General Relativity.

Einstein was dissatisfied by Special Relativity.

Why are physical laws only “invariant” to the restricted class of constant velocity observers?

In particular, how can we write universal laws of physics for observers that may be accelerating in a gravitational field?

Einstein knew that Newtonian Gravity was inconsistent with Special Relativity.

Gravity presents particular problem - no neutral particles unlike electromagnetism where uncharged particles can be used as inertial frame "markers".

Einstein wanted to build on Special Relativity - looked for Special Relativity inertial frames in the presence of a gravitational field.

Equivalence of Grav. and Inertial Mass.

Newtonian physics $\Rightarrow$

The mass, m, used in:- $F = ma$

is same m as used in: $F_{grav} = GMm/r^2$!

For object, mass m, dropping in Earth's gravitational field:

$$ma = F_{grav} = GMm/r^2$$

$\Rightarrow$ $$a = GM/r^2$$

$\Rightarrow$ All objects fall at the same rate irrespective of their mass.

Einstein suggested that any freely falling (ie accelerating!) observer in a gravitational field is equivalent to a constant velocity, Special Relativity observer!

i.e. all freely-falling observers see same physical laws – the laws of Special Relativity.

In non-uniform gravitational field - more complicated.

Observer in lift experimenting with 2 particles after a long time will see them "attract" - but external observer will see only that they are moving radially towards centre of Earth under gravity.

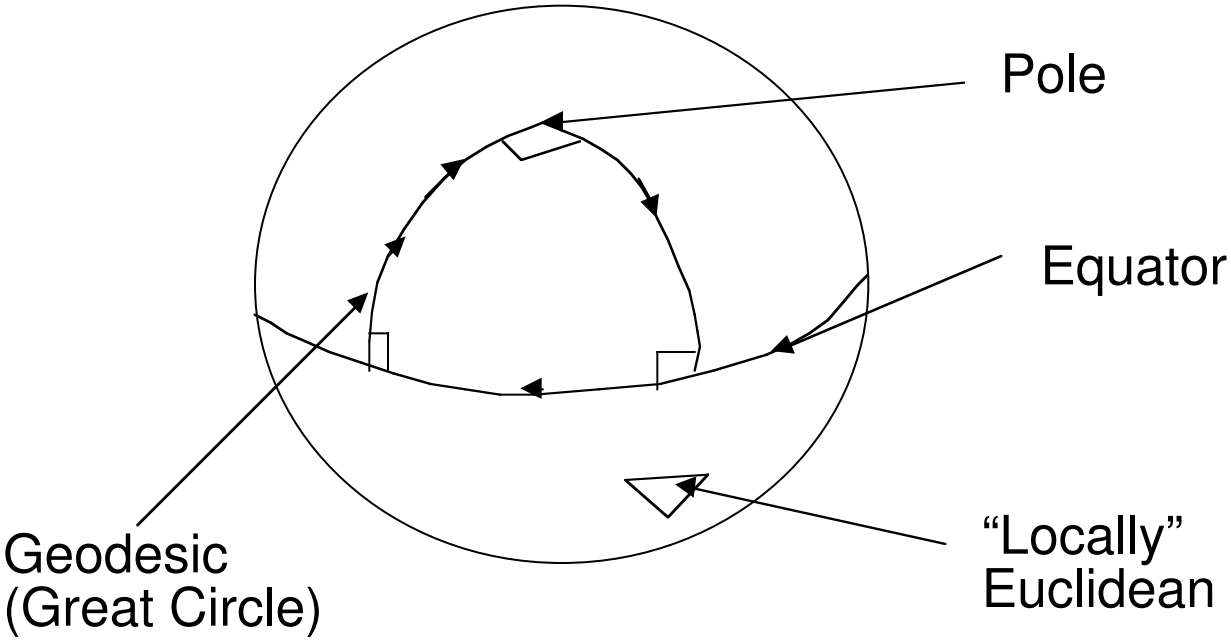
So free-fall frames are only Special Relativity frames over short distances.

Einstein noted similarity to geometry on a curved surface. Ordinary geometry works over small distances on a sphere but not over large distances.

$\Rightarrow$ In absence of gravity, space-time is flat but in presence of gravity space-time is curved!

$\Rightarrow$ Patch together Special Relativity frames to form curved space-time!

Sphere – example of a 2-D curved surface.



Locally → flat space→ Euclidean geometry

Globally → non-Euclidean

→ Equivalent of straight lines are "geodesics" (great circles) → shortest distance between two points but only "locally" straight.

→ No global definition of parallel

→ Angles of triangles made of geodesics may not add to 180 degrees!

In curved space-time, path of particle moving under no force except gravity is a geodesic

Einstein's Gravitational Field Equations.

Still need to know curvature of space-time caused by gravity.

Einstein guessed (for slow moving particles):-

curvature of space-time at $\underline{x}$	=	constant $\times$ ρ

where ρ is the mass density.

Summarising Einstein's view:-

When a planet orbits the Sun, it is trying to move in a straight line through a space-time that has been curved by the Sun's mass.

So maybe gravity is not a force at all but just a manifestation of the curvature of space-time.

