Einstein's Theories of Relativity

Shifting World Views, Separating the Classical from the Modern

Waseda University, SILS,
Introduction to History and Philosophy of Science

Absolute Time, Absolute Space

Newton had argued that underlying the distances we experience and measure is some absolute substrate in which the space that we experience can be imagined as embedded. He, likewise, claimed that underlying all of the durations that we experience and measure is some constant, uniform time. These concepts became known as absolute time and absolute space.

Even during his own lifetime, other philosophers and mathematicians such as Huygens and Leibniz had doubted the validity and practicality of such concepts.

One of Einstein's key insights was that we have no direct understanding of space and time and that they cannot be understood in any other way than through measurement. What this means is that it is only meaningful to talk about relative space and time – it is only meaningful to talk about the distances and durations that we measure.

Boltzmann, Lecture, 1899

"Many may have thought at the time of Lessing, Schiller and Goethe, that by constant further development of the ideal modes of poetry practiced by these masters dramatic literature would be provided for in perpetuity, whereas today one seeks quite different methods of dramatic poetry and the proper one may well not have been found yet. Just so, the old school of painting is confronted with impressionism, secessionism, pleinairism, and classical music with music of the future. Is not this last already out-of-date in turn? We therefore will cease to be amazed that theoretical physics is no exception to this general law of development."

Boltzmann's talk was a turn-of-the-century address. It was meant to capture the spirit of rapidly changing worldviews and scientific styles.

Non-Classical Mechanics

In 1902, Henri Poincaré stated that there is no *absolute space*, no *absolute time*, and no direct intuition of *simultaneity*. Moreover, he claimed that it might be possible to enunciate mechanical facts with reference to a non-Euclidean space.

It should be possible to,

Poincaré, 1904

"Construct a whole new mechanics, of which we only succeed in catching a glimpse, where inertia increasing with velocity, the velocity of light would become an impassible limit. The ordinary mechanics, more simple, would remain a first approximation, since it would be true for velocities not too great, so that we should still find the old dynamics under the new."

The Michelson-Morley Experiment

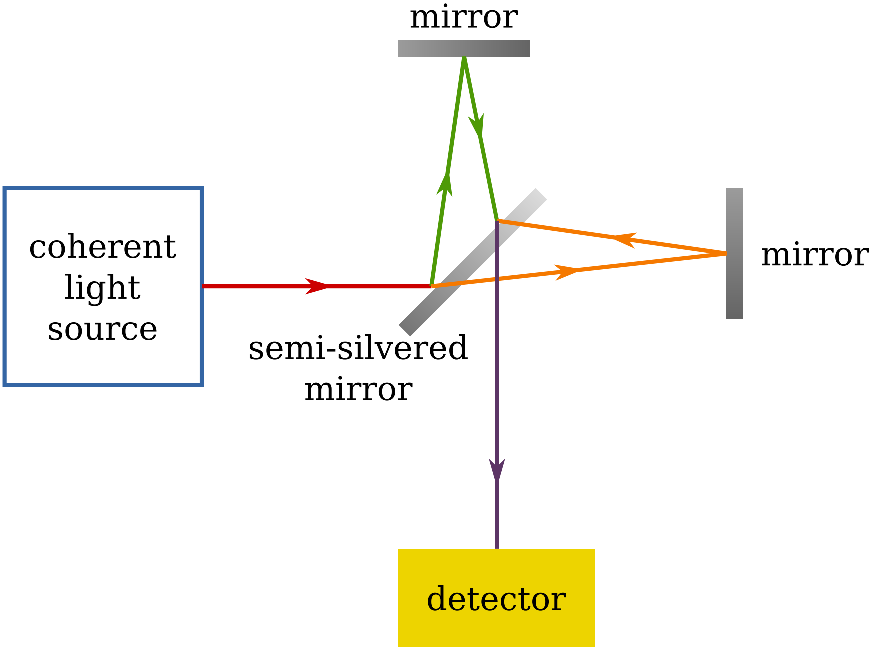
In the 19th century, physicists believed that light and electromagnetic phenomena took place in a medium, which they called ether.

In 1887, at the Case School for Applied Science in Cleveland, OH, Albert Michelson (1852–1931) and Edward Morley (1838–1923) carried out a series of precise measurements of the speed of two beams of light traveling at right angles to one another.

