over & over again. Classic example (bottom of p. 238): *lifetime of cosmic ray "muons"* – think of them as heavy electrons, decaying into electrons:
$\mu \rightarrow e + 2$ neutrinos, lifetime of μ at rest: 2.2×10^{-6} seconds
Explain the rest……incl. what the μ sees: length contraction!

Quiz # 80: A certain fast-moving particle is observed to have a lifetime of 2 seconds. If the same particle was *at rest* in the lab, its lifetime would be

(a) 2 seconds. (b) more than 2 seconds. (c) less than 2 seconds.
(d) can't answer without knowing its speed.

Quiz # 81: Suppose you drop a ball while riding on a train moving at constant velocity. If you measure the ball's acceleration, will you result be

(a) greater than (b) less than (c) equal to

the usual acceleration g due to gravity?

C.E. 30: (for $v/c = 0.5$, $\gamma = 1.15$)