Time in general relativity, cosmology, and beyond

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Introduction to Philosophy of Physics

The relevance of GR

GR will have consequences for

1. the debate between substantivalism and relationism,
2. the metaphysics of time and persistence,
3. (and other philosophical and foundational debates).

From SR to GR

It turns out that SR is limited in one important respect: it offers an account of difference between accelerated and inertial motion, and how this new kinematics can be built into Maxwell's electrodynamics, but only in the absence of gravity!

Two reasons why SR is not compatible with Newton's theory of gravity

1. Newton's theory is incompatible with the relativity of simultaneity and the fusion of space and time.
    - Newton's law of universal gravitation depends on the spatial distance between two bodies, but spatial distances depends on inertial frames in SR.
2. Newton's gravitational force acts instantaneously even between bodies a great distance apart, but SR posits finite propagation speed of any signal, including gravitation.

"The happiest thought of my life"

Einstein about this event of November 1907: "I was sitting in a chair in the patent office at Bern, when all of a sudden a thought occurred to me: 'if a person falls freely, he will not feel his own weight'."

⇒ You only feel a force in a gravitational field if something prevents you from following the trajectory of free fall...

- Einstein's realization: this lets you extend the principle of relativity

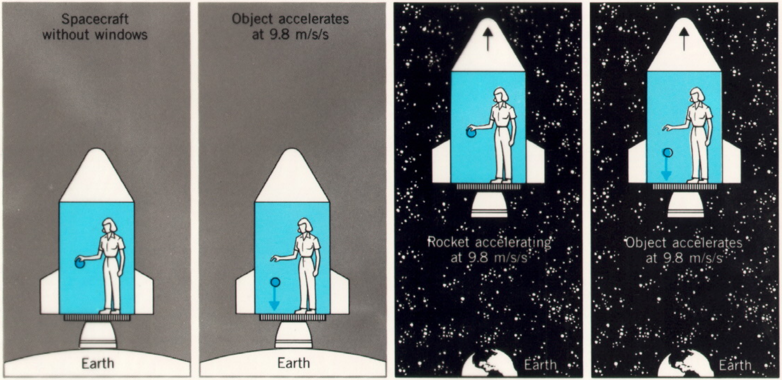
Principle (Principle of Equivalence (roughly))

"The laws of physics take the same form in frames that are freely falling in gravitational fields as they do in inertial frames." (Dainton, 286)

Principle (Weak Equivalence Principle (WEP, 'universality of free fall'))

The inertial mass of a body is proportional to its (passive) gravitational mass.

The rocket thought experiment



The principle of equivalence.

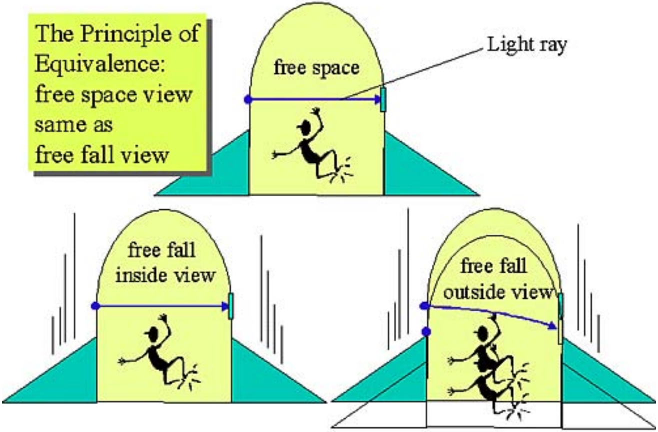
Principle (Strong Equivalence Principle (SEP))

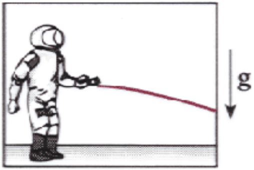
(i) An experiment carried out in 'free fall' in a uniform gravitational field will have the same outcome when carried out 'at rest' in an inertial laboratory in empty space. (ii) An experiment carried out 'at rest' in a uniform gravitational field will have the same outcome as if carried out in a uniformly accelerated laboratory in empty space. (cf. Maudlin, 135)

- SEP is stronger than WEP since it applies to all trajectories, including of light

