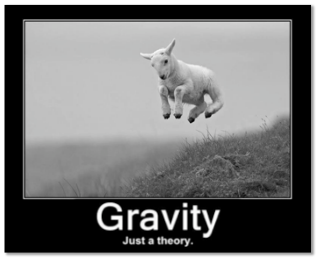
Friday, October 19

Newton vs. Einstein



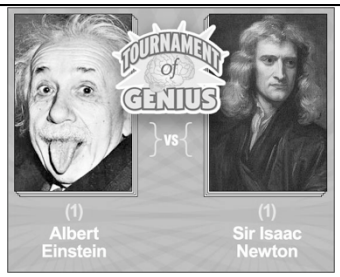
Guest lecturer: Barbara Ryden

Newton vs. Einstein

1) **Newton**: Gravity is a force acting between massive objects in static, Euclidean space.

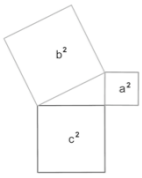
2) **Einstein**: Gravity is the result of the curvature of space-time by the presence of mass-energy.

3) On large scales, space can be Euclidean (flat), positively curved, or negatively curved.



Two very different ways of thinking about gravity and space.

The Way of Newton:

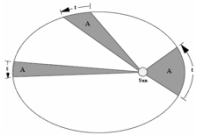


Space is **static** (not expanding or contracting) and **Euclidean**.

(**Euclidean** means that all Euclid's laws of geometry hold true; Euclidean space = "**flat** space".)

"Objects have a natural tendency to move on **straight lines** at **constant speed**."

However, we see planets moving on **curved orbits** at **varying speed.**



How do you explain **that**, Mr. Newton?

"There is a **force** acting on the planets – the force called **gravity**,"

Gravitational force depends on a property that we may call the **gravitational mass**, m_g.

$$F_g = G\frac{m_g M_g}{r^2}$$

Newton's 2nd law of motion gives the acceleration in response to **any** force (not just gravity)!

Acceleration depends on a property that we may call the **inertial mass**, m_i.

$$a = F / m_i$$

If a gravitational force is applied to an object with **gravitational mass** m_g and **inertial mass** m_i, its acceleration is

$$a = \frac{F_g}{m_i} = \frac{GM_g}{r^2} \times \frac{m_g}{m_i}$$

Objects falling side-by-side have the same acceleration (and thus, the same m_g/m_i).

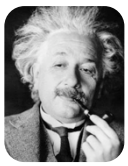
Truly astonishing and fundamental fact of physics:

$$m_g = m_i$$

for every known object!

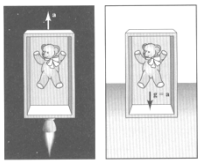
This equality is known as the **equivalence principle**.

The equivalence principle led Einstein to devise his theory of **General Relativity**.



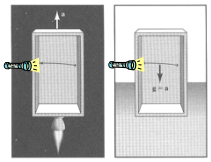
Let's do a thought experiment (*gedankenexperiment*), of the kind beloved by Einstein.

Two ways of thinking about a teddy bear:

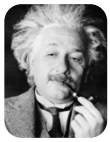


1) Bear has constant velocity,
box is accelerated upward by rocket.
2) Box has constant velocity,
bear is accelerated downward by gravity.

Two ways of thinking about **light**:



1) Light has constant velocity,
box is accelerated upward by rocket.
2) Box has constant velocity,
light is accelerated downward by gravity.



Einstein's insight:

Gravity affects the paths of photons,
even though they have no mass!

Mass and energy are interchangeable:
$E = mc^2$

Newton

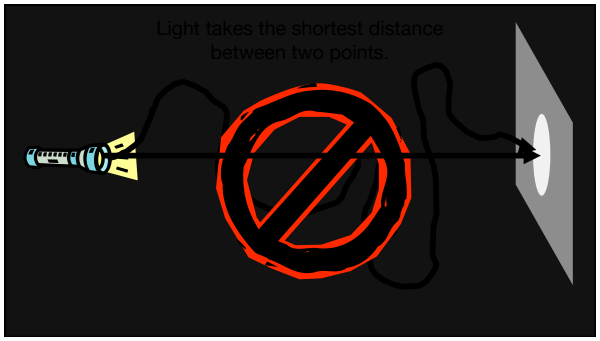
Mass & energy are very different things.

Space & time are very different things.

Einstein

Mass & energy are interchangeable:
$E = mc^2$

Space & time are interchangeable:
part of 4-dimensional space-time.



Light takes the shortest distance
between two points.

In flat space, the shortest distance
between two points is a straight line.

In the presence of gravity,
light follows a curved line.

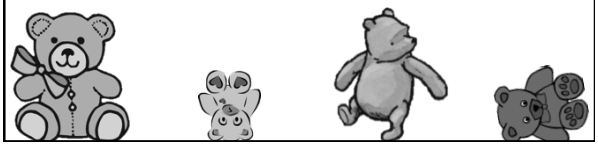
**In the presence of gravity,
space is not flat, but curved!**

A **third** way of thinking about a bear:

3) No forces are acting on the bear;
it's merely following the shortest distance
between two points in space-time.

Our new way of thinking about the teddy bear
naturally explains the equivalence principle.

All bears (and other objects!), regardless of size or mass,
are taking the shortest path through space-time.



The Way of Newton:

Mass tells gravity how much force to exert;
force tells mass how to move.

