The lull before the storm

- Newton developed his theory of gravity in 1687.
- Maxwell unified electricity and magnetism in 1873.
- It was verified experimentally by Hertz ca. 1887.
- This is what we often call “classical” physics.
- Physics seemed to be complete in the year 1900.
Two revolutions in physics

Shortly after 1900, physics changed dramatically:

• *Relativity*
  - Changed the way we think about *space and time*

• *Quantum physics*
  - Changed the way we think about *measurements*
From 1905 to 1908, Albert Einstein developed the theory of relativity.

The concept: The laws of physics are the same for all observers.

This concept implies that different observers measure different times and distances.

This gave rise to the sloppy slogan ‘everything is relative’.
‘Everything is relative’

• There is a common perception that relativity means ‘everything is relative’, nothing is absolute. That is misleading. The fundamental concept of relativity says exactly the opposite: The laws of physics are absolute, independent of the observer.

• For example, Maxwell’s equations hold for every observer. Since the velocity of light $c$ appears as constant in Maxwell’s equations, every observer has to measure the same velocity for light.

• Einstein’s thought experiments demonstrated that this ‘absolute’ principle implies that measurements are relative, that is, they depend on the observer.
General relativity

• Einstein followed up on special relativity with general relativity.

• It adds gravity, which warps space and time.

• Special relativity is important for fast-moving objects (for example in particle physics).

• General relativity is important for strong gravity (black holes, cosmology).
Principle of relativity:
- The *laws of physics are identical* for all observers.

Consequence:
- The speed of light *c is the same* for all observers.

**Special relativity** is restricted to observers moving at *constant velocity* (no acceleration).

**General relativity** applies to *all observers*, even those moving with acceleration.
The speed of light $c$

The seeds of relativity are already planted in Maxwell’s equations. They predict that an electromagnetic wave always propagates at the same speed (=$c$). Neither the motion of the light source nor that of the observer have any influence.
Einstein’s Gedankenexperiments

In one of his characteristic thought experiments, Einstein asked how two persons can observe the same speed of light when they are moving relative to each other ...
Thought experiment about the speed of light

- Maxwell equations say: Light always moves at the speed $c$.
- Einstein considered trains and flashlights:
  - Newton would expect that Joe’s flash propagates with $c$ from Joe’s point of view, and with $c+v$ from Jane’s view.
  - But Maxwell says that the flash propagates with $c$ for both. Therefore, velocities do not add up.
What about simultaneous events?

- Consider a boxcar moving with constant velocity with respect to Jane, who is standing on the ground. Joe rides at the center of the boxcar.

- Two lightning bolts strike the ends of the boxcar, leaving scorch marks at both ends and on the ground underneath (black dots).

- Jane finds herself halfway between the scorch marks on the ground.
Jane also observes that the two flashes reach her at the same time.

Since each light wave traveled the same distance at the same velocity $c$, we conclude that the lightning strikes are simultaneous in Jane’s frame.
The flashes reach Joe at different times

• Joe moves towards the flash in front while the light is traveling. Therefore, light from the front reaches him first. When Jane sees the two flashes, the light from the front has passed Joe already. And the light from the rear has not reached him yet.

• Since Joe stands at the center of the boxcar and \( c \) is constant, light must take the same time to reach him from both ends. The front flash arrived first, thus he concludes that it occurred first. The two events are not simultaneous in Joe’s frame.
What is “simultaneous”?

Einstein’s definition of “simultaneous” events:

- Two events are simultaneous if their light signals arrive simultaneously at an observer located half way between the two events. (The distances are measured in the reference frame of the observer).
- This definition is universal, but it gives different answers for different observers.
Consequences of Einstein’s relativity

‘Common sense’ assumptions break down in relativity:

- Time measurements depend on the motion of the observer. Events that seem to be simultaneous to one observer are not simultaneous to another.

- Distance measurements depend on the motion of the observer.

- Velocities don’t add up.
Frame of reference

- To judge motion, we use a frame of reference, such as the walls of a room.

- We judge how fast a ball is thrown by its position relative to the walls.

- We judge how high a ball is thrown by its distance from the floor.

- We judge our own motion the same way.
Is there an ‘absolute’ frame of reference which sits still?

- A big rock looks like a good reference frame.
- But the Earth rotates with $465\,\text{m/s}$. 
- And the Earth revolves around the Sun with $3\cdot10^4\,\text{m/s}$. 
- And the Sun revolves around the center of our galaxy with $2.3\cdot10^5\,\text{m/s}$. 
- And our galaxy orbits around a cluster of galaxies.
- At best one could argue that our universe sits still.
- But there are parts of our universe beyond the horizon ...
There is no ‘absolute’ reference frame

• No experiment using Newton’s laws or even Maxwell’s equations can determine whether I am moving or not.

• There is no ‘absolute’ reference frame, which stands still while other frames are moving.

This resembles the demise of the medieval Earth-centered model of the planets and the Sun: There was nothing special about the Earth that justified using it as the preferred reference frame.