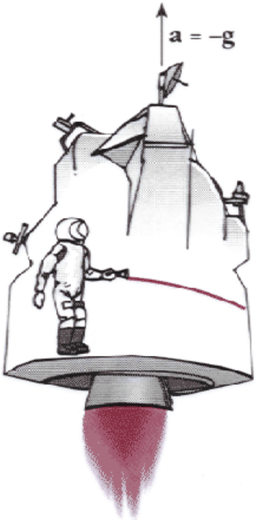
Prediction of the Principle of Equivalence:

Light should be affected by gravity





Laboratory in gravitational field



Accelerated laboratory

Principle (Einstein Equivalence Principle (EEP))

Effects due to inertia and effects due to gravity are manifestations of the same structure. This structure is called the inertio-gravitational field. Depending on the kinematical state of an observer, the inertio-gravitational field may be split into inertial and gravitational components differently.

- As result of WEP, gravity can be thought of as an aspect of spacetime which affects all bodies equally and thus has something to do with the structure of spacetime rather than a force acting on them.
- The SEP extends to light or indeed anything, and thus generalizes the conclusion from WEP.
- Similarly, the EEP suggests that there is one field ($g_{\mu\nu}$) which is responsible for both inertial and gravitational phenomena.

$\Rightarrow$ Gravity can be interpreted as the curvature of the spacetime geometry, and not as a force at all.

Spacetime curvature

- In Minkowski spacetime: the trajectories of light rays are paths of shortest possible distance, viz. zero

⇒ If gravity affects paths of light, and if paths of light are shortest distances, then it is not huge leap to say that gravity affects structure of spacetime itself.

Some consequences

Barry Dainton (2001). *Time and Space*. McGill-Queen's University Press.

1. "Gravity is nothing but the warping of space and time. Material bodies do not exert a gravitational pull on one another, rather material bodies warp space and time, and these warpings produce effects we associate with gravity—the effects Newton explained in terms of an attractive force" (Dainton, 288)
2. "Matter-induced curvature is transmitted through spacetime at the speed of light, not instantaneously." (ibid.)

A few more remarks

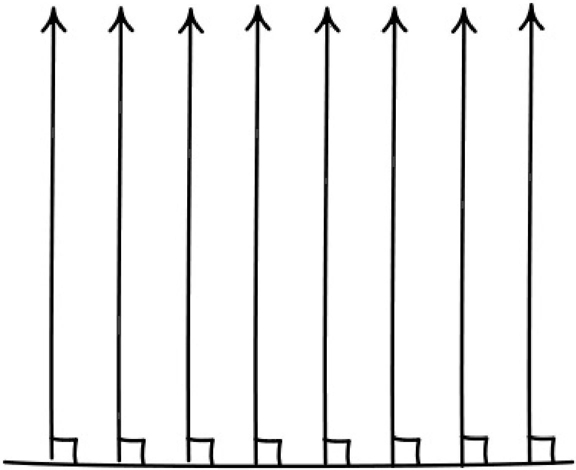
- geometry of spacetime is dynamic rather than static: changes as material objects move through spacetime
- In a curved spacetime, the equivalent of straight lines in Euclidean space are geodesics (= paths of shortest length).
- Mass affects the shape of geodesics, e.g. swing-by of spacecraft by massive planets

$\Rightarrow$ There is no force pulling us down on Earth, rather we feel pushed up.

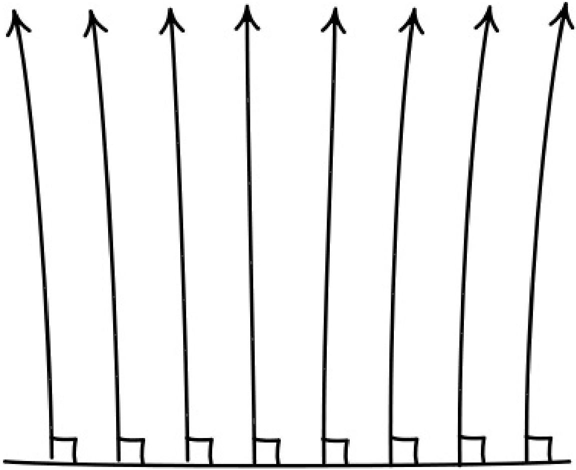
- Deviations from straight lines are due to the non-Euclidean nature of geometry, not to a universal force such as gravity.

