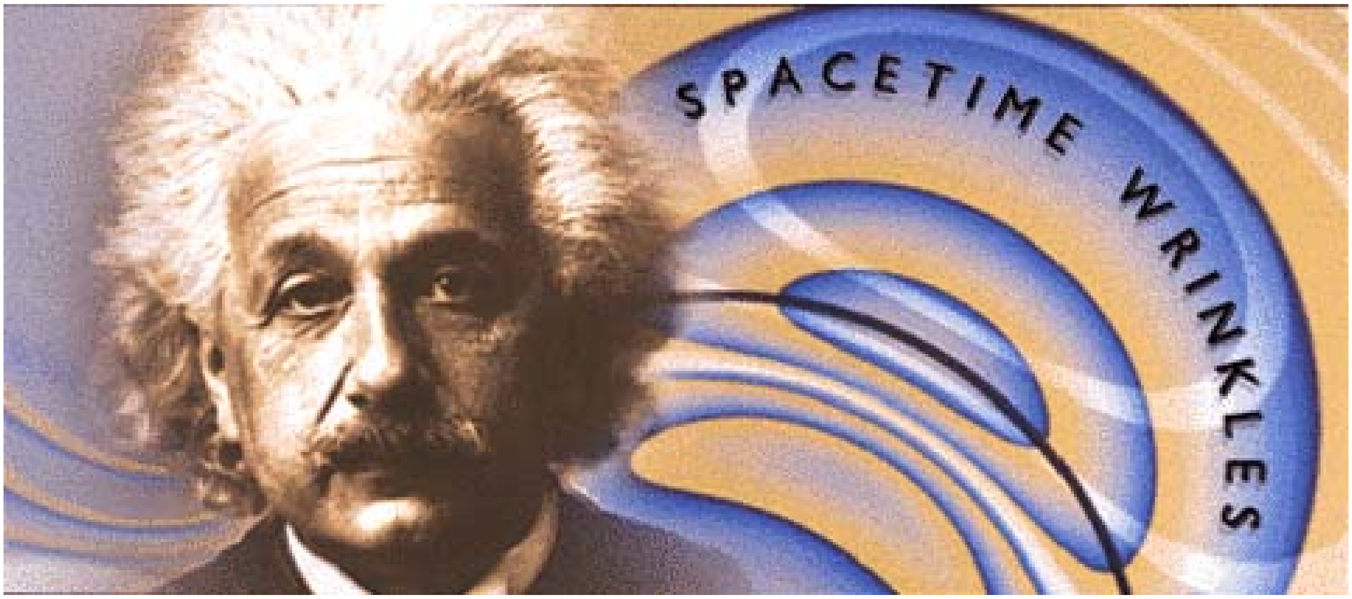
Lecture 2. General Relativity

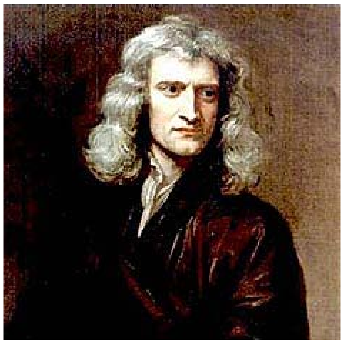
We know from the previous lecture that objects studied in Relativistic Astrophysics are space-time wrinkles. The curvature of space-time is the most central concept of the General Relativity created by Albert Einstein.



PART I. General Relativity for Pedestrians

1. From Newton to Einstein

Einstein's Special Theory of Relativity challenged long-held notions about space and time that had been established over two centuries earlier by Isaac Newton.



British scientist Sir Isaac Newton (1643-1727) formulated the laws of gravity (historical joke: after an apple falls from a tree).

Isaac Newton developed his three laws of motion and a theory of gravity (and the calculus needed to develop and express these theories in math). He set his concepts in a framework of Euclidian space, which is arena for physical processes running in time. Time was assumed to be absolute, i.e. nothing could affect its running. For two centuries the Newton's theory was very successful in celestial mechanics and optics.

