Spacetime

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Plan

1. What is space (and time)?
   - Introduction: on the nature of space (and time)
   - The classic debate: relationalism and substantivalism
   - Newton's bucket thought experiment
2. Special relativity
   - Einstein's reasoning and the basis of special relativity
   - Relativity of simultaneity
   - Relativity of simultaneity geometrically constructed
3. General relativity
   - From equivalence to spacetime curvature
   - Spacetime curvature
   - Evidence and Consequences

What is space?

What is the nature of (physical) space?

Huggett (2010, 89f)

> *Is [space] nothing more than the spatial properties of tangible things? [...] [O]nly the right conception of motion—and hence of space—will make sense of the laws [(and so of related issues such as that of determinism)]. It was precisely the issue of coming up with the right conception that motivated Descartes and Newton (and others) to investigate the notions of space and motion: they were attempting to explicate the concept used in their theories of motion. [This furnishes a prime example of] how apparently philosophical considerations were central to the founding of a new science.*

Nick Huggett (2010). *Everywhere and Everywhen: Adventures in Physics and Philosophy*. New York: Oxford University Press.

Do space and time exist?

- Do space and time have independent existence from objects they 'contain' (their 'occupants')?
- inaccessible by direct observation
- But this in itself doesn't imply that they do not exist: neutrinos and force fields are not directly observable either, but many believe they exist

What is the structure of space and time?

- Is space finite or infinite in extension? How many dimensions does it have? Is it Euclidean? Isotropic? Continuous or discrete?
- Is time finite or infinite? Does it have a beginning or an end? Is it one-dimensional? Linear or branching? Anisotropic, i.e. directed? Continuous or discrete?
- Are there different kinds of spaces or times?
- Are space and time affected by the presence and distribution of material bodies?

Why does time, but not space, have a direction?

- Time seems to have inherent directedness from the past towards the future, but space has no analogous feature
- directedness of time vs. directedness of anything in time
- 'flow' of time, 'passing' of time
- temporal passage: what is future will become present; what is present will become past; what is past was once present
- Is temporal passage objective feature of reality?

What is space?

Three conceptions of space:

1. space = matter (Plato, Descartes, which we will not discuss)
2. relational space (Leibniz, Mach)
3. absolute space (Newton)

Space: the classical debate

Relational space

Gottfried Leibniz (1646-1716)

- Second response to 'space-body' problem:

Position (Relationalism)

Space and time do not exist as independent substances, there is only the material content of the universe. Space and time are merely defined through spatiotemporal relations among the material objects in the universe (and their parts). Space is thus a (constructed) relational complex of relative positions of material objects, identifying fixed places relative to 'stationary' reference objects.

- Analogy: family tree

$\Rightarrow$ 'relational' account of space, 'relation(al)ism'

- Leibniz $\neq$ Descartes (e.g., for Leibniz, the vacuum is conceptually possible: there are places relative to reference objects that could be occupied but in fact are not)

$\Rightarrow$ modal aspect of relationalism

Absolute space (and time)

Isaac Newton (1643-1727)

Newton, Scholium in *Principia* (1687, as translated by Andrew Motte)

> *Absolute, true, and mathematical time, of itself, and from its own nature flows equably without regard to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time...*
>
> *Absolute space, in its own nature, without regard to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies; and which is vulgarly taken for immovable space... Absolute and relative space, are the same in figure and magnitude; but they do not remain always numerically the same.*

Absolute space (and time)

Position (Substantivalism)

Space and time exist as independent substances, i.e. they are existing particulars in their own right, over and above the material content of the universe. Space and time are continuous and pervasive media that extend everywhere and everywhen.

- Space is furthermore assumed to be infinite, infinitely divisible, homogeneous, self-similar, Euclidean in its geometry.
- There can obviously be a void, a 'vacuum'.
- Space and time are media, which penetrate all objects, cannot be acted upon, and involve primitive relations of spatial or spatiotemporal 'being located at' between material objects and places in space(time).