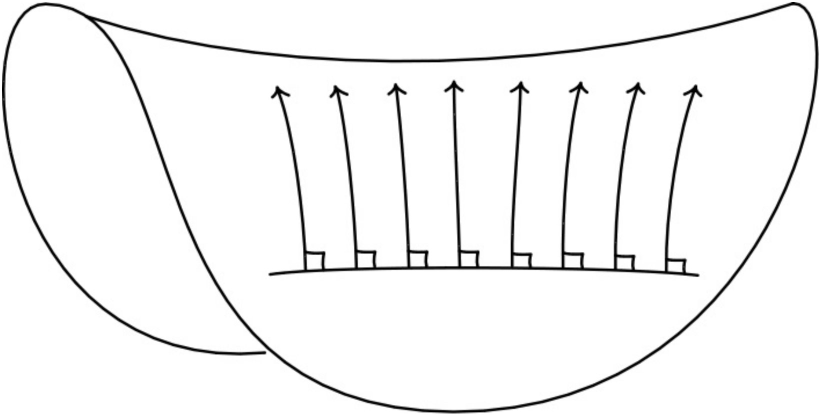
How geometry replaces force

Deviation in flat spacetime:

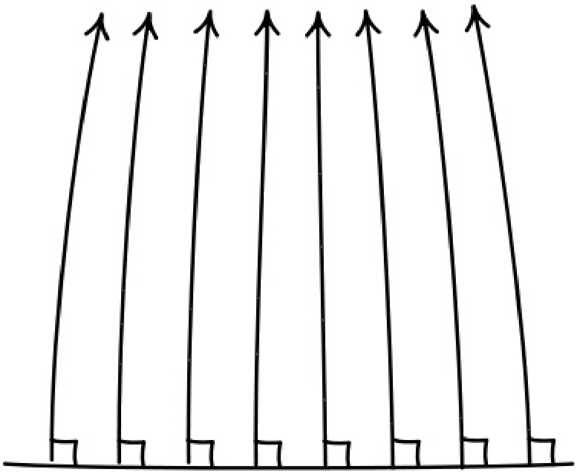


Deviation in negatively curved region of spacetime:





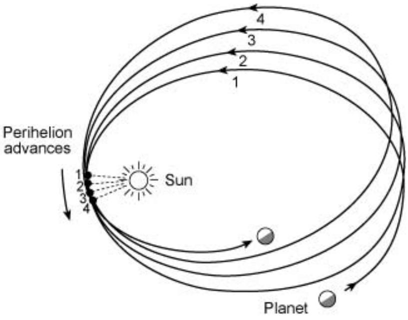
Deviation in positively curved region of spacetime:



Measurable consequences of GR

- precession of perihelion of Mercury (and other planets)
- deflection of light by the sun and other massive bodies
- slow down of clock in gravitational potential: the deeper the potential, the slower the clock
- cosmological predictions on structure and history of universe $\Rightarrow$ relativistic cosmology
- 'singularities': big bang (indirect evidence), black holes (observed)
- expansion of universe (observed), gravitational lensing (observed), gravitational waves (observed)