- If the light were moving in a medium, there should have been detectible time differences in the two directions.

There was no discernible difference. The light seemed to show no time difference based on its direction of travel.

Michelson carried out the experiment in 1881 and the two of them did it again in 1887. Both times they had null results.


mirror
coherent light source
semi-silvered mirror
mirror
detector

Details of the Experiment

Michelson believed the vibration of the apparatus nullified the results of his 1881 attempt.

Later, Lorentz pointed out by that the displacement sought would be smaller than Michelson had expected, so Michelson and Morley tried again in 1887. They built an iron and sandstone apparatus in Cleveland. Once again, they found nothing. They never even checked again after six months, as they had originally planed.

After Einstein published his paper, interest increased in these null results. In 1924, Morley and Miller carried out a run in a glass hut on top of a mountain, to avoid "*either drag*." They got a positive result. In 1930, Miller had Michelson's sandstone apparatus installed on Mount Wilson, but in a metal housing. It produced a null result. Eventually, people lost interest.

Albert Einstein (1879–1955), Early Years

- From a middle-class Jewish family. They moved around between Germany, Italy and Switzerland when he was young.
- Educated at Swiss Federal Institute of Technology and University of Zurich.
- Worked in the Swiss patent office.
- In 1905, his *miracle year*, published five papers, some of the most important in the 20th-century physics.

Albert Einstein (1879–1955), Later Years

- In 1914, became professor at Berlin University and member of the Prussian academy. Refused to sign the 1914 manifesto “To the Civilized World.”
- In 1915, published the general theory of relativity. Became an international celebrity when the theory was experimentally confirmed.
- In 1933, when the National Socialist (Nazis) party was elected, he renounced his German citizenship, again, and never returned to Germany.
- Was instrumental in mobilizing the scientific community to work on the atomic bomb, although he did not do substantial war work.
- Spent the post-war years working toward international peace.

Einstein's Work

- Developed the special and general theories of relativity.
- Was instrumental to the development of early quantum theory but never agreed with quantum mechanics.
- Spent his later years working in isolation on a unified field theory – a theory of everything.
- Wrote books popularizing his theories and on more philosophical subjects.

The Special Theory of Relativity

- "On the Electrodynamics of Moving Bodies," 1905. Einstein wanted to call it the "theory of invariance."
- The point of the theory was to show that the equations of electromagnetism are the same in any frame of reference.
- It was called relativity theory by Plank in 1906.

Principle of Relativity

There is no privileged point of view from which to say who is in motion and who is at rest.

Principle of the Constancy of the Speed of Light

The speed of light in a vacuum will always be the same.

Principles of Special Relativity

From "On the Electrodynamics of Moving Bodies:"

Principle of Special Relativity

"The same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good." (The laws of the electrodynamic field are the same for all inertial frames.)

Principle of the Constancy of the Speed of Light

"Light is always propagated in empty space with a definite velocity, c, which is independent of the state of motion of the emitting body." (The velocity of light, $c = 299,792,458\ m/s$, is constant in every reference frame.)

The Speed of Light

The fundamental assumption of the theory of relativity is that the speed of light is constant to all observers, irregardless of their speed, or the speed of the emitting light source.

This makes the speed of light unlike the speed of any other moving object.

Hence, the velocity of everything else has to be determined on the basis of this constant, $c \approx 300,000\ km/s$.

In order to determine the velocity of everything else, observers are imagined to use theoretical rigid yardsticks and synchronize their clocks with pulses of light.

Measuring Time and Distance

Einstein claims that it is impossible to have a direct, intuitive understanding of time and space.

In order to know the distance between two objects, we have to use rigid measures to mark off the distance relative to some rigid body, some physical reference frame. *There is no direct, abstract knowledge of distances*.

In order to know the time between two events, we have have to record the time it takes for a beam of light to get from our eye to the event and back. Then we measure the distance and calculate the time. *There is no direct perception, or understanding, of time intervals*.

In order to talk about simultaneity at a distance you have to synchronize two clocks: you start with one, send a light signal to the other and adjust for the time that the light takes to arrive.

