SPACE, TIME, MATTER AND GRAVITY: THE RELATIVISTIC REVOLUTION

Soon after the revelation of electromagnetic theory given by Maxwell, physicists began to realise that there was a discordance between EM theory and Newtonian dynamics. Key here were Lorentz, Fitzgerald, and Poincare, at the end of the 19th century & the beginning of the 20th century. However it was a young and completely unknown Einstein who realised in 1905 that the solution of this problem lay in a re-evaluation of the concepts of space, time, & simultaneity. In 1908 Minkowski observed that Einstein's ideas could be formulated as a theory of 'spacetime'. This thoery was called 'special relativity'

However by far the most radical step was to come. Special relativity did not apply to accelerating bodies. In a remarkable piece of pure theory, Einstein argued that the solution here lay in his equivalence principle, which established a connection between gravitational fields, accelerations, and spacetime. It took him 8 years to then find the right theory, which led to the conclusion that spacetime itself was a field, acted upon by masses (and in turn acting on them).

This theory (the 'General Theory of Relativity') was hardly understood by most physicists at the time – its acceptance came only because of the authority of Einstein & a few other well-known physicists, and 2 observational confirmations. Some of its predictions (eg., the Big Bang', and black holes), were too radical even for Einstein. The great majority of physicists ignored it – it seemed to be so irrelevant to almost any physical process.

The theory is now a central pillar of modern astrophysics (see next slide set).

SPACETIME & the GRAVITATIONAL FIELD

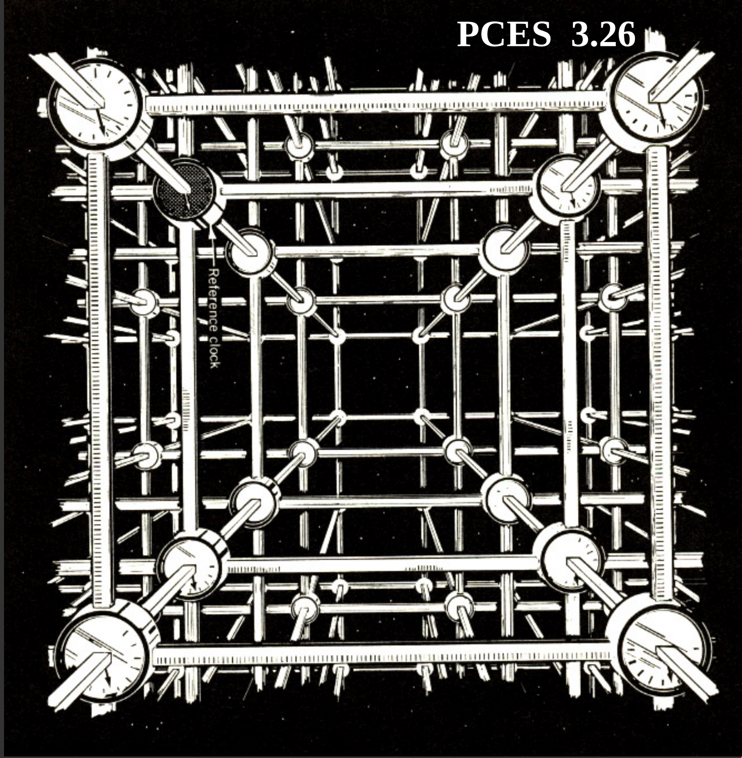
A. Einstein (1879-1955) in California (mid-1930’s)

In many ways the revolution accomplished by Einstein is the most staggering intellectual achievement by a single individual in all of history, at least in science. In contrast to Newton’s work, Einstein’s theory of gravitation came not because it was demanded by observation, but because it was demanded by Einstein, who was looking for a general theory to understand spacetime, gravity, and all fields living in spacetime. The extraordinary result he found was that spacetime is itself a field, and gravity is a distortion of this field, caused by matter. He was never able to unify this field with the other fields around, and the search for such a unification is still with us. He also made many other fundamental contributions to physics, as we will see later.