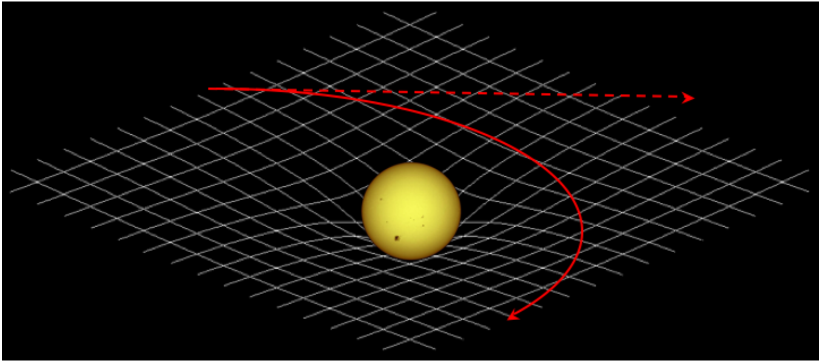
The precession of Mercury's perihelion



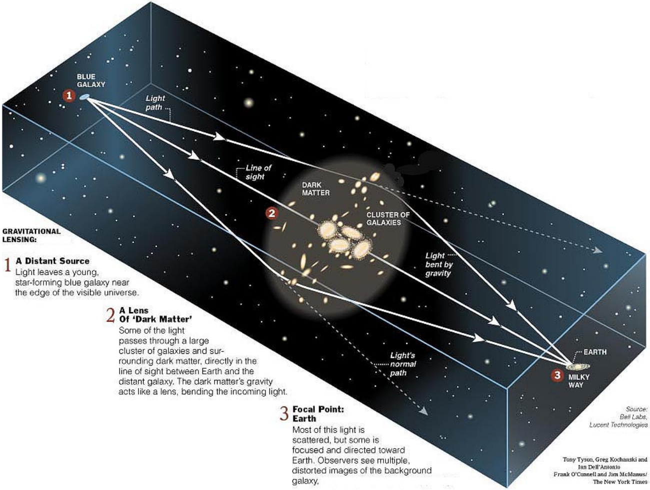
- Newton's theory could not (fully) account for precession of Mercury's perihelion
- Einstein correctly derived the precession from his field equations in 1916 ("I was beside myself with ecstasy for days")

Deflection of light around sun

Deflection of light from star passing by close to Sun by 1.75 arc-secs

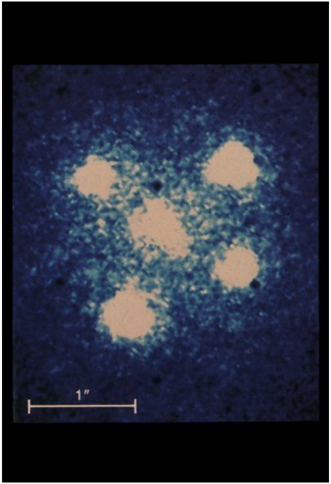


Gravitational lensing



Einstein's Cross (pulsar in northern constellation of Pegasus):

An observation of gravitational lensing



Relativistic cosmology

1. global ('cosmological') vs. local solutions to Einstein field equation

Principle (Cosmological)

Both the spacetime structure and the matter distribution are spatially isotropic about us.

- The cosmological principle is reasonably well confirmed by the distribution of the cosmic microwave background radiation and the large-scale distribution of luminous matter in galaxies.

From basic principles to FLRW spacetimes

Principle (Copernican)

We are not privileged observers.

- The Copernican principle is a (plausible, but unconfirmed) assumption.
- Together, the two principles imply that all observers see a spatially isotropic universe.
- This, in turn, implies that the universe is spatially homogenous. We thus arrive at the

Principle (Strong cosmological principle)

On large spatial scales, our universe is homogeneous and isotropic, i.e. homogeneity and isotropy are spatial symmetries of any spacetime that is a cosmological solution to the Einstein field equation.

Friedmann-Lemaître-Robertson-Walker (FLRW) spacetimes

It can be shown that the FLRW spacetimes are the only spatially isotropic and homogeneous spacetimes in GR:

- Cosmological principle ⇒ space will have constant curvature (negative, zero, positive)
- contributions by Aleksandr Friedmann, Georges Lemaître, Howard Percy Robertson, Arthur Geoffrey Walker, found exact solutions to Einstein field equation

⇒ Friedmann-Lemaître-Robertson-Walker spacetimes

- These models are spatially homogeneous and isotropic, simply-connected, open or closed.
- They are non-static: expanding or contracting universe

⇒ big bang model of cosmology

FLRW spacetimes

- In these spacetimes, there is a natural foliation into spatial slices totally ordered by a 'cosmic time', because there is only one way in which FLRW spacetimes can be foliated to have constant spatial curvature.
- The cosmic time is the time measured by observers at rest with respect to the matter content (and so their worldlines are orthogonal to the spatial folia).

