Special relativity

Before discussing some of the history and results of Einstein's ideas, I want to emphasize a major point to keep in mind:

No matter how fast something moves, or how strong a gravitational field it is in, if it is in free fall then it measures all local effects (at small distances from it, over a short time) to be normal.

This means that the effects we will describe cannot be used to make a person's lifetime seem longer to *them*, although it *can* be used to make that person's lifetime seem longer to other who are moving differently.

With that firmly in mind, what is special relativity? In the late 1800s a crisis was developing in physics. Newton's laws had reigned for two centuries as the pinnacle of science, and they had the benefit of appealing to common sense as well. For example, suppose that I were riding a train that was going 50 miles per hour, and I threw a baseball in that same direction at 50 miles per hour. If you were standing next to the tracks, how fast would you see the ball go? Obviously, it would be $50 + 50 = 100$ miles per hour.

But near the end of the 19th century another great theory had developed. This was Maxwell's theory of electromagnetism, which unified the previously disparate subjects of optics, electricity, and magnetism. Although it was superbly successful in its domain, it predicted some things that were not common sense at all. For example, suppose that I were on a train going 50 miles per hour and I shone a beam of light in the direction the train was moving. You, on the side of the tracks, would according to Maxwell see the light moving at the same rate that I would, even though you might think that you should see it going 50 miles per hour faster. Even worse, when the speed of light was measured by Michelson and Morley, they found it agreed with Maxwell; the speed of light in a vacuum is the same for every observer no matter what their motion.

Into this environment came Einstein. In 1905 he proposed his special theory of relativity. If you want to go into the mathematical details, please check out

http://www.astro.umd.edu/∼miller/teaching/astr498/

lectures 2 and 3. Here we will just summarize the main results, using the Lorentz factor $\gamma = 1/\sqrt{1 - v^2/c^2}$, where v is the speed that is measured by an observer and $c \approx 300,000$ km s^{-1} is the speed of light in a vacuum. In each of the following, we assume that I have measured you as moving at a speed v relative to me.

- Your mass appears to me to be increased by a factor γ.
- Your clock appears to me to run more slowly by a factor γ.

- Lengths along the direction of your motion appear to me to be shrunk by a factor γ.

Remember, though, our fundamental consideration. It means that to *you*, everything seems normal; your mass is the same, lengths are the same, and your clock appears to run normally. Oddly, though, if you look at me you find all those effects are reciprocated: my mass is increased, my clock runs slowly, and my lengths are contracted. It doesn't make sense, does it? One of the tough lessons we learn from studying science is that many times the way nature actually works really *doesn't* conform to our intuition. But why should it? We have evolved to experience things vastly larger than atoms, moving much more slowly than the speed of light, in gravity that is actually pretty weak, and over times that are extremely short compared to the age of the Earth or the universe. There is no reason, therefore, that our intuition should be valid in other domains.

What we can do, though, is test the predictions of special relativity as thoroughly as possible. If it passes those tests, we have greater confidence in its predictions even if it doesn't make sense at a gut level. Check out the more detailed lectures I referred to above for successful tests of special relativity, but suffice it to say that not a single failure has ever been established.

General relativity

Einstein wasn't finished, though. Special relativity only dealt with frames of reference that moved by each other at constant speed. In November of 1915 he came up with general relativity, which allowed for accelerations and turns out to be our best current theory of gravitation.

The basic idea is that the gravity from an object (you, me, a star, a black hole, whatever) warps spacetime, which is a combination of space and time. Big, dense things warp spacetime more than little, fluffy things. Black holes affect spacetime as much as it can be affected, to the extent that close enough to the center (or "singularity") of a black hole, not even light can escape. This point of no return is called an "event horizon". By the way, far away from a gravitating object everything is normal. For example, if we somehow replaced the Sun with a black hole that had the same mass as the Sun, the Earth would continue to orbit just as it always has, although we would freeze quickly because of the lack of sunlight.

One aspect of the warping of spacetime is that time runs differently depending on how deep you are in a gravitational well. As always, any observer will find that their own clocks appear to run at the same rate as always. However, if we stayed far away from an object with strong gravity (such as a neutron star or black hole) while someone else went close, we would see their clock running slowly while they saw ours running quickly. The factor between the rates gets larger without limit as one approaches the event horizon.

What could super-advanced aliens do with this? Suppose our aliens are tough enough to withstand the crushing gravity of a black hole, and that they have an unlimited supply of rocket fuel. In that case, they could hover just outside the event horizon of the hole and watch the universe appear to move at a very rapid rate. For example, if an alien wanted to see what things will be like a trillion years from now, it would only have to hang out very close to (but outside!) the horizon for a few years of its subjective time, then come back out again. However, as we discuss in the main lecture, traveling *back* in time is a lot more difficult although it *might* not be impossible.