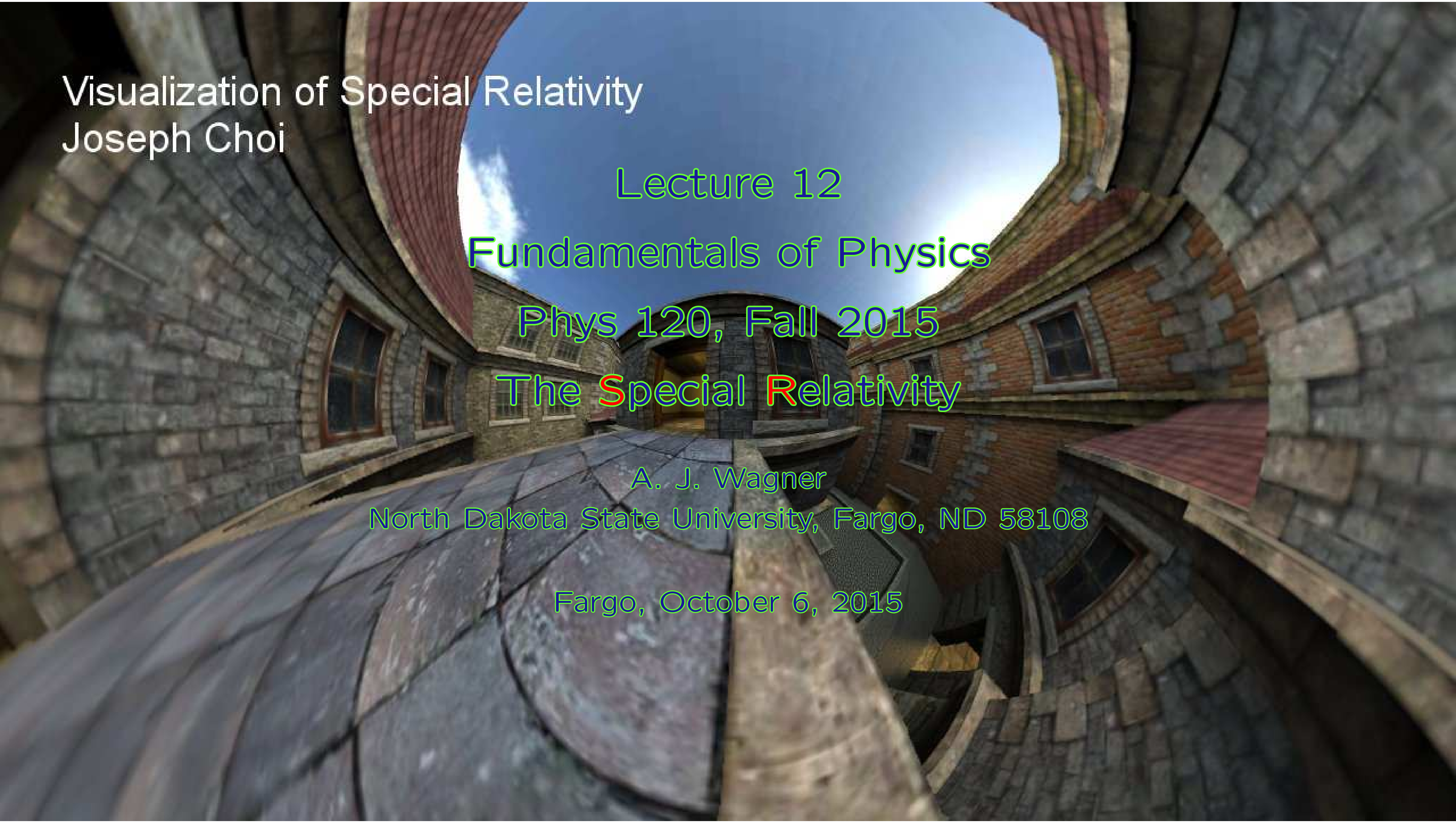

Lecture 12

Fundamentals of Physics

Phys 120, Fall 2015

The Special Relativity

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Overview

- Einstein
- Galilean relativity
- The relativity principle
- The constancy of the speed of light
- The theory of the ether
- The relativity of time
- the relativity of space and mass

Knowledge by 1900

Lord William Thomson Kelvin stated in an address to physicists at the British Association for the Advancement of Science in 1900 that:

There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

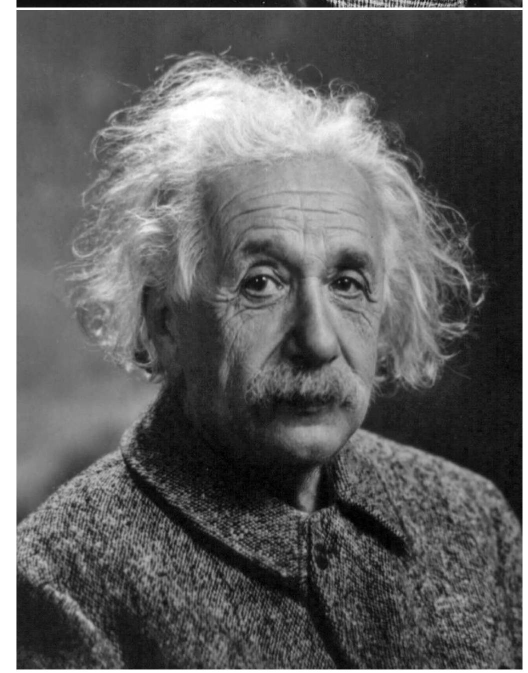
Most scientists felt that now that the known "grand unifying principles" — Newton's laws and the laws of thermodynamics and electromagnetism — were complete and permanent.

Einstein's special theory of relativity

You will learn about unexpected effects that happen when objects move at high speeds, comparable to the speed of light. You learn that space, time and mass are not quite what you thought they were.
Einstein's theory is built on two simple ideas and all of its odd conclusions are off-shoots of these.
The theory has a reputation for being difficult, but this comes really from its strangeness rather than any inherent difficulty. Its conclusions violate common sense. *The main requirement for understanding this theory is not intelligence but mental flexibility.*

Einstein

Learned to speak only at 3 years.
Was a dreamer and dropped out of high school.
Completed highschool in Switzerland.
Failed entrance exam of University.
Managed in second attempt.
Spent time at university in cafes and physics laboratories more than lectures.
Graduated with the help of friends.
With help managed to find a job as a patent clerk.
This gave him time to think deeply about some puzzling questions. The answers to these questions brought him to the forefront of science and made him famous.



Galilean relativity

Consider throwing a ball when you are moving already. You throw the ball with 10 mi/h while you are moving with 5 mi/h. In your **reference frame**, how fast is the ball moving?

In the **reference frame** of a stationary observer, how fast is the ball moving?

You can say that you and the stationary observer are in **relative motion**.

A **theory of relativity** is any theory that works out answers to questions concerning observers that are in **relative motion**.

Concept check

If I were throwing the ball backwards with 5 mi/h, how fast will the ball be moving relative to me?

How fast will the ball be moving relative to the stationary observer?

Galilean relativity and light

Let us imagine the example with a thrown ball, but instead with a light beam that is emitted and a person moving with a noticeable fraction of the speed of light.

Say I am moving with 25% of the speed of light (which we will call c= 300,000 km/s). When I shine a flashlight forward, how fast will the light move with respect to a stationary observer?

What will happen if I shine the light backward?

But what we expect from common sense is not what we observe in experiments!

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.

Concept check

What about acceleration? Can this be detected without looking outside?

(a) Yes, you can do simple experiments to tell you whether you are accelerating.
(b) Yes, but the experiments must involve light beams.
(c) No.

The constancy of lightspeed

Can you move along with a light-beam? What does stationary light look like?

To Einstein near stationary light seemed absurd. Maxwell's theory of electromagnetic fields predicts that any disturbance in a field must travel outward at a speed of c.

Einstein felt that this law, like all laws of physics, should be correct within any moving reference frame.

> **The Principle of the Constancy of Lightspeed**
> The speed of light (and 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.

Think about the light thought experiment with this principle in mind!

How do we know that light goes the same speed for all observers?

Strange though the constancy of lightspeed may seem, it's verified daily. However, most experiments involve fast-moving microscopic particles rather than spaceships. In one especially striking experiment in 1964, a subatomic particle moving at nearly lightspeed emitted electromagnetic radiation both forward and backward. Galilean relativity predicts that the forward-moving radiation should mover much faster than c while the backward-moving radiation should mover much slower than c, as measured in the laboratory*. But measurements showed that both radiation beams more at speed c relative to the laboratory.

*If you think carefully about this, this is not the full story. Comparing this to the sound traveling away from a car, the speed will be the speed of sound with respect to the air, i.e. the medium. See next slide.

Why didn't anyone notice this before?