Einstein's General Theory of Relativity (1916)

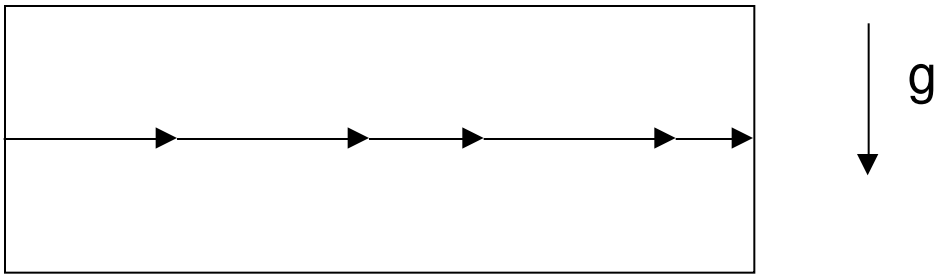
explained small observed deviations in Mercury's orbit, which were unexplained by Newtonian theory.

Also predicted that the path of light passing close to Sun should be bent by space-time curvature.

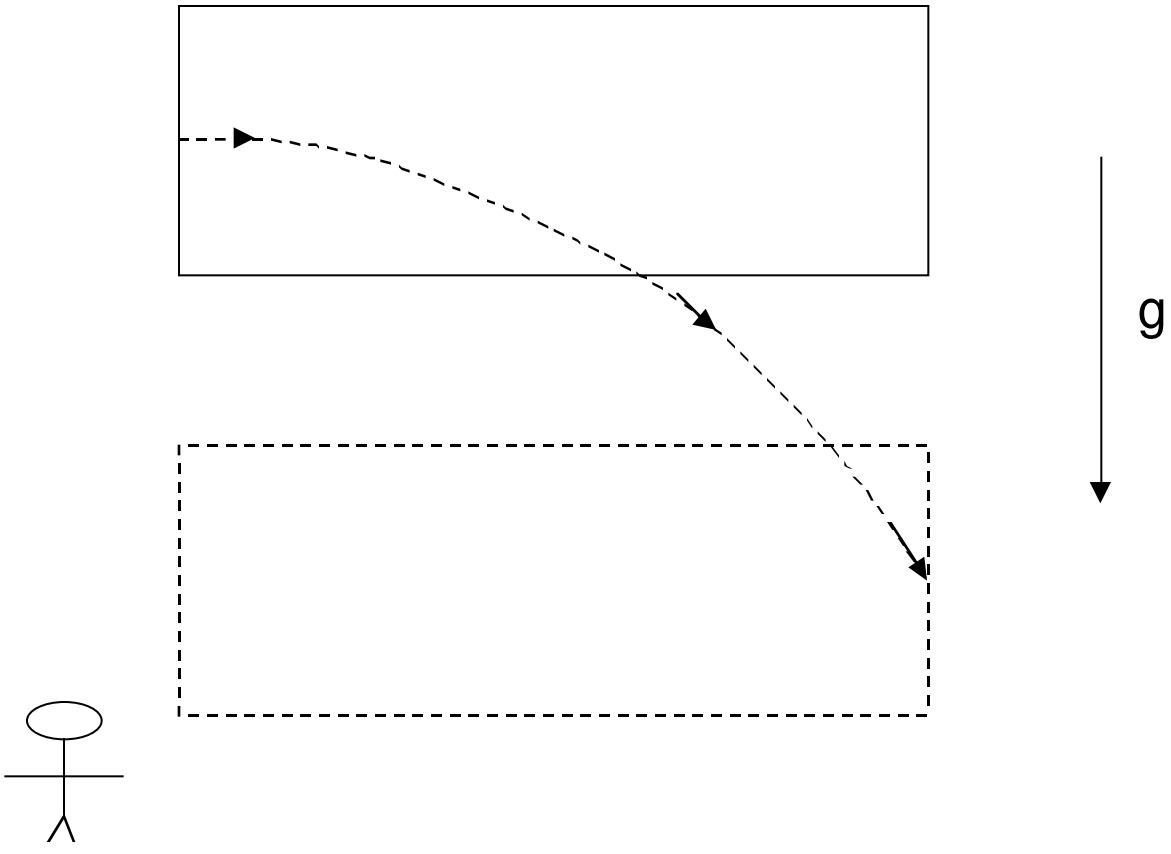
Arthur Eddington observationally confirmed this effect during the Solar Eclipse of 1919.

Gravity Curves the Path of Light.

Freely-falling Observer – sees light travel across a freely-falling lift in a straight line as required by Special Relativity.



External observer at rest on Earth is not in free-fall – hence sees curved path. Looks like Earth's Gravity is attracting light.



Absolute vs Relative.

So does General Relativity tell us whether Newton or Mach was right?

Are measurements made with respect to an absolute space or are they made with respect to the mass frame of distant objects?

Einstein considered himself a follower of Mach but his General Relativity theory lies somewhere between the two.

In GR the mass of the distant Universe tells us where the Special Relativity frames are.

But once in a free-fall frame, the distant Universe is irrelevant to physics ie particle masses are independent of distant mass distribution.

GR Predictions for Cosmology.

Einstein didn't predict expanding Big Bang Universe - discovered by Hubble in 1927.

But General Relativity predicts 2 cases:-

Either present expansion rate is too fast to be slowed down by the mass of the Universe.

Or if expansion rate is slow, the mass density of the Universe may be large enough to stop the expansion and start a contraction.

Critical density the Universe must have today for recollapse is ρ_{crit}. If ρ_0 is the current Universal mass density then if $\Omega_0 = \rho_0/\rho_{crit} > 1$ then Universe will recollapse.

Hubble Space Telescope is checking the expansion rate of the Universe. Much work also done on obtaining mass density, ρ_0.

Current preference is for a Universe whose mass is just enough to start the contraction.

This is the model preferred by Einstein in his later years and which bears his name.