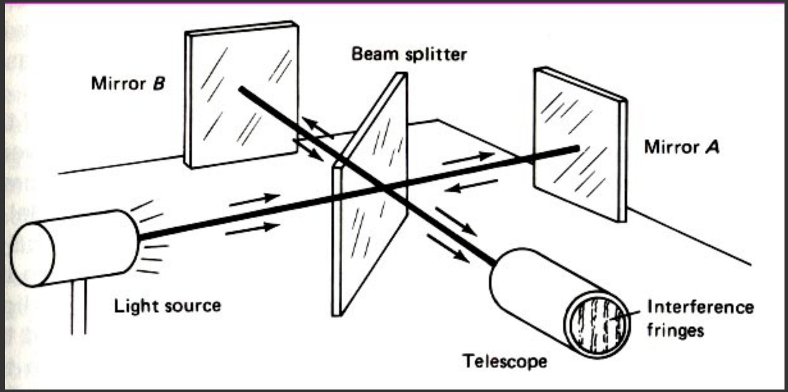
SPACETIME: RODS & CLOCKS

As we already learned in discussing Newton, it is not entirely straightforward to define space & time. By the 19th century physicists were used to doing this by imagining some network of rods and clocks, giving standard measures of length and time. In one’s imagination one could then assume that each POINT in space and time was defined by an imaginary lattice of rods & clocks. It was universally assumed that

(i) space was Euclidean
(ii) time and space were separate.

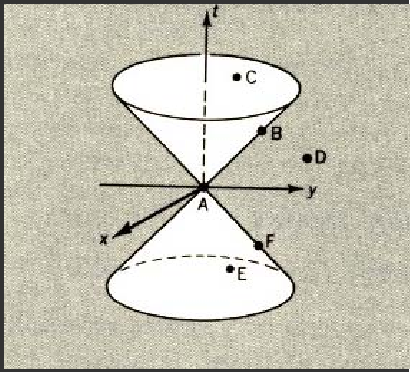


This meant, amongst many other things, that relative velocities added to each other – so that if, eg., person (A) measured light to have a velocity c in some direction, then another person (B) moving in the same direction at a velocity v relative to (A) would see the light moving at a velocity c’ = c-v.



Unfortunately this led to problems- it conflicted with Maxwell’s equations, in which any observer would see light moving at c in any direction, no matter the velocity of the observer! The famous Michelson-Morley experiment (1895) showed the earth always moved at a velocity c relative to starlight- so something was wrong!

SPECIAL RELATIVITY



Coordinates in spacetime (2-d space)

Various people contributed to what is now called the theory of "Special Relativity", but the overall framework & many of the key results were in Einstein's 1905 paper. Einstein started from a simple basic principle, the PRINCIPLE of RELATIVITY:

The laws of physics are the same in all inertial frames

As noticed by Einstein, this forced a choice between Maxwell's theory & Newton's laws- according to Newton, velocities were additive, but in Maxwell's theory, the velocity of light was the same in any reference frame. Einstein plumped for Maxwell (without actually knowing about the Michelson-Morley experiment).

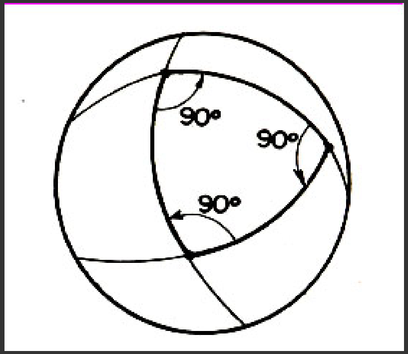
The fact that velocities are not additive means a fundamental change in our understanding of space and time- the length of an object depends on what reference frame it is measured in, and likewise for time intervals. The precise mathematical description of these ideas is well beyond this course.

There are, however, things that do not change from one reference frame to another- these INVARIANTS are in some sense more "real" than things which depend on the reference frame. The most important is the INTERVAL s, defined by

$$s^2 = c^2t^2 - l^2$$

Its invariance tells us that space & time cannot be separated, and that the common sense idea, that distances l and time intervals t are absolute, is simply wrong.

