Lecture 16

Fundamentals of Physics

Phys 120, Fall 2015

General Relativity

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Overview

- What is a straight line

- The equivalence principle

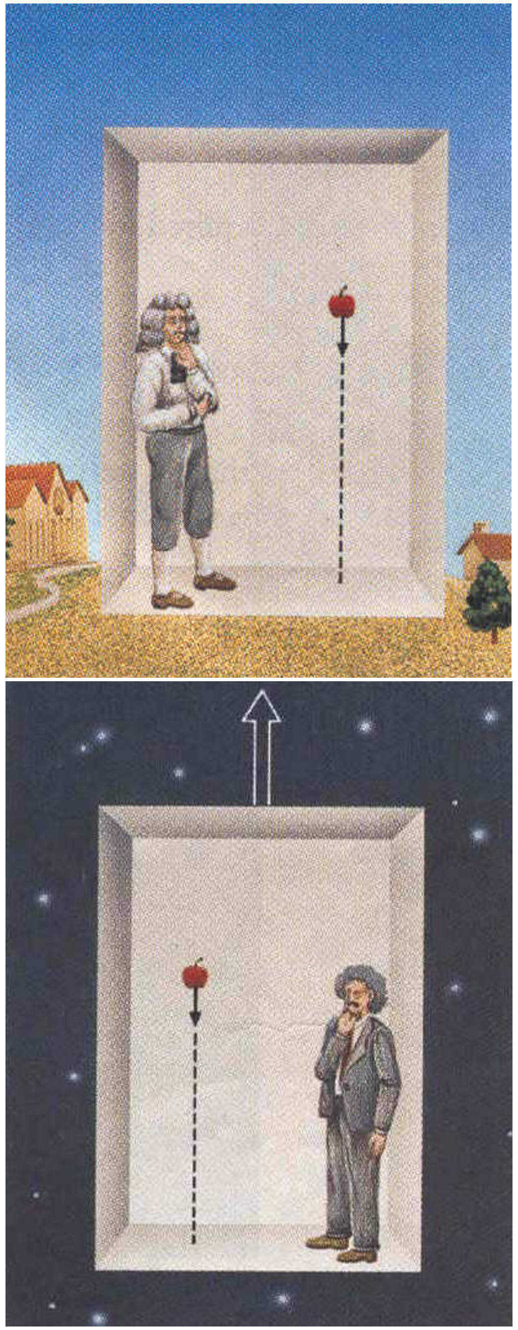
- Gravity and clocks

Accelerated observers

We described what happened to observers moving in **inertial frames** relative to each other. We found that we something special happened when an twin was accelerated.

So we need to understand what happens for accelerated observers.

Similarity between acceleration and gravity



Imagine you are in a box with no windows.
Is there any difference between this box sitting on earth or being accelerated with 10 m/s^2 in space? Can you tell the difference?
Let us look at a falling apple. If the box is sitting on the ground the apple will fall with an acceleration of $g = 10m/s^2$.
If the box is accelerated in space, then the apple will move with the constant velocity it had when it was released (according to Galileo and Newton), but your box is accelerated and it will appear to you as if the apple was falling with and acceleration equal to the acceleration of your box.
Is there any experiment you could perform inside the box to tell if you are sitting on a planet experiencing gravity or if you are being accelerated in space?

Einstein's Equivalence principle

The Equivalence Principle
No experiment performed inside a closed room can tell you whether you are at rest in the presence of gravity or accelerating in the absence of gravity.

What is a straight line?

How would you define a straight line?

The best physical definition we have for a straight line is the direction a light takes.

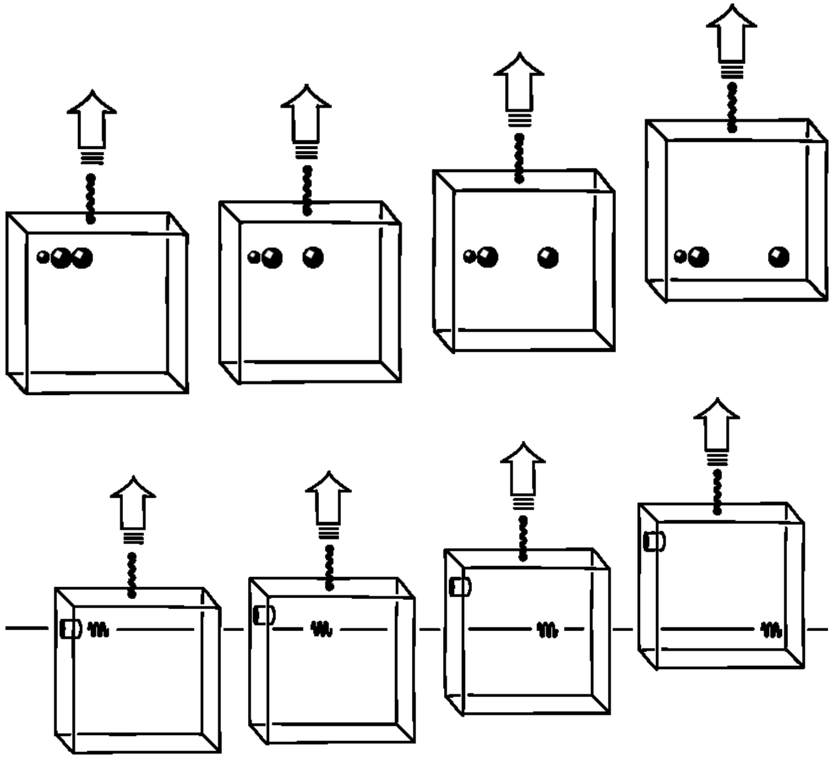
But does light always go straight?