According to Newton's theory of gravitation, masses experience an attractive force between them, a force which acts at a distance, resulting in their acceleration toward each other. The strength of that force depends on the size of the masses and is inversely proportional to square of the distance between them. In Newton's universe, space existed independent of the matter in it. Both space and time were absolute, regardless of the motion of the observer and the matter contained within space. No substance controlled the motions of the moon, Earth and planets; only the force of gravity. But Newton's theory of gravitation was a "descriptive" theory; it didn't explain how the force of gravity was exerted. Newton's laws satisfactorily explained most phenomena studied for the next two hundred years. Toward the end of the 19th century, however, as measuring devices grew more and more precise, the list of puzzling inconsistencies was growing.

The picture of old Einstein was replaced here by this one.

German-Swiss-American physicist Albert Einstein (1879-1955) expanded Newton's work by formulating the theory of general relativity.

In 1905, Albert Einstein published his famous Special Theory of Relativity and overthrew commonsense assumptions about space and time.

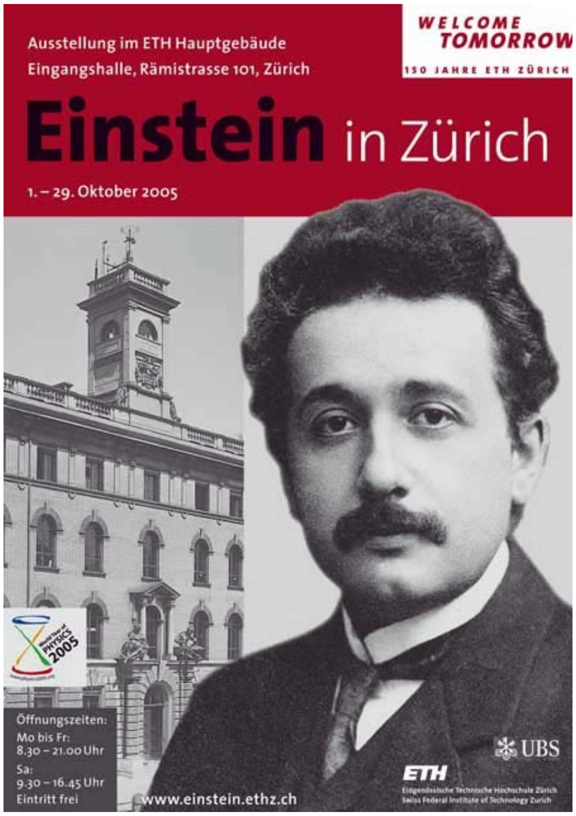
Relative to the observer, both are altered near the speed of light: distances appear to stretch; clocks tick more slowly. A decade and a year later, Einstein further challenged conventional wisdom by describing gravity as the warping of space-time, not a force acting at a distance.

Since then, Einstein's revolutionary insights have largely stood the test of time. One by one, his predictions have been borne out by experiment and observation. But it wasn't until much later that scientists accepted one of the most dramatic ramifications of Einstein's theory of gravitation: the existence of black holes from whose extreme gravity nothing, not even light, can escape. Major advances in computation are only now enabling scientists to simulate how black holes form, evolve, and interact. They're betting on powerful instruments now under construction to confirm that these exotic objects actually exist. We will consider Black holes in more detail in Lecture 4.

Although he is regarded as one of the most brilliant mathematical physicists of the century, Einstein thought of himself as much as a philosopher as a scientist. Certainly his theories relating matter, energy, space, time and gravity have guided

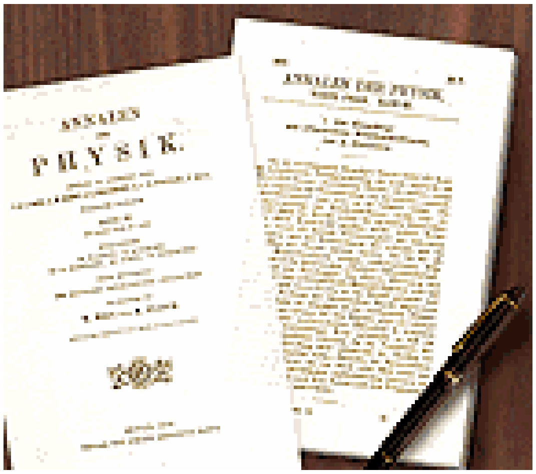
much of the work in theoretical physics since 1905. His famous "thought experiments," based on intuition and imagination rather than laboratory work, propelled us beyond the mechanistic, unchanging "clockwork universe" of Newton and the other classical physicists into a relativistic universe. Here clocks run slower or faster depending on the speed of travel or location in the universe, and "true" distances are stretched or shrunk by gravity.