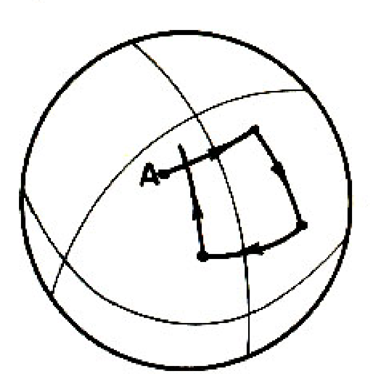
NON-EUCLIDEAN GEOMETRY



On a curved surface, the 3 internal angles of a large triangle don’t add to 180 degrees

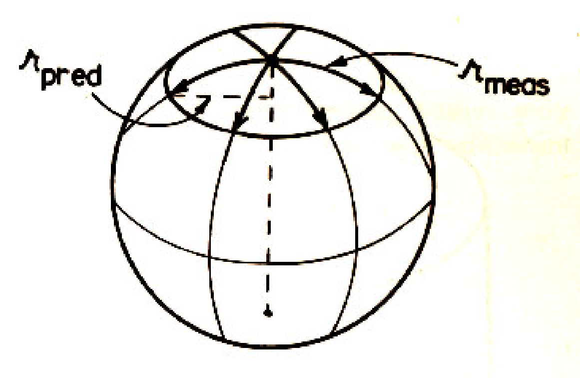
Geometry is the branch of mathematics dealing with the relationships between points, lines, angles, etc.; these define the structure of the space they exist in. To see how non-Euclidean geometry could work, imagine a being confined to 2 dimensions- with no awareness at all of any higher dimensions.

Now suppose this being finds that (i) the angles in a triangle don’t add up to 180°; that (ii) If one tries to draw a square by joining 4 equal lines with right angles, then the lines don’t close up; and that (iii) if one measures the area of a circle, it is not proportional to the square of the radius. How can this be explained?



On a curved surface, a large square, with right-angled corners, will not close

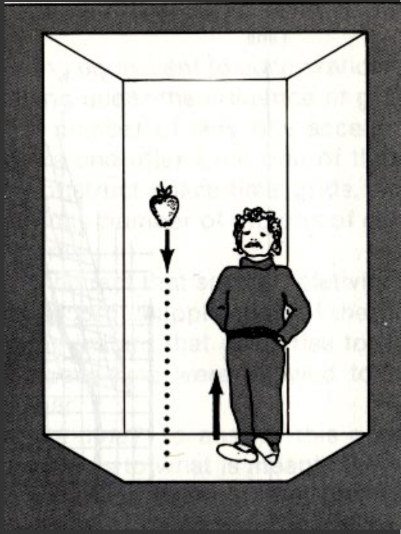
Since we live in a higher dimension, the explanation is very easy for us to see- the 2-d space in which these results are found is CURVED. For a being only aware of the 2-d space, the internal geometry of the space is seen as NON-EUCLIDEAN. Notice that for very small objects (small squares, triangles, circles, etc), the geometry does appear Euclidean- we only get deviations for large objects. You can try this out on a balloon or some other curved surface.



On a curved surface, as one increases the radius of a circle, the area deviates more and more from the standard result

In General Relativity, it is 4-dimensional SPACETIME that has a non-Euclidean geometry…

The PRINCIPLE of EQUIVALENCE



A simple thought experiment ("gedanken" experiment), of Einstein, has someone inside an elevator or closed box. The point is that from inside, one cannot distinguish a box in an inertial frame from one falling in a uniform gravitational field. This can be used as the starting point of a far-reaching argument. Notice first that this implies the identity of gravitational and inertial mass. The inertial mass is the mass which is being accelerated, ie., the mass m appearing in F = ma, which we can call m_i. The gravitational mass is the mass which measures how strongly the system feels a gravitational field- remember if our system is being attracted by some other mass M, the force on it is