Light in an accelerated box

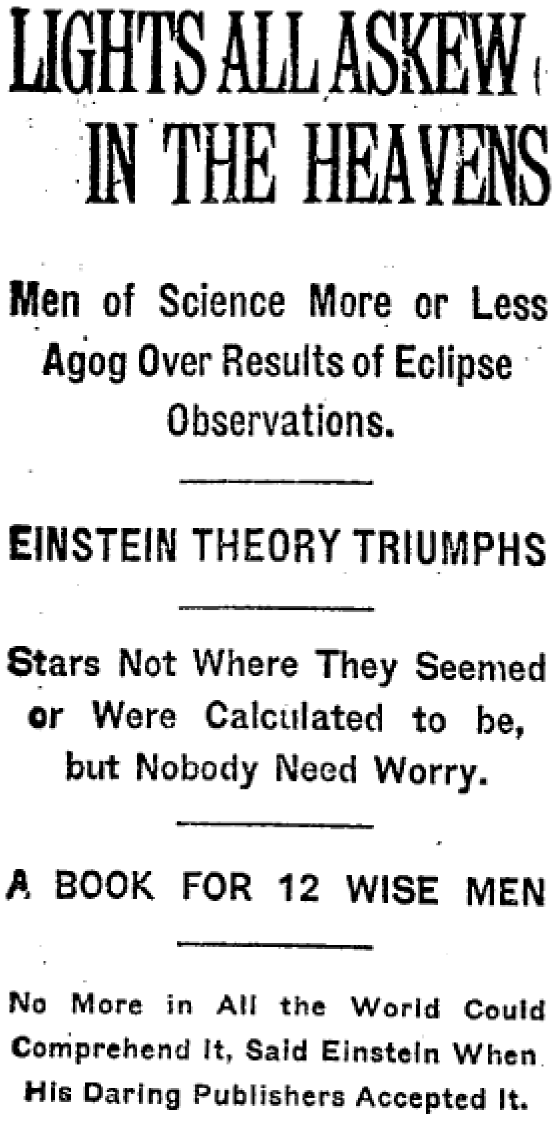
Imagine throwing a rock forward in the accelerated box. It will move in a straight line, but seen from the accelerated box it appears to be falling as if it was thrown on earth.

Now imagine a flashlight shining into the box. The light will also move in a straight line, but due to the acceleration of the box the light now appears to be “falling” to an observer in the accelerated box.

The equivalence principle states that the same should happen to a light-beam on earth so light has to be attracted by a gravitational field! (Otherwise you would have found a mechanism to distinguish between being in an accelerated box and being in a stationary box feeling gravity).



How do we know that gravity bends light?



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

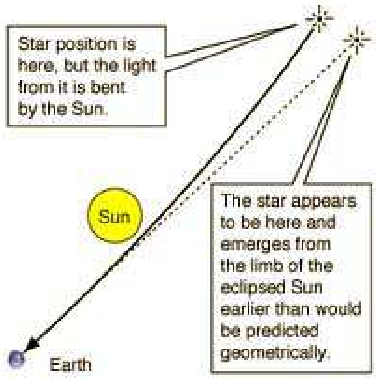
EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