Young Einstein 100 years later !



Einstein's legacy is a universe in which space and time are woven into a single fabric – space-time. It is matter that causes space-time to curve and whose motion and properties are, in turn, altered by that curvature.

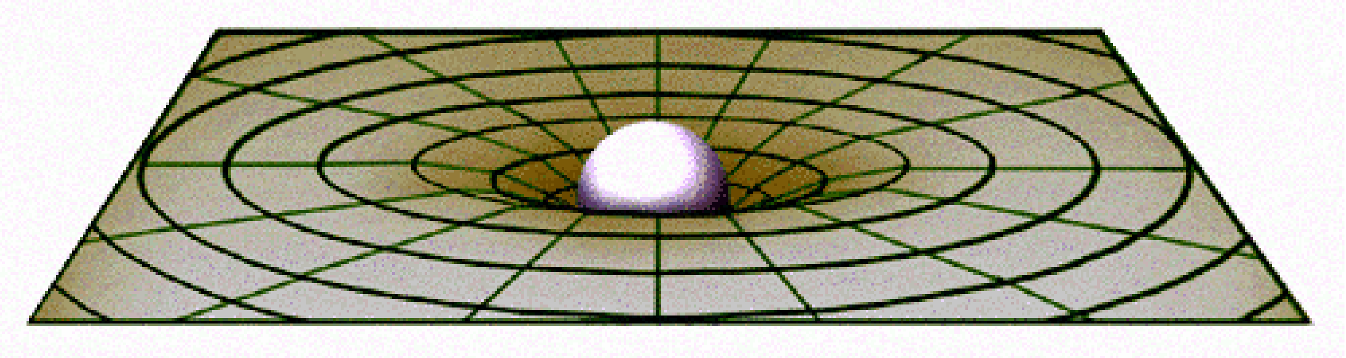
For your information, Einstein's college record as an unenthusiastic student is fairly well known. So, too, his independence and questioning of authority, all of which may have prevented him from landing an entry-level academic position once he graduated in 1900 with a degree in physics. Yet despite this unpromising start, Einstein changed the world through the power of his unconventional imagination.



Einstein's 1916 paper on General Relativity. In 1916 Einstein expanded his Special Relativity to include the effect of gravitation on the shape of space and the flow of time. This theory, referred to as the General Theory of Relativity, proposed that matter causes space to curve.

2. Embedding Diagrams

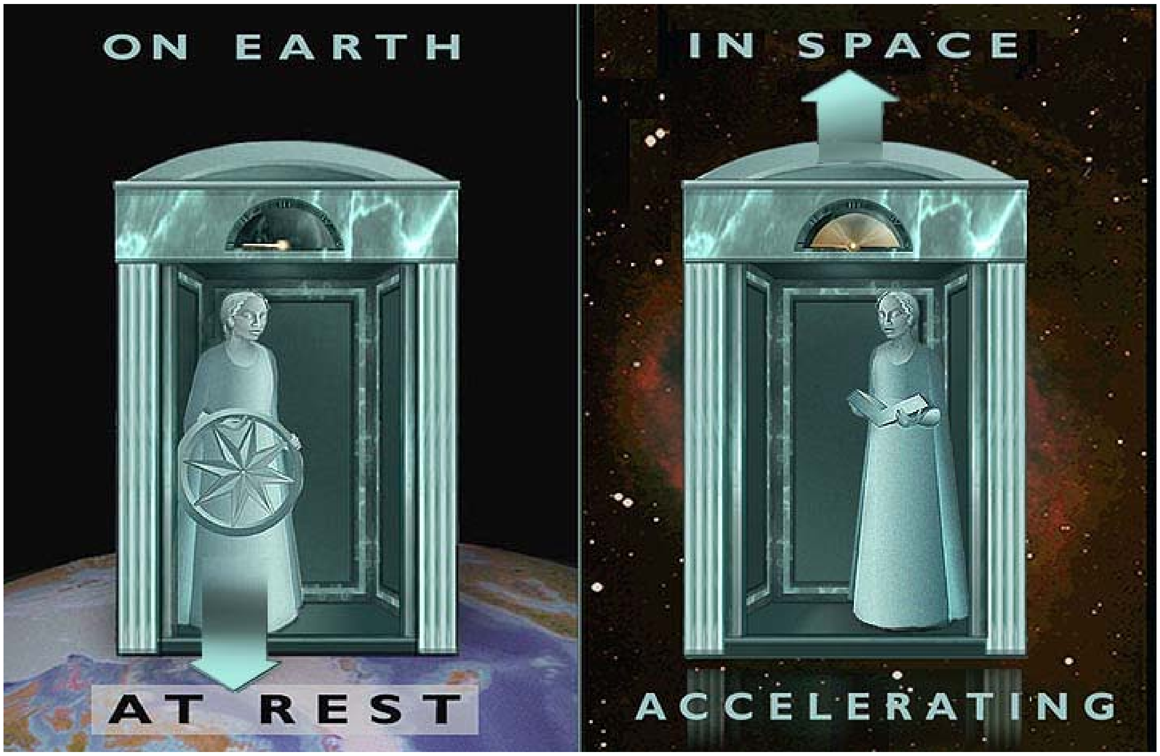
Picture a bowling ball on a stretched rubber sheet.