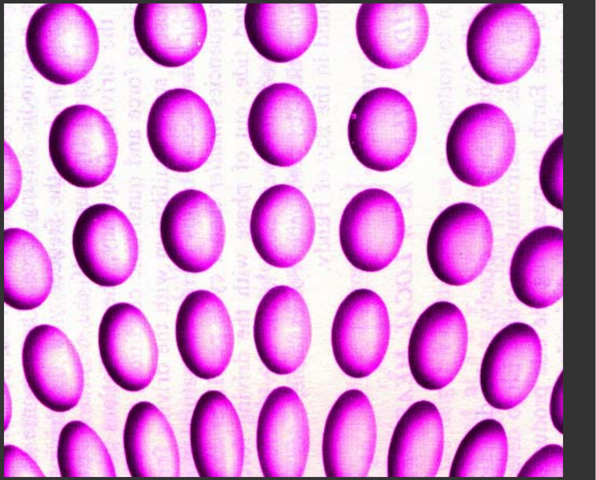
$$F = \frac{GM}{r^2} m_G$$

where the mass here we call m_G, the gravitational mass- notice thqt m_G is like a "gravitational charge", analogous to the electrical charge in Coulomb's law. To say that these two masses are the same "mass" m is the point at issue – this is the principle of equivalence.

This equivalence has been the subject of many experiments since the first one of Eotvos in 1920- always with the result that $m_i = m_G$, within experimental error.

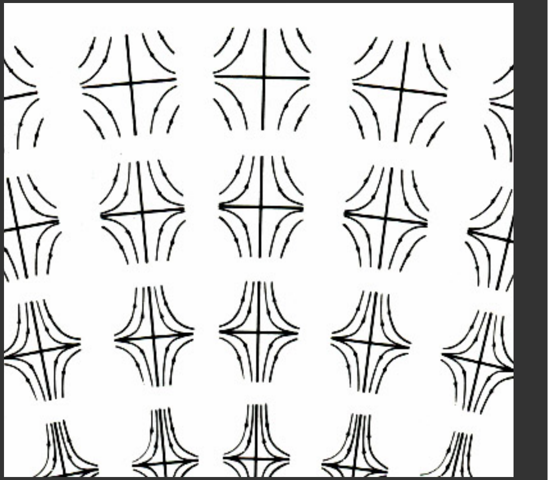
Eotvos experiment ( )

GENERAL RELATIVITY

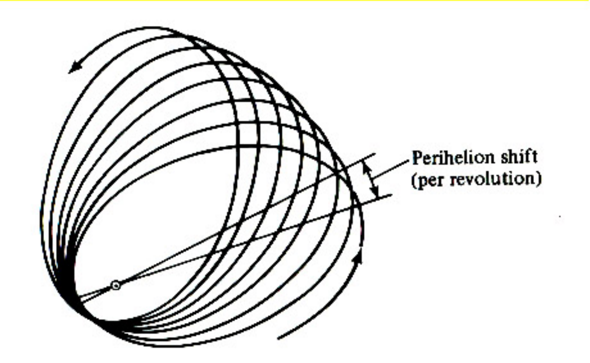


There is however one way to distinguish gravitational from inertial forces - gravity causes TIDAL forces, because the gravitational field is inevitably non-uniform. At right we see how the field near a body like the earth affects a fluid drop (the earth is below the picture); we assume these spheres are falling in the field, but the field isn't uniform (in an inertial frame the drops would all remain spherical).

One can in a simplified way think of the strength of these tidal forces as being proportional to the spacetime curvature (though to completely specify this we need more information). The essential content of Einstein's theory- which took him 8 years to find after formulating the principle of equivalence- is that the curvature at any point is proportional to the "stress-energy tensor" (roughly, the energy density- and mass is counted here as energy via $E = mc^2$). I don't write any equations here!