Inertial Frames

In the special theory, we assume that observers are traveling in different reference frames, at *different but constant* velocities.

Each observer can only directly measure the distances in her own frame. Each observer can only directly read the clocks immediately next to her.

In order to determine the distances in the other frame, or in order to read the clocks that are far away from her, she has to send out a beam of light and make a calculation.

Consequences of Special Relativity

We imagine that there are two coordinate systems of points, or inertial frames $K(x, y, z, t)$ and $K'(x', y', z', t')$, moving relative to one another along the x axis. (We can always rotate the frames so that this is the case.)

We then generate a series of four equations to transform each point in one system to a point in the other system. We get $y = y'$ and $z = z'$, but we get strange results for the transformation from x and t to x' and t'.

We find that distances are shortened, while time is lengthened, by a factor of

$$\sqrt{1 - \frac{v^2}{c^2}}.$$

This means that distances appear to be shortened and time appears to be running slowly, *in the other frame of reference*. The equation also implies that these results are negligible for low speeds. (Consider the relationship between c and v.)

Time and Space

The consequences of these simple assumptions are very peculiar.

- Each observer sees his own measuring devices as constant but they get *out of sync* with those of other observers moving at different speeds.
- For speeds close to c, time appears to elongate (clocks run slower), while distances diminish (yardsticks get shorter). (Not to the observes moving at these speeds, but to others who are observing them.)

These effects are irrelevant in most cases, but at speeds approaching that of light, and hence for sub-atomic phenomena (because of the speeds of electrons and other sub-atomic particles), they are measurable.

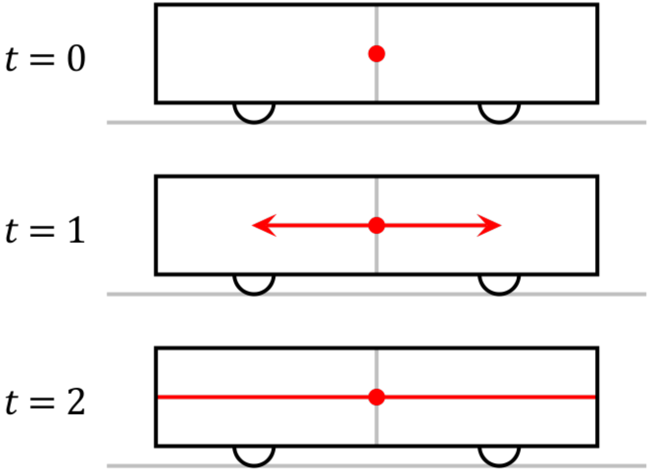
Simultaneous Events

This theory implies that there are no such things as *absolutely* simultaneous events. Events which appear to be simultaneous in one reference frame will occur at different times in another reference frame.

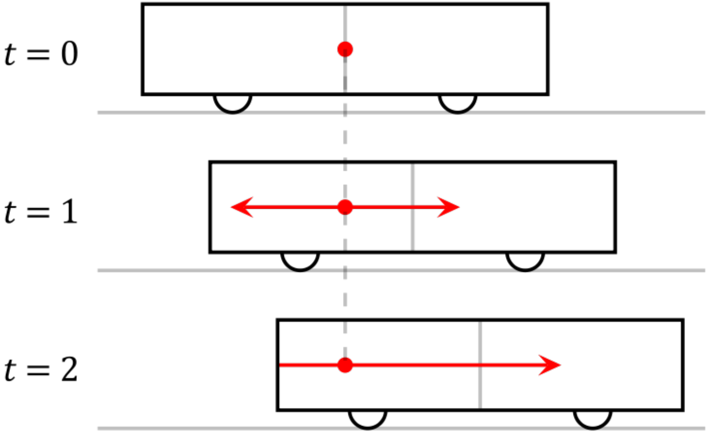
If two events appear to be simultaneous to the stationary observer, the moving observer will see the event toward which she is moving as occurring before the other.

