Astro 350

Lecture 16

Oct. 5, 2012

Announcements:

- **HW 4** due
- **Discussion 5** available, due next Wednesday
- **HW 5** available, due at start of class next Friday

Last time: began relativity

- space is 3-dimensional *Q: meaning?*
- defined events *Q: what's that?*
- set of all (x, y, z) points *Q: is what?*
- set of all (x, y, z, t) points *Q: is what?*

event–localized occurrence in space and time
$\Rightarrow$ unique set of (x, y, z, t) space+time coordinates

Set of all possible events = "**spacetime**"
need 4 coordinates $\rightarrow$ spacetime is 4-dimensional

Light and Spacetime

consider flash of light, emitted from lightbulb at rest
spherical pulse spreads at constant speed

$$c_{\text{emitter at rest}} = 3 \times 10^8 \text{ m/s} = 186,000 \text{miles/sec} \qquad (1)$$

diagram: pulse in space

Frames of Reference

in cosmology, physics, astronomy:
a "*frame of reference*" corresponds to a *point of view*
as seen by some observer
i.e., a description of the world fixed to an observer
and thus in which that observer is *at rest*

if different observers are moving relative to each other
then each describes the world in a different frame
mathematically: each frame = a *coordinate system*
often with the observer at the origin

Q: in what frame(s) do highway speed limits apply?
Q: for Aristotle, what frame(s) are special?

The Principle of Relativity

existed (in part) even before Einstein:
Galileo knew it, and so did Newton:

> "The motions of bodes included in a given space are the same among themselves, whether the space is at rest or moves uniformly forward in a straight line"
>
> –Cosmologist Sir Ike Newton

Q: what's Ike going on about?

Q: why does this contradict Aristotle?

Galilean Relativity Principle

the motion of a *system of bodies* (matter)
relative to each other is *the same*
for any constant-velocity ("inertial") motion of the entire system
e.g., planet motion vs SS motion

- which means:

in a closed room, it is *impossible* to detect absolute motion by means of *any experiment* using matter

- we can only measure object's motions *relative* to each other

$\Rightarrow$ in closed non-accelerating room: can't tell if you're moving!

- there are no special or "preferred" reference frames!
  Contrary to Aristotle!

- T-Shirt/Bumper Sticker/Text Message/Twitter version:
  "only relative motion counts" (for matter)

But how does *light* weigh in?
Can you use light to tell if a closed room is moving?

The Ether

Consider a moving lightbulb

Newton, Galileo say: if emitter has speed v
then bystander sees light move at speed $c + v$
sped up ahead, slowed down behind
$\rightarrow$ can tell "closed-room" absolute motion
by looking at light

In Newton/Galileo framework:

- light defines (& requires!) a special universal "rest frame"
- in viewpoint where light is wave
  needs medium to wave in (e.g., water waves need water)
- late 19th century: **"luminiferous ether"**
  invisible, neutral, massless substance
  defines *absolute cosmic rest frame*

Something's Gotta Give

Michelson & Morley experiment (1890s, done in Chicago!)

setup: measure *difference* in speed of light
  in two perpendicular directions
  repeat for different directions

result: *never see a difference in speeds!*

but: the Earth is moving around Sun
  if ether exists, Earth orbit moves us relative to it
  light should be slower in direction of Earth motion
  yet never seen, so conclude

⋆ no experiment can detect ether or it effects–doesn't exist!

⋆ speed of light *constant:* c, *universal*, and

∞ *independent* of motion of observer

Q: which means in practice?

Universal speed of light means:
everyone always measures light speed to be same value

$$c_{\text{anybody}} = c_{\text{universal}} = 3 \times 10^8 \text{ m/s} = 186,000 \text{ miles/sec} \quad (2)$$

regardless of motion of emitter, observer

Leads to counter-intuitive (=bizarre) circumstances!

consider "ultrabullet" train
goes at 100,000 miles/sec, shines headlights
★ passengers measure headlight beam speed = 186,000 miles/sec
but also
★ trackside bystanders measure beam = 186,000 miles/sec too!
not Galileo result 286,000 miles/sec!

This is (some of) the weirdness of relativity

Paradigm Shift: Special Relativity

How to cope with lightspeed universality & ether non-existence?

