

Einstein's Relativity

Introduction

Near the end of the 19th Century and into the early 20th Century some advances in physics and some astronomical observations were at odds with Newtonian physics. The Michelson-Morley experiment did not detect differences in the speed of light expected to result from the earth's motion through the theorized stationary *luminiferous aether*. Maxwell's Equations predicted a constant speed of light, independent of the motion of source and observer. In 1905, Einstein published his Special Theory of Relativity to address these contradictions. Special Relativity discarded the notion of absolute time and space and replaced them with a fluid *spacetime*.

Special Relativity and Newtonian gravity were not compatible. For Newton, gravity was a force, acting instantaneously over distances, while Einstein's relativity requires that the time between cause and effect be limited by distance and the speed of light. It took Einstein ten years to formulate General Relativity with its field equations that replaced Newton's gravitational force acting through a distance with the warping of spacetime in the presence of matter and energy.

In the years that followed, experiments in particle accelerators and observations by astronomers have confirmed the accuracy of predictions made with Einstein's theories. It is worth noting that the 2020 Nobel Prize in Physics was divided, one half awarded to Roger Penrose "for the discovery (in 1965) that black hole formation is a robust prediction of the general theory of relativity", the other half jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object (black hole) at the centre of our galaxy."

Course Organization

The first six weeks will focus mainly on special relativity. The last seven weeks will focus on general relativity, which is mainly a theory of gravity. Course materials will mainly consist of charts, animations, and a few short videos. Each topic begins with an overview that provides a basic understanding of the topic. Topic overviews rely on diagrams and other visual aids. For many topics, the overview includes videos. *Thought experiments*, similar to Einstein's, are presented to better visualize some topics.

Preliminary Topic List

1. Background and history prior to Einstein's theories.
 - a. Galileo's and Newton's Principle of Relativity.
 - b. Light: Prevailing theories and speed measurements.
 - c. Contradictions with Newtonian physics.
 - d. Maxwell's Equations and Lorentz's theories.
 - e. Mercury's orbit is not what Newton predicts.
 - f. Einstein's thoughts and an overview of Special Relativity.
2. Space and time
 - a. We can measure space and time with ever more precision.
 - b. The "arrow of time" that flows only toward the future is more difficult to define.
 - c. Einstein's spacetime conflicts with our innate concepts of absolute space and time.
 - d. A light clock: Deriving formulas for time dilation and length contraction from a simple thought experiment and a little high school algebra.
 - e. Why we cannot go faster than light.
3. How do we define simultaneity and is it the same for all observers?
4. The "Twin Paradox" and an introduction to spacetime diagrams.
5. What will two space travelers measure as their separation velocity, if they are going in opposite directions at 60% of the speed of light? Can the speed of an object, as measured by any observer, ever exceed the speed of light?
6. Energy and $E=mc^2$
 - a. The famous equation is a consequence of Special Relativity but was not included in Einstein's original, June 30, 1905 paper, "On the Electrodynamics of Moving Bodies."
 - b. Einstein defined it with a statement, not as an equation, in his September 27, 1905 short note, "Does the Inertia of a Body Depend Upon Its Energy-Content?"
 - c. A thought experiment involving momentum provides insight and justification.
7. Traveling to distant stars using a theoretically possible relativistic rocket.
8. How Einstein's *principle of equivalence*, which states that no experiment performed inside a rocket can distinguish between it being stationary along a gravitational field or under equivalent acceleration in open space, helped him visualize General Relativity.
9. Overview of the field equations defined in the General Theory of Relativity.
 - a. Matter and energy curve spacetime
 - b. The curvature of spacetime defines paths of motion for matter.
10. Predictions and verifications of General Relativity
 - a. A more accurate model for the orbits of planets, especially Mercury's.
 - b. Gravitational bending of starlight confirmed by Sir Arthur Eddington in 1919.
 - c. An expanding universe and Einstein's cosmological constant.
 - d. The possibility of black holes.

- e. The “Big Bang.”
 - f. Balance sheet for the total energy in the universe.
 - g. Closed time-like loops.
11. Situations where the General Theory of Relativity may not hold true:
- a. Inside the event horizon of a black hole.
 - b. Prior to and for an instant after the Big Bang.
 - c. At subatomic scales.
12. Advanced topics
- a. The theories of relativity vs. quantum mechanics
 - b. Dark matter, dark energy and the accelerated expansion of the universe