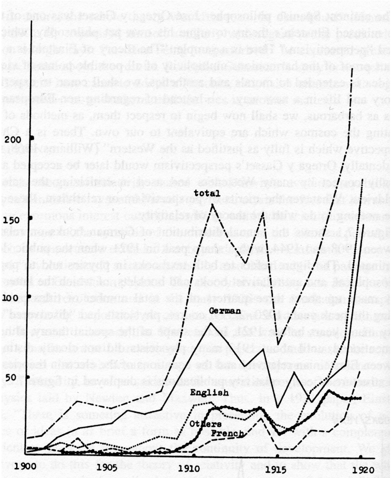
Simultaneity is not frame independent.

Simultaneity: Inside the Car



Simultaneity: On the Track





Papers on relativity

The special theory was only interesting to a small group of specialists, mostly mathematicians.

They applied the predictions to experimental results for sub-atomic particles.

They demonstrated how the mechanical laws of all moving systems could be mapped into one another in a general spacetime geometry.

They determined the invariant spacetime interval between any two events. [Minkowski, etc.]

Einstein, 1922

"My first thought on the general theory of relativity was conceived two years later, in 1907. The idea occurred suddenly… I came to realize that all the natural laws except the law of gravity could be discussed within the framework of the special theory of relativity. I wanted to find the reason for this, but I could not attain this goal easily… The breakthrough came suddenly one day. I was sitting on a chair in my patent office in Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his own weight. I was taken aback. This simple thought experiment made a deep impression on me."

Principles of General Relativity

The General Principle of Relativity

All the laws of physics are exactly the same in every frame of reference, whether stationary, in constant motion, or *changing motion*.

- This includes gravity.

Principle of Equivalence

We have no way of deciding on a privileged reference frame. Hence, to the same effects we must attribute the same causes.

- That is, there is no way to distinguish between things like gravity and acceleration, etc.

A Thought Experiment

We imagine a spacious room in which an observer can perform experiments.

1. If the room is in a region of space with no massy bodies, the observer will experience a lack of ‘gravity.’
2. If the room is pulled by something else at the same acceleration with which bodies fall towards earth, the observer will experience the ‘law of gravity.’
3. If the room is in freefall towards a massy body, the observer will experience a lack of ‘gravity.’
4. If the room is on the surface of the earth, the observer will experience the ‘law of gravity.’

The principle of equivalence tells us that we have no way of knowing what our situation is.

General Relativity

Einstein set out to make a field theory in which gravitation was the result of the spacetime field in the same way that electromagnetic force was the result of the electromagnetic field. The theory was published in 1915, in the middle of WWI.

The claims were even stranger than those of the special theory:

- Space and time make up a continuous four-dimensional manifold, analogous to an electromagnetic field.
- Massy objects distort this field in a regular way, producing the gravitational effect.
- Light is subject to this effect and will be 'bent' in the vicinity of large objects.
- Time elongates – that is, clocks run slower – near large objects.

Predictions of the Theory

The new theory of gravity made a number of predictions that could be tested against empirical facts.

- There were difficulties resolving the orbit of Mercury (its perihelion) under Newton's theory, but Einstein was able to get a closer fit between the data and his theory.
- General relativity predicted that light would be shifted towards the red end of the spectrum as it moved away from heavy bodies – gravitational redshift. But this was difficult to detect and the experimental results were ambiguous.
- The deflection of light by the sun should be detectable in a solar eclipse.

The Solar Eclipse of 1919

Einstein calculated that under Newton's theory stars near the sun would be deflected 0.8 seconds of arc ($0.0000\bar{2}^\circ$), while under his theory they would be deflected by 1.7 seconds ($0.00047\bar{2}^\circ$).

In 1919, Arthur Eddington (1882–1944) organized a joint expedition with two observation sites to observe a full solar eclipse. There were three different telescopes which took 28 photos, most of which were of poor quality.

The majority of the plates were discarded due to suspicion that there were systematic errors with the telescope.

