LECTURE 21: RELATIVITY AND SPACETIME

Nature and nature's laws lay hid in night,
God said, "Let Newton be," and all was light.
It did not last; the devil howling "Ho!
Let Einstein be!" restored the status quo.

21.1 RELATIVITY AND INTUITION

Our "intuition" is based primarily on our everyday experience.

In our everyday experience, we always move *much* slower than the speed of light.

We should not be too surprised if our "intuition" about what happens to things moving near the speed of light turns out to be wrong.

21.2 SPECIAL RELATIVITY

Einstein's theory of "special" relativity (1905) is based on two postulates:

(1) The laws of physics are the same for any observer moving at a uniform (unchanging) velocity.

(2) The speed of light in a vacuum is a universal constant ($c \approx 300,000$ km/sec).

Note that (1) implies that there is no such thing as "absolute rest"; any uniformly moving observer can consider herself "at rest."

These postulates look contradictory. If a man on a train moving at velocity v shines a flashlight straight ahead, it seems as though an observer on the ground should see the beam move at speed $v + c$.

Einstein had theoretical and experimental reasons for believing (1) *and* (2). By thinking carefully about how one can measure time, distance, and speed, he showed that they are *not* contradictory. In the train example, both observers see the beam move at speed c, but time flows at different rates for the two of them.

21.3 RELATIVITY OF TIME: AN EXAMPLE

(See accompanying diagram.)

A woman on a skateboard holds a box 1.5 meters tall, with a mirrored top and bottom. A light beam (or even a single photon) bounces up and down between the two mirrors.

The skateboard moves to the right at $0.8c$, 80% of the speed of light, as seen by the man on the ground.

How long does it take the skateboard to go from A to C?

Woman's answer: Light beam goes up once, down once, travels $2 \times 1.5 = 3$ meters. Time required is 3 meters/(3×10^8 meters/sec) $= 10^{-8}$ seconds.

Man's answer: Light beam travels zig-zag path, *longer* than 3 meters. Time required is longer than 10^{-8} seconds. (To be specific, it is $(5/3) \times 10^{-8}$ seconds.)

21.4 RELATIVITY AND TIME

This result holds for any clocks, not just light beam clocks. Time passes at different rates for observers moving relative to one another.

If the relative speeds are small compared to c, the differences in time flow are very small.

Experimental tests:

Precise clocks on airplanes flying east run slow compared to clocks on the ground.

Some subatomic particles "decay" (split into less massive particles) in fractions of a second. If they move near the speed of light, they live much longer.

21.5 OTHER CONSEQUENCES OF RELATIVITY

Observers moving relative to each other:

- Do not agree on what events are simultaneous.
- Do not agree on the lengths of objects.

No object or particle of non-zero mass can be accelerated to the speed of light. Particles of zero mass must move at the speed of light.

No signal or information can propagate faster than light.

There is an equivalence between mass and energy, $E = mc^2$.

21.6 SPACETIME

Everyday intuition: Space and time are distinct from each other.

Relativity: Different observers split space and time differently. Only "spacetime" has an observer-independent reality.

An analogy: Observers at rest but facing different directions make different divisions between "right/left" and "forward/back." Observers moving relative to each other are "facing different directions in spacetime."

If relative velocities are much smaller than c, everyday intuition works fine.

21.7 GENERALIZING RELATIVITY

Einstein quickly became dissatisfied with his first postulate (see 21.2) because of its restriction to uniformly moving observers.

In 1907, he suggested a generalization:

(1) The laws of physics are the same for any freely falling observer (i.e., the observer may be gravitationally accelerated).

Developing the theory of *general relativity* based on this postulate took Einstein another eight years. He reached two remarkable conclusions:

- Spacetime can be curved.
- This curvature produces the effects that we call gravity.

21.8 SUMMARY

Special Relativity is based on two postulates:

(1) The laws of physics are the same for all uniformly moving observers.
(2) The speed of light in a vacuum is a universal constant.

From these postulates, one finds that time flows at different rates for observers moving at different velocities. This remarkable prediction, and many other predictions of special relativity, are confirmed by numerous experiments.

Observers moving at different velocities see a different division between space and time.

If relative velocities are much smaller than c, the effects of relativity are very small.

Generalizing (1) to freely falling observers leads to General Relativity, Einstein's theory of gravity.