Maxwell (and other 19th cent. physicists) thought of light as a wave and then the speed would be relative to the medium*. It was theorized that this medium (obviously present in the empty regions of outer space) was some **ether**. But then one should be able to measure how fast one is going with respect to the ether, but every measurement of that relative motion failed!

We now believe that there is no medium for electromagnetic waves!

*Amazingly, Maxwell's equations though did not include the effect of an ether.

Two concepts we are trying to match

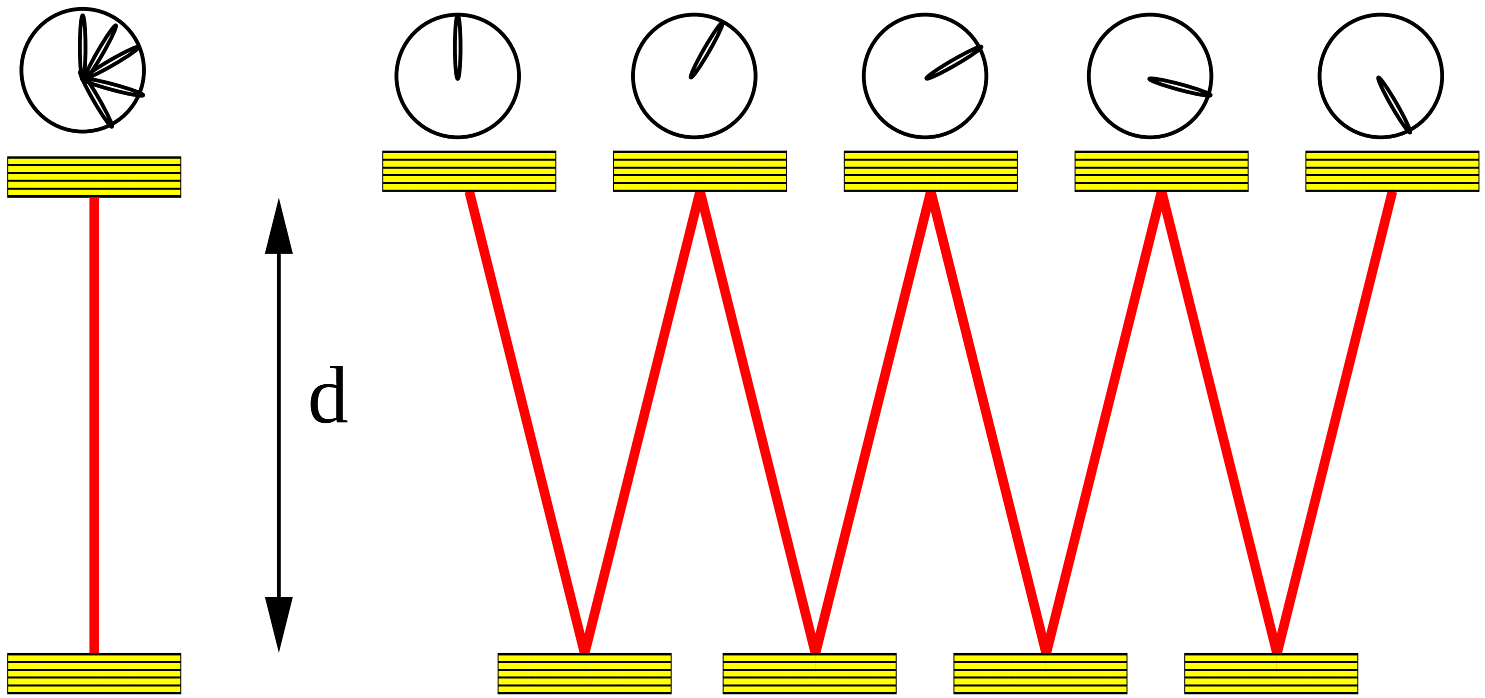
1. The laws of Physics are the same for all observers independent of how fast they are moving (assuming though that their motion is not accelerated – more on that later in General Relativity).

2. The speed of light c is a constant, and it is the same for all observers.

As we saw above we have to abandon our Galilean sense of relativity. If you shine a light it will move with velocity c with respect to you, but an observer that moves with velocity v also sees that the light is moving with the same speed c.

Consequences: relativity of time

A light clock consists of two mirrors with a light beam bouncing up and down.



The distance the light travels in the moving clock is larger, that means that the clock must be going slower*!

*Stationary time unit: $t = 2\frac{d}{c}$, moving time unit $d^2 + (vt)^2 = (ct)^2 \Rightarrow t = 2\frac{d}{c}\frac{1}{\sqrt{1-v^2/c^2}}$

Concept check

Which clock is correct?