The large ball will cause a deformation in the sheet's surface. A baseball dropped onto the sheet will roll toward the bowling ball. Einstein theorized that smaller masses travel toward larger masses not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object. Physicists illustrate this idea using embedding diagrams.

Contrary to appearances, an embedding diagram does not depict the three-dimensional "space" of our everyday experience. Rather it shows how a 2D slice through familiar 3D space is curved downwards when embedded in flattened hyperspace. We cannot fully envision this hyperspace; it contains seven dimensions, including one for time! Flattening it to 3D allows us to represent the curvature. Embedding diagrams can help us visualize the implications of Einstein's General Theory of Relativity.

3. The Principle of Equivalence



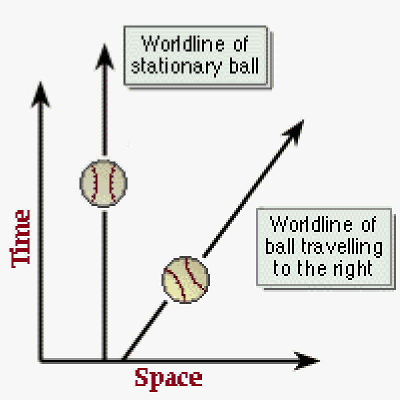
The basic postulate of the Theory of General Relativity states that a uniform gravitational field (like that near the Earth) is equivalent to a uniform acceleration.

What this means, in effect, is that a person cannot tell the difference between (a) standing on the Earth, feeling the effects of gravity as a downward pull and (b) standing in a very smooth elevator that is accelerating upwards at just the right rate of exactly 32 feet per second squared.

In both cases, a person would feel the same downward pull of gravity. Einstein asserted that these effects were actually the same. A far cry from Newton's view of gravity as a force acting at a distance!

4. World lines

Imagine that time is like a spatial dimension, and it is plotted on the y-axis of a sheet of graph paper before us. Let the x-axis be one of the three spatial dimensions of our world. A ball travelling to the right would be depicted as a line with a positive slope. A ball at rest would be plotted as a straight vertical line. Because physicists do think of time as a dimension similar to a spatial dimension, they draw diagrams, like the one described above, to illustrate the trajectory of a particle which they term that particle's "world line."



An important point to realize is that one can always rotate the paper and redraw the axes so that one of the balls appears to be sitting still (its world line will simply be a vertical line). The choice of axes is really somewhat arbitrary, but the fact that the balls are moving apart is evident no matter how the coordinate axes are drawn.

If space-time is flat and one works with inertial frames of reference the world lines of free particles are straight lines. For particles moving with acceleration the world lines are curved. The fact that all bodies move with the same acceleration in given gravitational field means that this gravitational field is really manifestation of properties of space-time itself.