There is no universal, ‘absolute’ time in relativity

- Einstein postulated that the velocity of light $c$ is the same for all observers. That led to the consequence that two observers measure different times, if they are moving relative to each other.

- We are forced to concede that not all observers can agree on a common time.

- We can’t have it both ways, common laws of physics and a common time.
What is time?

If you do not ask me what is time, I know it. When you ask me, I cannot tell it.

Saint Augustine

I do not define time, space, place, and motion, as being well known to all.

Newton
But we can agree on how to measure time
... even if different observers measure different times.

A light clock: Light beam bouncing between two mirrors

Mort looks at Velma’s clock and notices that light takes a longer round trip along the dashed path. He concludes that Velma’s clock runs slower than his.

(Horizontal distances exaggerated)
What about swapping observers?

Both observers think the other’s clock runs slow.

Let’s look at Mort’s clock from Velma’s reference frame:

Now it is Velma who says Mort’s clock runs slower than hers.
Three common relativistic effects

• **Time dilation**
  If two observers move relative to each other, each of them thinks that the other’s clock runs slower.

• **Length contraction**
  If two observers move relative to each other, each of them thinks that the other has shrunk along the direction of motion.

• **Mass (energy) increase**
  An observer thinks that the mass of a fast-moving object has increased. Since mass can be converted to energy via $E = mc^2$, the energy also increases.
Relativistic effects become large for velocities near the velocity of light $c$.

Newton’s laws stay correct at ordinary velocities.
Atomic clocks measure time dilation

- Atomic clocks were flown around the Earth in jets at 1000 miles/h.
- Compared to a stationary clock they were 0.15 microseconds behind, in agreement with time dilation.
- In a sense, the clocks that traveled aged less (although not by much). Can humans avoid aging by traveling fast? How fast?
- This effect needs to be considered for the Global Positioning System.

First atomic clock: 1949  
Miniature atomic clock: 2003
Global Positioning System (GPS)

Network of satellites orbiting Earth at 14,000 km/h. Each of them carries an atomic clock and sends out radio waves with time and location signals. From 4 satellites one obtains the 4 variables x, y, z, t.

A GPS receiver compares time signals from several satellites.

The distance from each satellite is the travel time of the signal, multiplied by the velocity of light \( c = 1 \text{ foot/nsec} \). This works because of special relativity: \( c \) does not depend on satellite motion.

The position is obtained from the distances to four satellites (next slide).
Triangulation with 3 satellites

Knowing the distance from one satellite defines a sphere around the satellite. Knowing distances from two satellites defines a circle (intersecting spheres). Spheres around three satellites intersect at two points (one at the surface). Distances from four GPS satellites will intersect at just one point.
Cosmic muons live longer than expected

Without time dilation and length contraction, a muon (red streak) created by a cosmic ray would decay before arriving on the ground. Its lifetime is shorter than the height of the atmosphere divided by the velocity of light. Two viewpoints:

- We think that the clock of a fast muon runs slow.
- The muon thinks that its clock is perfectly normal. Instead, the height of the rapidly approaching atmosphere has shrunk due to length contraction. That’s why it survives the trip.
Mass increase of fast particles

The *mass increase* of a charged elementary particle can be determined by deflecting it with a magnet. If a particle has gained mass, it is deflected less by the same magnetic force $F$ (compare Newton’s $F = ma$).

Electrons have been accelerated up to an energy of 50 GeV, where their mass has increased $10^5$ times.
The energy increase at high velocity can be viewed either as kinetic energy or as a mass increase (from the rest mass $m_0$ to the actual mass $m$).

Einstein generalized this observation and concluded that all types of energy can be converted to mass. Likewise, mass is just another form of energy:

\[ E = mc^2 \]

Since $c^2$ is huge, a very small amount of mass creates an enormous amount of energy.

This explains the energy of nuclear bombs and the Sun.
Particle physicists simplify their equations by using the velocity of light $c$ as unit:

$$c = 1$$

Einstein’s formula then simply becomes:

$$E = m$$

Now it is obvious that energy and mass are the same.
How Einstein discovered his famous formula ...