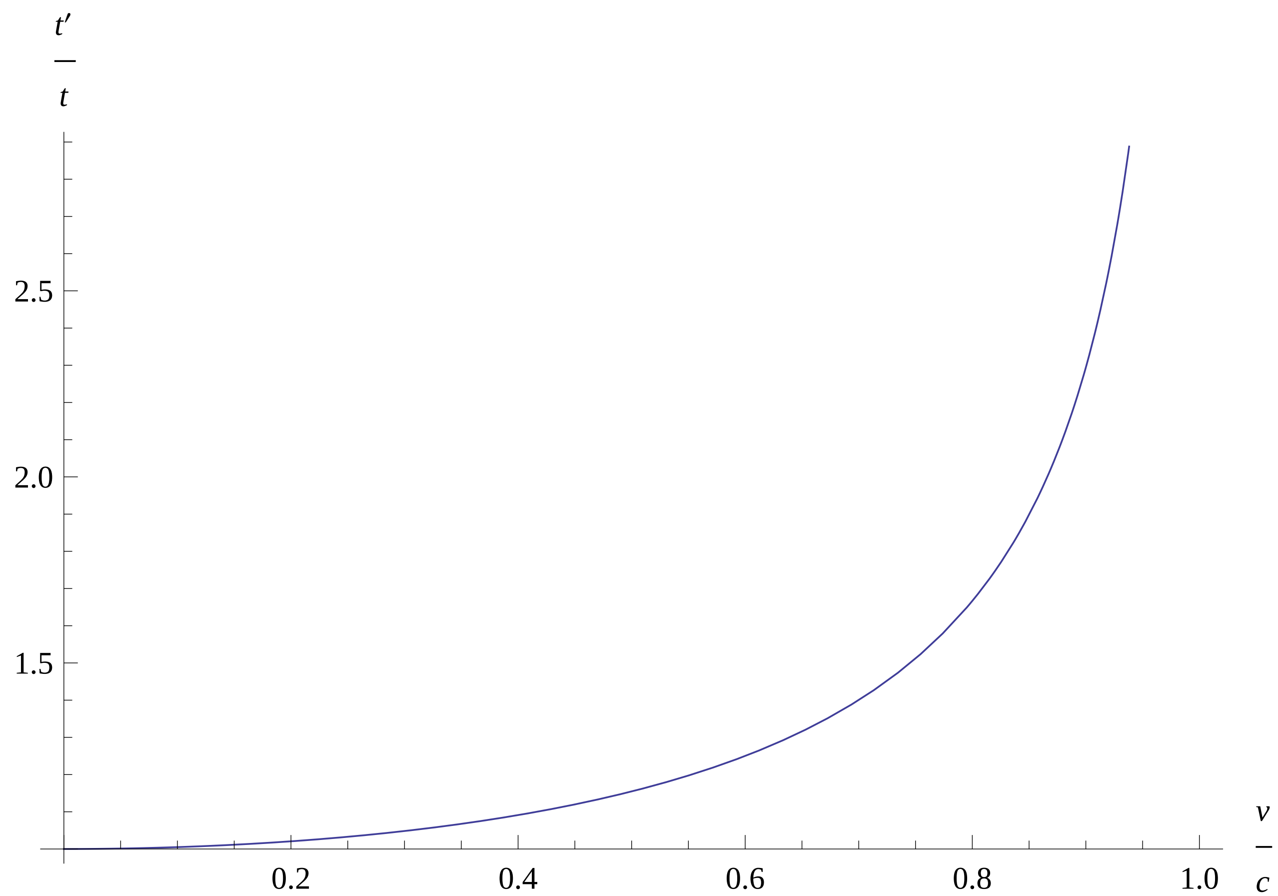
If the moving clock is slow, then what does the situation look like for a person traveling with the moving clock?

What does that tell us about time?

How slow is the clock?

Simple trigonometry mentioned above shows that

$$t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$$



Concept check

If I have a 10 minute ice-cream cone and pass by you at 75% c, how long will my ice-cream cone appear to take to melt to you as a stationary observer?

Solution

$$
\begin{aligned}
t &= \frac{10min}{\sqrt{1-(0.75)^2}} \\
&= \frac{10min}{\sqrt{1-0.5625}} \\
&= \frac{10min}{\sqrt{0.4375}} \\
&= \frac{10min}{0.6614\cdots} \\
&\approx 15min
\end{aligned}
$$

The twin paradox

Imagine that I get into a very fast spaceship and travel around the galaxy at 0.95 c. This means that you will observe that my time progresses 3.2 times slower than yours. If I am on my way for 50 years, only 16 years will have passed for me.