Leibniz's objections to substantivalism: different kinds of shifts

1. static shift: shift location of all material bodies uniformly in one direction without changing the relative distances and motions among them
2. kinematic shift: change the state of motion of all material bodies such that all relative distances and motions among them remain the same (and so the bodies are not accelerated)
3. dynamic shift: subject all material bodies in universe to a force such that they are all accelerated by the same amount in the same direction without changing the relative distances or motions among them

Galilean frames

- Galilean frames: reference frame that are either at rest, or moving uniformly with respect to one another
- uniform motion: rectilinear motion at constant velocity
- with Newtonian absolute space: any Galilean frame is in some state of absolute motion which is uniform
- consider e.g. Newton's law of universal gravitation:

$$F_G = G_N \frac{m_1 m_2}{r^2}$$

  $\Rightarrow$ makes no reference to absolute position, velocity
- turns out all Newtonian physics is like that

$\Rightarrow$ undetectability of both static and kinematic shifts

The argument from indiscernability

Principle (of the Identity of Indiscernibles (PII))

Any two entities which have the same genuine properties are identical.

1. Substantivalists claim that the two possible worlds either related to one another by a static or kinematic shift as described above are distinct. (Premise to be reduced to absurdity)
2. Two possible worlds related by such shifts share all their genuine properties, i.e. they are 'indiscernible'.
3. PII
4. From (2) and (3), these possible worlds are identical.

∴ From (1) and (4), substantivalism is false.

Objections to the argument from indiscernability

- PII itself is highly controversial: Max Black's two indiscernible spheres in an otherwise empty universe
- If indiscernability is understood metaphysically, i.e. as not only applying to observable properties, then substantivalists will hardly accept premise (2).
- But this response will not work for empiricist substantivalists, i.e. under the assumption that only properties differences in which are in principle detectable are in fact genuine.

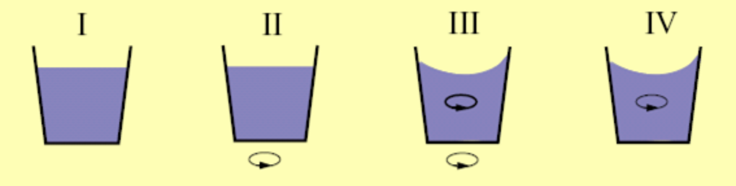
Question

Does absolute space have any observable consequences?

- Science routinely posits unobservable entities, thereby assuming scientific realism with respect to unobservable entities
- but: must have observable effects
- Unsurprisingly, Newton argues that it does, while Leibniz denies this...

⇒ in the famous Scholium to the Definitions of his *Principia*, Newton illustrates how absolute accelerations have observable effects with one particular type of absolute acceleration: rotation...

Newton's bucket thought experiment



	I	II	III	IV
Bucket	at rest	rotates	rotates	at rest
Water	at rest	at rest	rotates	rotates
Relative motion	no	yes	no	yes
Surface	flat	flat	concave	concave

⇒ Surface form of water (flat or concave) is not determined by relative motion, but...

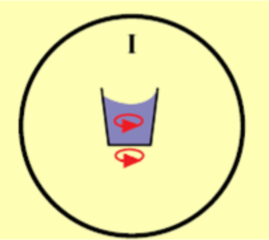
- Newton: by absolute motion of water (relative to absolute space)

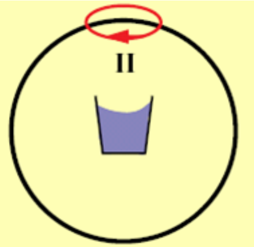
Ernst Mach's interpretation of Newton's bucket

Mach's idea:

The surface of water is concave because of the motion of the bucket and the water relative to the shell of distant masses.

⇒ equivalence of the following two situations: (1) bucket and water rotate, but the shell of distant masses rests, (2) bucket and water at rest, shell rotates.

(1) 

(2) 

Newton: surface in (2) remains flat!

