

From Newton to Einstein—the origins of general relativity

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One hundred years ago in November 1915, Albert Einstein presented to the Prussian Academy of Sciences his new theory of general relativity. It is fair to say the theory turned out to be a great success.

General relativity was built on Einstein's [special relativity](#), which

provided solutions to some of the greatest puzzles of the 19th century theoretical [physics](#).

So in order to grasp the meaning and significance of [general relativity](#), it is worth reflecting on the state of physics in the 19th century to see how Einstein came to realise that space, time and geometry are not absolute but depend on the physical environment.

The beauty of invariance

In the 17th century, Isaac Newton developed a [set of equations](#) that described the physical properties of the world around us. These equations were very successful, from a description of the flight of a cannonball, to the motion of the planets.

They also had a very appealing property: all observers, regardless of whether they are moving or not – i.e. regardless of which "[inertial frame](#)" they are in – are equivalent when it comes to their description of the world around them. So two individuals moving in different directions would see events unfold in the same way.

Even though formally these individuals would see things in a different way – one might say that things move from left to right, whereas the other might say they move from right to left – still the fundamental description of the unfolding events would remain the same, and the laws of physics derived by these individuals would have literally the same form.

But in the 19th century, people started noticing that not everything plays accordingly to this rule.

Problems with electromagnetism

The [19th century](#) was a time of extensive study of the phenomena of electricity, magnetism and light. In 1865 James Clerk Maxwell published a set of equations that combined all these phenomena into a single phenomenon of "electromagnetism".

Soon after Maxwell's discovery, people realised that there is something strange when it comes to his equations. Their form changes when we move from one inertial frame to another. So an individual who is not moving can observe distinctively different physical phenomena than a person who is moving.

All the beauty of invariance and irrelevance of observers that we had got used to in Newtonian physics was gone. It now looked like some frames were preferable to others when it came to describing events in nature.

Then, at the turn of the 20th century, a new mathematical transformation was discovered that could preserve the structure of Maxwell's equations when moving from one frame to another. Although many people contributed to this discovery, we now refer to it as the "[Lorentz transformation](#)".

The Lorentz transformation was different from the standard transformation of inertial frames that had been used in the Newtonian physics. In Newtonian physics, length and time are absolute, so the length of an object in one frame is the same as the length of that object in another frame. Also, time passes in the same way in one frame as in the other frame.

However, if taken literally, the Lorentz transformation implies that time and length do actually change, depending on which frame of reference you are in.

Principle of relativity

This got Einstein wondering whether the transformation that preserved the structure of Maxwell's equations was merely a mathematical trick or whether there was something fundamental about it. He wondered whether time and space were absolute, or whether the principle of invariance of the laws of physics should be paramount.

In 1905, Einstein decided that it is the invariance of the laws of physics that should have the highest status, and postulated the principle of relativity: that all inertial frames are equivalent, the observer's motion (with constant velocity) is irrelevant, and that all laws of physics should have the same form in all inertial frames.

When combined with electromagnetism, this principle would require that the transformation from one inertial frame to another must have a structure of the Lorentz transformation, meaning that time and space are no longer absolute and change their properties when changing from one inertial frame to another.

What about gravity?

In 1907 Einstein realised that his theory was not complete. The principle of relativity was only applicable to observers moving with a constant velocity. It also did not fit with the Newtonian description of gravity.

Einstein, being a patent officer, did not have access to laboratory equipment. To compensate, he had to engage himself in thought experiments. He considered various scenarios in his head and worked through them step by step.

These thought experiments showed to him that gravity is not different from acceleration. So standing stationary on the Earth feels just the same as standing in a rocket ship accelerating at a constant 1G.

It also showed that the accelerated observer would observe that fundamental geometrical properties change. For example, that the number π (a mathematical constant) could no longer be defined as a ratio of a circle's circumference to its diameter.

So it was not just [time](#) and space that lost their absolute meaning, but Einstein realised that also geometry itself was not absolute and could be susceptible to physical conditions.

The road to general relativity

All this reasoning convinced Einstein that the geometry of the spacetime and the physical processes that take place in the spacetime, are related to each other and that one can affect the other.

It also led to a striking conclusion: what we perceive as gravity is just a consequence of the motion through the spacetime. The larger the curvature of the spacetime the stronger gravity is.

It took Einstein eight years to find the relation between the geometry of spacetime and physics.

The equations that he presented in 1915 not only led to a completely different interpretation of events around us but also provided an explanation for some baffling or yet to be discovered phenomena: from the anomalous orbit of the planet Mercury, through the bending of light by the Sun's gravity, to predicting the existence of black holes and expanding universe.

It was a bumpy road from Newtownian physics to special and then general relativity. But each step, driven by Einstein's insight, drove inexorably towards a picture of the universe that persists to this day.

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