If you are 22 years old now, you will then be 72 year when I return. I will be 48 + 16 years, i.e. 64 years old, and I will be younger than you!

As crazy as this sounds, this has been experimentally verified, if in a less astounding way. Clocks traveling on planes around the globe have been shown to run more slowly that stationary clocks!

Concept check

It is physically possible for your mother to leave Earth after you were born and return

(a) before you were born;
(b) before she was born;
(c) younger than you;
(d) older than you;
(e) younger than she was when she left;
(f) older than she was when she left.

Concept check

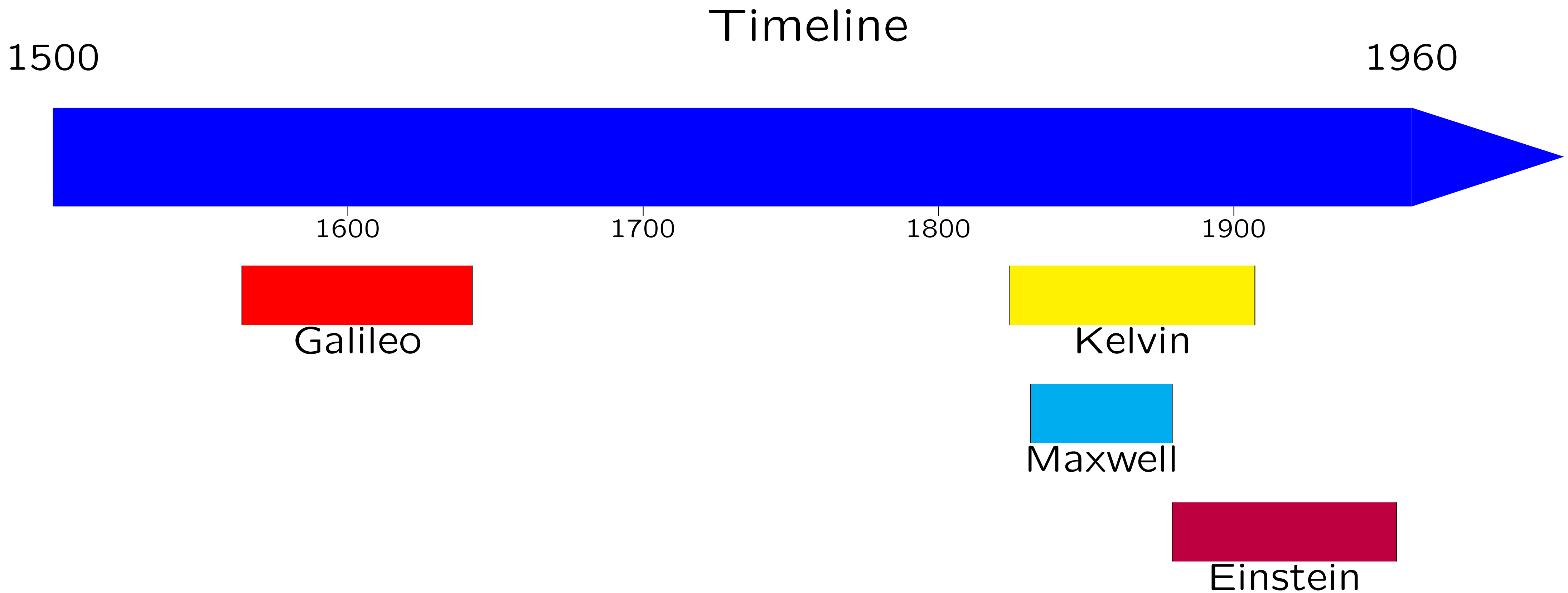
Do we see this in ordinary application?

How much will you age, if you travel at 100 m/s (=360 km/h like a jet plane) for one year?

Answer:

$$
\begin{aligned}
t &= \frac{1 year}{\sqrt{1 - 100/300,000,000}} \\
&= 0.9999996 years
\end{aligned}
$$

which is something you are unlikely to detect unless you use an atomic clock.


Timeline
1500
1960
1600
1700
1800
1900
Galileo
Kelvin
Maxwell
Einstein

Outlook

Thursday we will learn that distances and masses are also different for observers moving with different speeds.

We will see that mass is related to energy and we will discuss the famous formula

$$e = mc^2$$