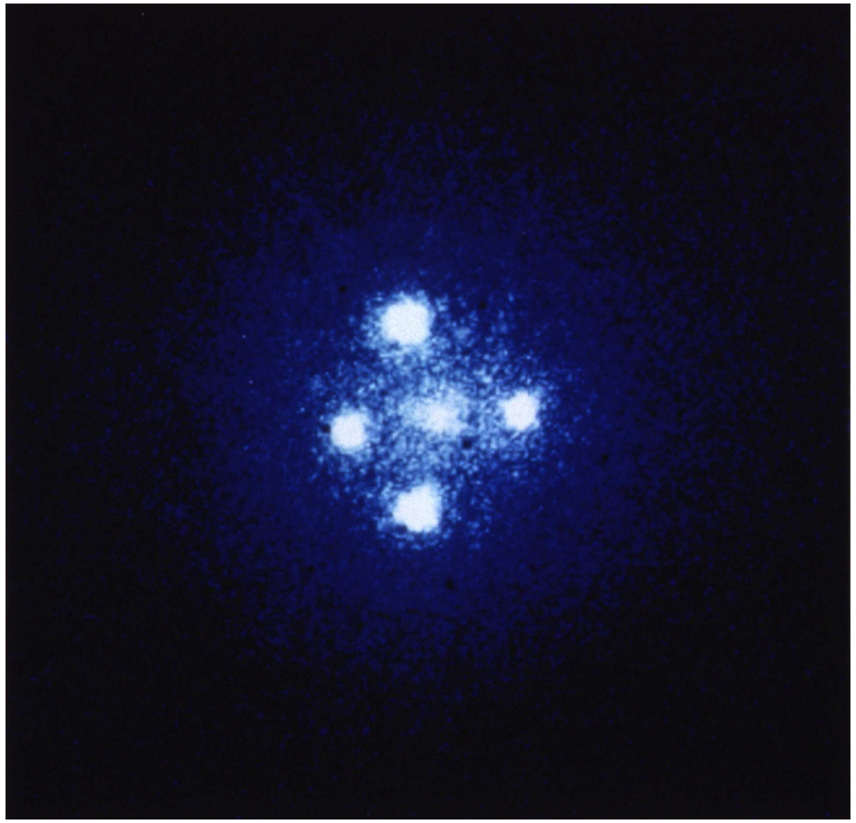
A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Earth gravity is too weak to bend light very much. But the sun is massive enough to measurably bend the light from distant stars as the light passes close to the sun. The first measurement of this effect was made during a total eclipse of the sun in 1919, when astronomers could photograph the stars that appear near the edge of the sun and that the amount of curvature agrees with Einstein's predictions. The success of these measurements made Einstein a star overnight.



Einstein's cross



The Einstein Cross or Q2237+030 or QSO 2237+0305 is a gravitationally lensed quasar that sits directly behind ZW 2237+030, Huchra's Lens. Four images of the same distant quasar appear around a foreground galaxy due to strong gravitational lensing.

Curved space

If light defined straight lines and light is bent by gravity, then *space itself is bent, or curved, or warped, by gravity*. In curved space, even the straightest possible path must be curved.

Unfortunately curved space is not something that Einstein or anybody else could visualize. But the mathematician Bernhard Riemann had developed the mathematics of curved spaces, and Einstein extensively drew on this bit of previously obscure mathematics.

However, we have to do with analogies. Assume that your world is two-dimensional. You only have two directions to go in, but everything else remains the same. You can define straight lines as the shortest distances between two points. Now let us consider two dimensional space that is curved. The easiest to imagine is a sphere. Can you tell, locally, that your space is curved?

No, but if you look at large distances differences become apparent. For instance the sum of all angles in a triangle is no longer 180°! Parallel lines merge! Lots of things are different at large scales.

Caveat for your imagination

At this point, many students develop the misconception that there must be a fourth spatial dimension into which three-dimensional space is curving. This is wrong. Our two-dimensional analogy is meant to be imagined with no reference to any “embedding” of those two dimensions in a third dimension; the real three-dimensional space is curved despite the absence of a fourth spatial dimension into which three-dimensional space is curving.

How do we know that space is curved?

But does bending of light really show space to be curved or does it merely show that light beams bend in ordinary or “flat” three-dimensional space? The latter possibility was ruled out by an experiment in 1972 in which a spacecraft orbiting Mars beamed back radar signals sent from Earth. The radar beam’s travel time was measured at a time of year when the line of sight from Earth to Mars passed near the sun. This travel-time measurement can tell whether the bent light beam travels through a flat space or through a warped space. Here’s how.

It’s easy to use the observed curved path on a flat sheet of paper and seeing how much longer it is than a straight line. In the experiment, the answer was about 10 m, so if the radar beam was merely bending in a flat space, it should have been delayed by about 30 billionth of a second, the time taken by light (and radar) to travel 10m. But you can’t use a flat sheet of paper to measure distances in a warped space, for the same reason that you can’t determine the distance from Los Angeles to London by making measurements on a flat map: The “scale” keeps changing because of the curvature. Einstein’s formulas predicted a delay of 200 millionths of a second, 7000 times longer than the predicted delay in a flat space. The experiment confirmed Einstein’s prediction.

Time dilation

We know from the special theory of relativity that space and time are intimately related. We should therefore not be surprised to learn that gravity also has an effect on time.

The deeper we are in a gravitational potential well, the slower a clock will move. This makes a measurable difference for atomic clocks at the Royal Greenwich Observatory, UK (80 ft) and the National Bureau of Standards in Boulder, CO (5400 ft): the Boulder clock gains about five microseconds every year on the Greenwich clock!