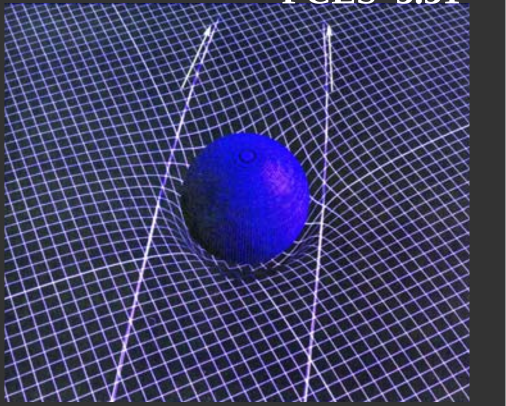


Tidal forces near a massive body- force lines on a drop shown below.



The 1st success of the theory came immediately- the tidal forces cause explained the slow precession of Mercury's orbit (the slow rotation in its orientation), shown at left.

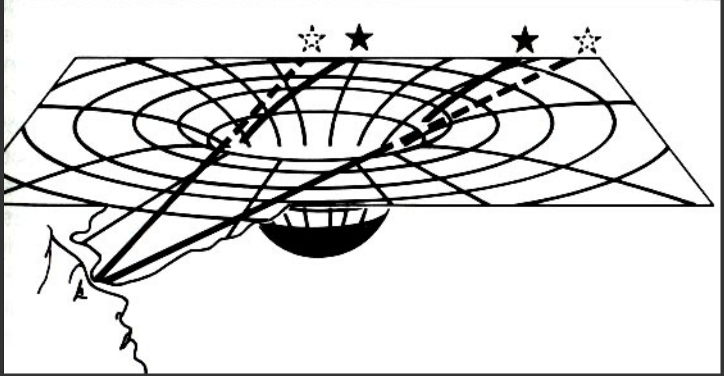
GRAVITATIONAL LIGHT-BENDING



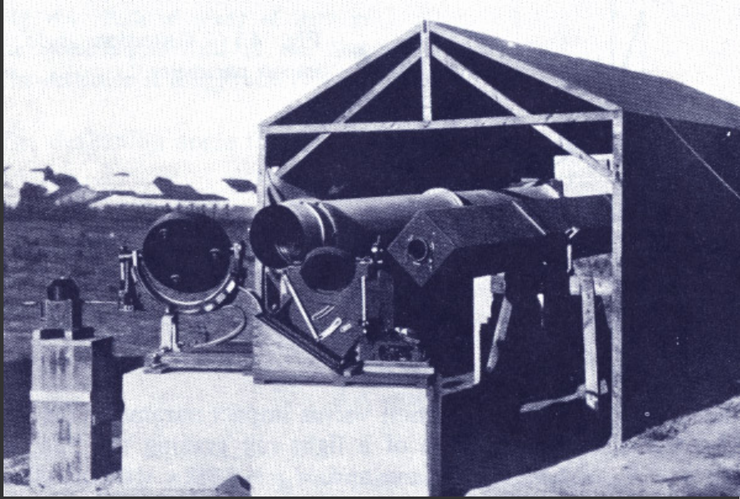
Bending of light moving through the curved space near a massive body

One of the simplest tests of general relativity (and the one whose spectacular success in 1919 made Einstein famous) is the bending of light by the distorted spacetime around any massive object. This bending is NOT the same as one would calculate by just assuming the light to be pulled sideways by the sun's gravity as it passes- hence the interest of the test. Under the direction Sir Arthur Eddington, the Royal Society sent 2 expeditions (to the Brazilian island of Sobral, and to Principe) to measure the displacement of stars near the sun, during a solar eclipse. The confirmation of Einstein's predictions was given in a historic meeting in London, where they were announced as the greatest advance in science since Newton. This gave Einstein worldwide celebrity. All subsequent tests (now done with radio waves) give agreement with theory.

However, this was a "weak field" test. It was easy in 1919 to think that Einstein's theory was of little practical interest.



Deflection of starlight near the sun



The instruments used at Sobral in 1919.