FLRW spacetimes

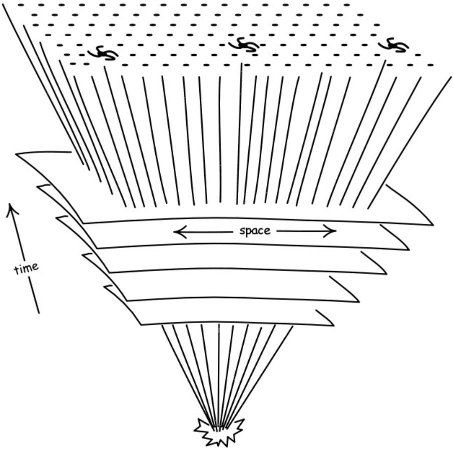


Abbildung: An expanding FLRW spacetime (Image: Norton, Einstein for Everyone)

FLRW spacetimes

- Since the spatial folia have constant curvature, there are exactly three possibilities for their geometry (if they are simply-connected):
  1. positive: spherical geometry
  2. zero: Euclidean, flat geometry
  3. negative: hyperbolic geometry

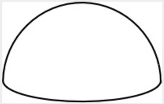
Cosmology	I	II	III
Average mass density	Greater than critical	Critical	Less than critical
Geometry of space	Spherical positive curvature 	Flat, Euclidean zero curvature 	Hyperbolic negative curvature 
Dynamics	Expands and collapses to big crunch	Expands indefinitely	Expands indefinitely

Abbildung: Three spatial geometries (Image: Norton, Einstein for Everyone)

FLRW spacetimes

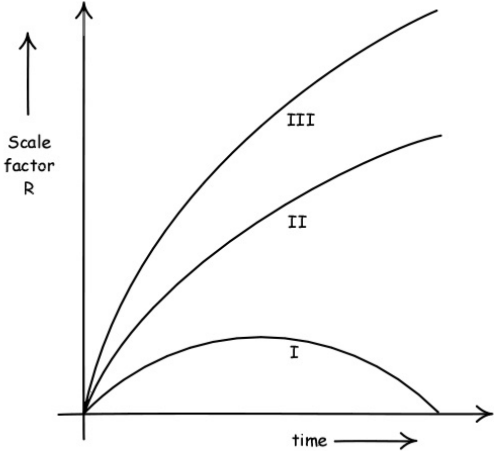


Abbildung: The scale factor in the three spatial geometries **(Image: Norton, Einstein for Everyone)**

Our visible universe

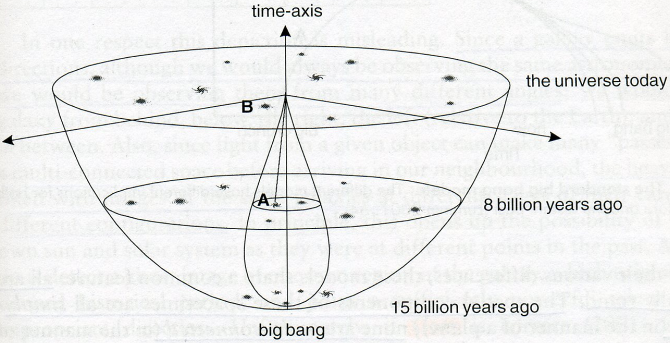


Figure 18.6 The visible universe. The "teardrop" shape shows the region of the expanding universe that is visible from present day Earth (located at the intersection of the two spatial axes). Light emitted by objects outside this region has not had time to reach us yet. Light from galaxy A has taken 8 billion years to reach us, so we see it as it was 8 billion years ago. Galaxy B will not be visible from Earth for another 8 billion years or so.

Three basic features of the standard model

C Smeenk and G Ellis (2017). Philosophy of cosmology. In E. Zalta (ed.), ***Stanford Encyclopedia of Philosophy***. https://plato.stanford.edu/entries/cosmology/

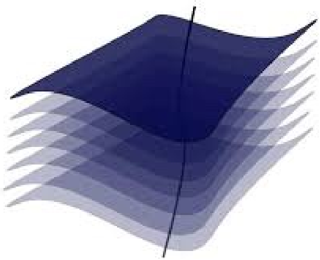
1. The universe is dynamical, i.e., changes over time, with seven discernible epochs: quantum gravity, inflation, big bang nucleosynthesis, decoupling, dark ages, structure formation, dark energy domination
2. The expansion rate varies over time and depends on which type of matter dominates.
3. Models with ordinary matter have a singularity at a finite time in the past ('big bang')

Time in GR

- As we will see when we discuss time travel, physical spacetime in GR can have an unusual topology. [Blackboard]
- But these spacetimes just have an unusual topology—there is no curvature.
- In many ways, curvature is more characteristic of general-relativistic spacetimes—particularly locally.
- It is the local curvature, which determines the lightcone structure.
- Example: Misner spacetime [blackboard]

Foliation

- foliation: carving up a 4-dimensional spacetime into 3-dimensional 'spatial' slices totally ordered by a 'time' parameter



- Not all general-relativistic spacetime afford a foliation.