The Way of Einstein:

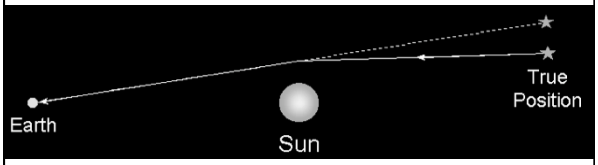
Mass-energy tells space-time how to curve;
curved space-time tells mass-energy how to move.

Einstein's view of gravity is
mathematically complicated.

However, it works better than Newton's when
gravity is strong (near massive objects).

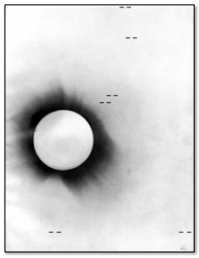
Example: Einstein's theory correctly predicts
the effect known as "gravitational lensing".

Einstein: Mass & energy cause space to curve.
This curvature causes an **observed** bending of the path of light.



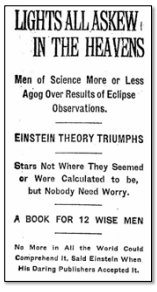
This effect is called **gravitational lensing**.

Gravitational lensing by the Sun:



Total solar eclipse,
May 29, 1919
(photographic negative)

New York Times,
Nov 10, 1919



LIGHTS ALL ASKEW IN THE HEAVENS

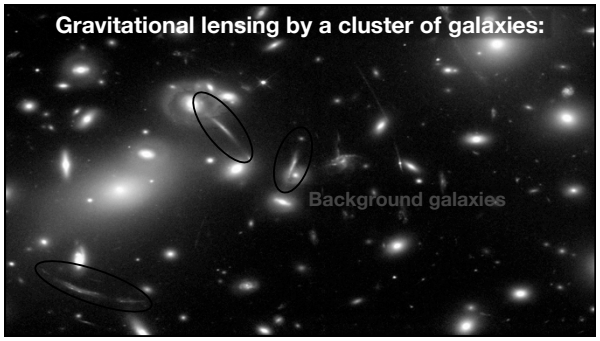
Men of Science More or Less Agog Over Results of Eclipse Observations.

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.



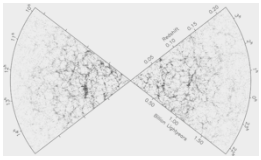
The Big Question:

Locally, space is "dimpled" by stars, planets, etc…

…but what is its **global** curvature on large scales?

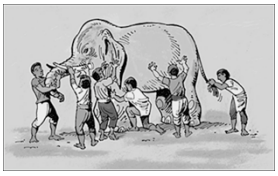
The Cosmological Principle:

On large scales (bigger than clusters of galaxies) the universe is homogeneous and isotropic.



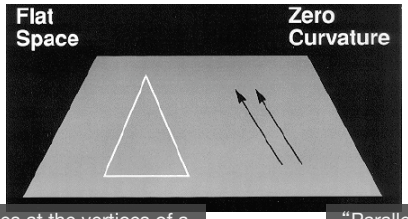
homogeneous = the same at all locations
isotropic = the same in all directions

Einstein: **If** the distribution of mass-energy is homogeneous & isotropic, **then** the curvature of space is homogeneous & isotropic.



There are only **3** ways in which space can have homogeneous, isotropic curvature.

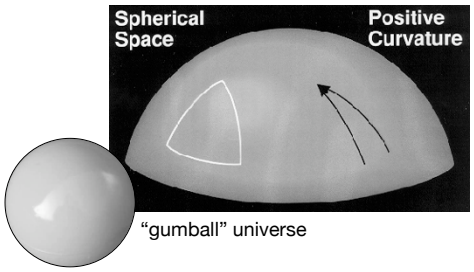
This two-dimensional space is Euclidean, or **flat**:



"Angles at the vertices of a triangle add to 180 degrees."

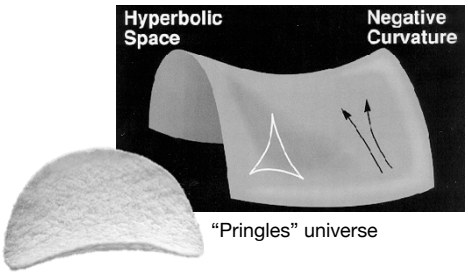
"Parallel lines never meet."

This two-dimensional space has **positive** curvature:

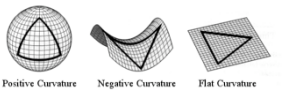


"gumball" universe

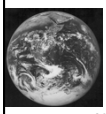
This two-dimensional space has **negative** curvature:



"Pringles" universe

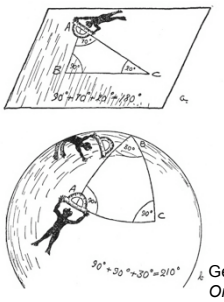


If space has positive curvature, it has a finite volume, but no boundary.



(Analogy: the Earth's surface has positive curvature. It has a finite area, but no edge.)

If space has negative curvature or is flat, it has an infinite volume, unless a boundary is imposed.



Measuring the curvature of space is easy… in principle.

Flat: angles of triangle add to 180°

Positive: angles add to **>180°**

Negative: angles add to **<180°**

George Gamow, *One Two Three Infinity*

In practice, curvature is hard to see on scales smaller than the radius of curvature.

We're going to need a bigger triangle…