Newton's and Einsteins gravitational theory

For familiar situations like the fall of a stone, general relativity's predictions are nearly identical to Newton's. For exotic situations such as near a black hole or during the creation of the universe, general relativity's predictions differ enormously from Newton's. Conceptually the two theories differ radically:

Newton	Einstein
Gravitational effects are due to gravitational forces.	Gravitational effects are due to the curvature of spacetime. Spacetime's geometry is determined by the distribution of masses.
Planets move along ellipses.	Planets move along straight lines in curved spacetime.

Einstein's theory is more correct in that it predicts the outcome of experiments better (so far perfectly within measurement uncertainty) while Newton's theory is only valid in the regions where it agrees with Einstein's theory.

Concept check

Since accelerations can mimic the effects of gravity, accelerations should be able to cancel gravity. Thus, a person could experience weightlessness by
a) blasting off from Earth, straight upward, at an acceleration of 1g;
b) falling from a high place such as a diving board or airplane (skydiving);
c) orbiting earth;
d) standing on the surface of the moon.

Concept check

The equator is a “straightest possible” line on the surface of a globe. Are other east-west circles of latitude “straightest possible” lines?

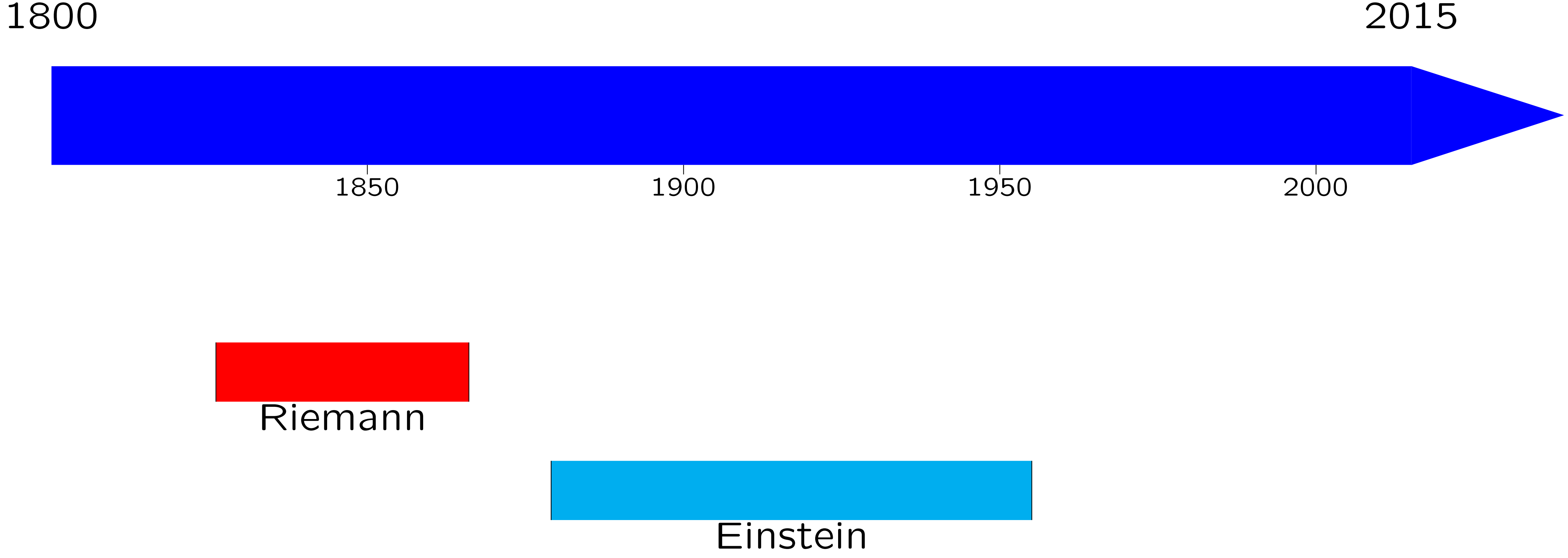
a) Yes.
b) No, they curve more than the equator’s curvature.
c) No, they curve less than the equator’s curvature.
d) No, despite the fact that their curvature is the same as the equator’s curvature.

How do we know that general relativity is accurate?

There are many practical examples, the precession of Mercury, the bending of light by the sun, the delay of radio waves sent by spacecraft from Mars, all of which are correctly predicted by this theory.

Let us look at another one: motion of planets around the center of our galaxy!
Timelapse movie of stars at the center of our galaxy.

Timeline



Summary

- The equivalence principle
- Light follows the straight path
- Light bends, so space is curved
- Time is slower in strong gravity
- Evidence for the general theory of relativity.