One approach: "separate but equal"

- matter and light are fundamentally different
- special rules for light
- logically possible but lousy idea–if lotsa exceptions
  - get more general rule

Q: so what is an alternative approach?

Einstein's approach: "radical democracy"

upgrade principle of relativity:
in a closed room, it is *impossible* to detect absolute motion
by means of *any experiment at all*

Big Al says:
no absolute rest, motion for *anything* – matter or light
(or anything else you dream up)!
relative motions are all that ever counts!

Special Theory of Relativity a.k.a. "special relativity"

- Einstein's revisions & upgrade of Newton's laws
  to accommodate the upgraded relativity principle
- does not yet include gravity! will do this soon, but
  will require generalized, modified relativity

A Train in a Thunderstorm

Experiment:

- Train, car length L, with passenger Angelina in middle
- moving at some speed v past bystander Brad
- two lightning bolts strike front, back of train
- Brad stands at midpoint of burn marks
  sees flashes simultaneously
- of course: everyone sees light moving at same speed c

iClicker Poll Twofer: Train in a Thunderstorm

Does bystander Brad think bolts were simultaneous?

A yes

B no

Does Angelina in car midpoint think bolts were simultaneous?

A yes

B no

The Relativity of Simultaneity

bystander Brad: two flashes each travel same distance $L/2$
so take same time $t = L/2c$
$\Rightarrow$ Brad sez: bolts were so totally simultaneous, dude!

passenger Angelina: train motion carries her
toward front flash, away from back flash
$\Rightarrow$ sees front flash first, then back flash later
But she thinks each flash traveled same distance $L/2$
so concludes they took same travel time $L/2c$
$\Rightarrow$ Angelina sez: you lying dog, the lightning bolts
were totally *not* simultaneous!

Q: so who's right?
Q: what's the larger lesson?

Who's right? Neither lying (about this), but disagree

- "simultaneous" is not a universally agreed condition

  relativity of simultaneity

- observers with different motion perceive time differently

More Philosophical Commentary on Time

Strange things are afoot at the Circle-K.

– Cosmologist Ted "Theodore" Logan

Mirrors as Clocks

build "clock" in train car, height L

- mirrors on floor, ceiling reflect light up & down
- one "tick" per light bounce

`www: light clock animation`

in train frame: clock at rest (so $x = constant = 0$)

- light pathlength $d = \sqrt{x^2 + y^2} = y = L$
- tick duration $(\Delta t)_{\text{rest}} = L/c$ (since $d = c\Delta t$)

in trackside frame, train moving at speed v

- light zigzag due to mirror motion $\rightarrow$ path longer!

  Q: why? what will this mean?

in trackside frame, train moving at speed v

- during tick time $(\Delta t)_{\text{moving}}$ horizontal motion $x = v(\Delta t)_{\text{moving}}$
- light pathlength

$$d = \sqrt{x^2 + y^2} = \sqrt{v^2(\Delta t)^2_{\text{moving}} + L^2} \tag{3}$$

- tick duration $(\Delta t)_{\text{moving}} = d/c$, which means

$$d^2 = c^2(\Delta t)^2_{\text{moving}} = v^2(\Delta t)^2_{\text{moving}} + L^2 \tag{4}$$

$$(c^2 - v^2)(\Delta t)^2_{\text{moving}} = L^2 \tag{5}$$

which gives

$$(\Delta t)_{\text{moving}} = \frac{L}{\sqrt{c^2 - v^2}} = \frac{c}{\sqrt{c^2 - v^2}}\,\frac{L}{c} \tag{6}$$

$$= \frac{(\Delta t)_{\text{rest}}}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{7}$$

Q: which means? and is bizarre because?

time dilation

we find

$$(\Delta t)_{\text{moving}} = \frac{(\Delta t)_{\text{rest}}}{\sqrt{1-\frac{v^2}{c^2}}} \quad (8)$$

$$= (\text{number} > 1) \times (\Delta t)_{\text{rest}} \quad (9)$$

which means:

$$(\Delta t)_{\text{moving}} > (\Delta t)_{\text{rest}}$$

- ⋆ moving clocks don't appear to keep same time as clocks at rest! Namely,
- ⋆ moving clock appears to have longer ticks!
- ⋆ moving clocks appear to run slow!
- ⋆ time depends on state of motion! not universal!