The Results and Announcement

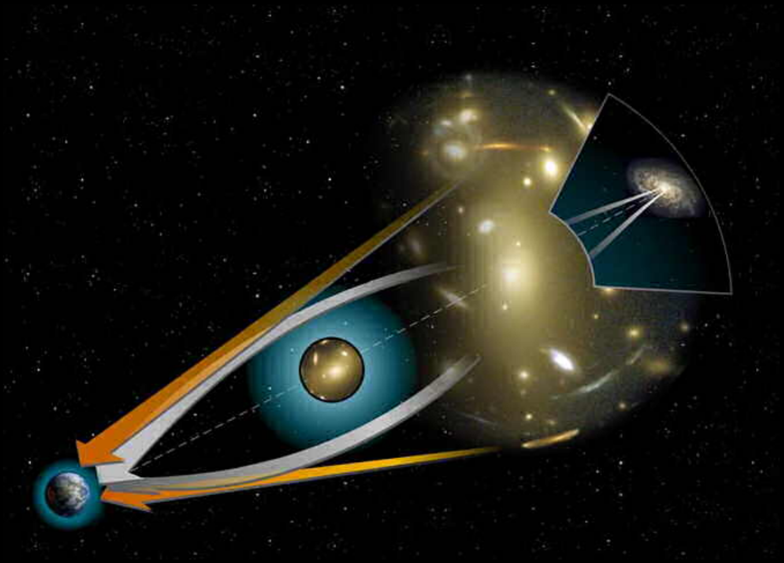
In the end the following results were announced:

Location	Low	Mean	High
Brazil			
8 good photos	1.713	1.98	2.247
18 poor photos	0.140	0.86	1.580
West Africa			
4 poor photos	0.944	1.62	2.276

At the meeting of the Royal Society, it was announced that

> "A very definite result has been obtained that light is deflected in accordance with Einstein's law of gravitation."

A Gravitational Lens



The Reception

The result of this announcement was that first the theory, and then its inventor, became world famous. Particularly in the US and Britain.

J.J. Thompson is reported to have called the discovery "one of the most momentous, if not the most momentous pronouncements in human history."

This fueled anti-Semitic feelings among many Germans who felt that Einstein was intentionally garnering foreign attention for his "Jewish" theories.

In fact, Einstein's fame in the States requires some explanation.

Newspaper Headlines

Initially, the Anglo press got carried away and they peppered their articles with intriguing phrases that were composed of simple words but seemed to make no sense, “curved space,” “four dimensions,” “finite universe,” etc.

London Times

“The ideals of Aristotle and Euclid and Newton which are the basis of all or present conceptions prove in fact not to correspond with what can be observed in the fabric of the universe… Space is merely a relation between two sets of data, and an infinite number of times may coexists. Here and there, past and present, are relative, not absolute, and change according to the ordinates and coordinates selected.”

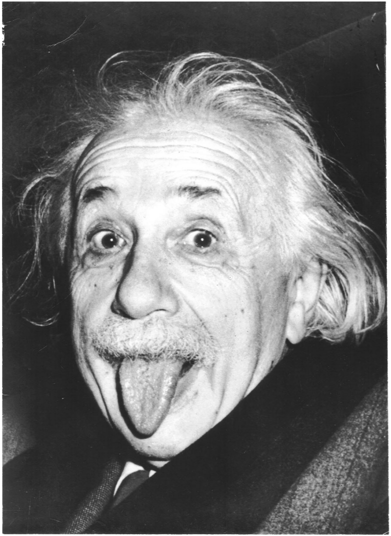
The press created an image of an aloof and disruptive character, bent on the destruction of commonsense ideas.

Celebrity Status

When he finally came to the US, however, the American press loved him.

Far from the frightening Dr. Einstein, destroyer of time and space, he was informal, friendly, humorous, goofy and spoke in sound bites.

The US press fell in love with him and the Europeans reacted to this. He became a scientific celebrity and remains an iconic scientist to this day.



Overview

The theory of relativity sets our ideas about space and time on a secure foundation, although they are no longer directly intuitive.

The general theory of relativity explains gravity as a characteristic of space and time, so that we no longer have to imagine that there is a force that acts instantaneously on bodies across vast distances.

These theories were immensely important in 20th century physics and were used to understand astronomical and cosmological objects (black holes, quasars, gravitational lenses, etc.), as well as objects moving near the speed of light, such as sub-atomic particles (photons, electrons, neutrinos, etc.). It has even been directly used in practical applications, such as the Global Positioning System (GPS).

From Nearby it Looks Quite Different...

Einstein, Letter to Solovine, 1949

"You imagine that I look back on my life's work with calm satisfaction. But from nearby it looks quite different. There is not a single concept of which I am convinced that it will stand firm, and I feel uncertain whether I am in general on the right track."