Time in SR and in GR: comparison

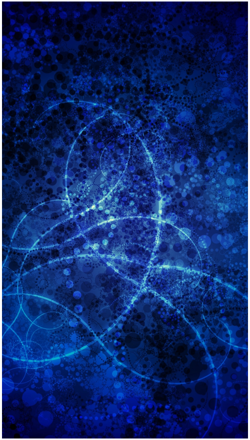
- SR: Minkowski spacetime can be foliated, though the foliations are highly non-unique
- GR: some general-relativistic spacetimes cannot be foliated into subsequent 'nows'; in those spacetimes, there seems to be no hope to define a global 'flow' of time
- However, some foliable GR spacetimes naturally privilege one foliation over all others (e.g., by resulting in time slices of constant curvature).
- Either way, a global sequence of 'nows' becomes a contingent matter, depending on contingent facts about the distribution of matter, or on the grounds of privileging one foliation over others.

Time beyond GR

Now that GR is ever more confirmed, what would force us to abandon it as a fundamental theory of gravity?

- More specifically, do we need to replace GR with a quantum theory of gravity?

Quantum gravity



http://www.viralnovelty.net/

- Why do we need a quantum theory of gravity?

⇒ We need a theory to combine (classical or quantum) gravity with quantum matter.

- Problem: there are no empirical constraints (other than known/old physics)
- Approaches: string theory, loop quantum gravity, causal set theory, and many others

A generic prediction of fundamental quantum theories of gravity

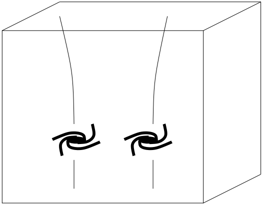
Huggett, Nick and Wüthrich, Christian. Emergent spacetime and empirical (in)coherence. *Studies in the History and Philosophy of Modern Physics* 44 (2013): 276-285.

- Now, many approaches to formulating a quantum theory of gravity (including causal set theory and LQG) either presuppose or entail that fundamentally, there is neither space nor time—although that denial comes in degrees, and differs from approach to approach.
- In the language of physics: spacetime theories such as GR as 'effective' and spacetime itself 'emergent', much like thermodynamics is an effective theory and temperature is emergent, as it is built up from the collective behaviour of gas molecules.

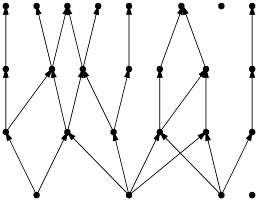
Beyond Spacetime, `beyondspacetime.net`

General project by Nick Huggett and CW on the 'emergence' of spacetime from less-than-fully spatiotemporal degrees of freedom.

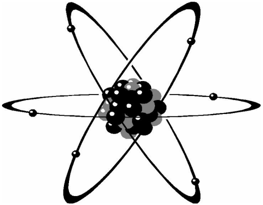
The non-fundamentality of spacetime

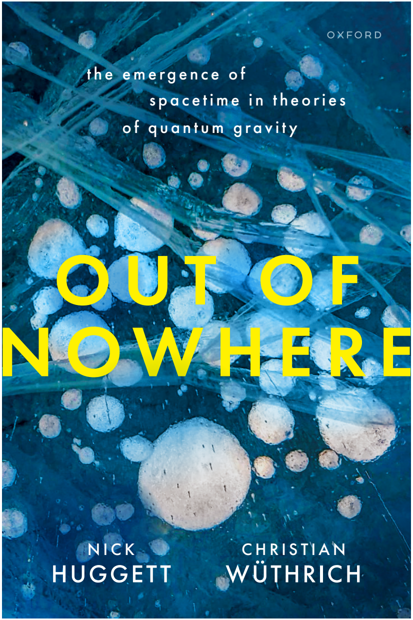


emergent



fundamental




OXFORD
the emergence of
spacetime in theories
of quantum gravity
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