The bucket: discussion

- Initially, relationalism did not seem to have the resources to describe the physics adequately.
- Although Mach gives new hope to the relationalist (though perhaps not to the Cartesian), his explanation has a significant weakness: by what mechanism or force would the distribution of distant stars or galaxies give rise to a 'standard rotation' on Earth such that the surface of the water would turn concave?

Taking stock

- Newton was (partially) successful in establishing explanatory necessity of absolute acceleration (bucket experiment),
- but he also needed absolute velocity (change of which is absolute acceleration), which has no detectable consequences.
- As the French mathematician Henri Cartan has shown in the 1920s and 1930s, it is possible to reformulate Newtonian mechanics without recourse to absolute velocities.
- Still, there are unobservable absolute positions.

Albert Einstein (1879-1955)

- German-born Swiss-American physicist
- Annus mirabilis 1905
- special and general relativity, photoelectric effect, contributions to statistical mechanics, quantum theory, early advocate of atomic theory
- 1921 Nobel Prize in Physics ‘for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect’
- Einstein-Hilbert action, Bose-Einstein statistics, Einstein field equation, Einstein-Poincaré synchronisation, Einstein notation, Einstein tensor, Einstein-Podolsky-Rosen paradox, Einstein refrigerator

Albert Einstein's famous 1905 article

Albert Einstein. On the electrodynamics of moving bodies. *Annalen der Physik* 17 (1905): 891-921.

Einstein (1905, 891)

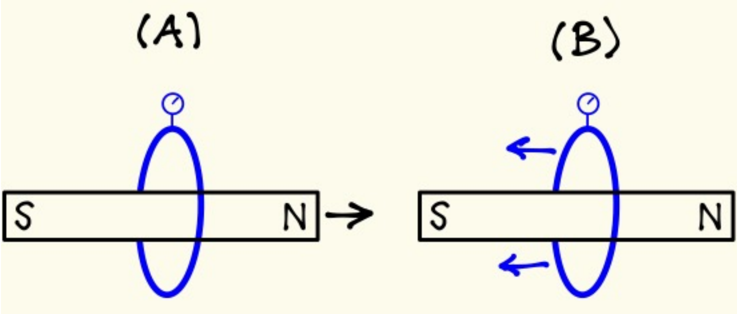
It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion...

Einstein's comparison: magnet and conductor

Maxwell's theory of electrodynamics has two implications:

1. An (absolutely) moving magnetic field induces an electric field (e.g., in a conductor at rest).
2. An electric field is induced in an absolutely moving conductor in a magnetic field.

Einstein's comparison: magnet and conductor



	(A)	(B)
magnet is moving (absolutely)	yes	no
conductor is moving (absolutely)	no	yes
relative motion	yes	yes
induced e-field by (1)	yes	no
induced e-field by (2)	no	yes
measurable current resulting	yes	yes

Einstein's comparison: magnet and conductor

- In fact, the measured current is exactly the same—the two situations (A) and (B) are observationally indistinguishable.

⇒ In other words, only a relative motion of magnet and conductor leads to observational differences.

Introducing the Principle of Relativity

Einstein (1905, 891)

> *Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the 'light medium', suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good...*

Introducing the Light Postulate

Einstein (1905, 891f)

We will raise this conjecture (the purport of which will hereafter be called the 'Principle of Relativity') to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a 'luminiferous aether' will prove to be superfluous inasmuch as the view here to be developed will not require an 'absolutely stationary space'...

The Postulates of Special Relativity (SR)

Michel Janssen (2014). Appendix: Special relativity. In Michel Janssen and Christoph Lehner, *The Cambridge Companion to Einstein*. Cambridge: Cambridge University Press, 455-506.

Postulate (Relativity Principle)

"The same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good [= inertial frames]." (Einstein 1905, 891)

Postulate (Light Postulate)

"Light propagates through empty space with a definite velocity which is independent of the state of motion of the emitting body." (ibid)

Postulate (Isotropy and homogeneity)

(Space and time are isotropic and homogeneous.)

Apparent contradiction between the postulates

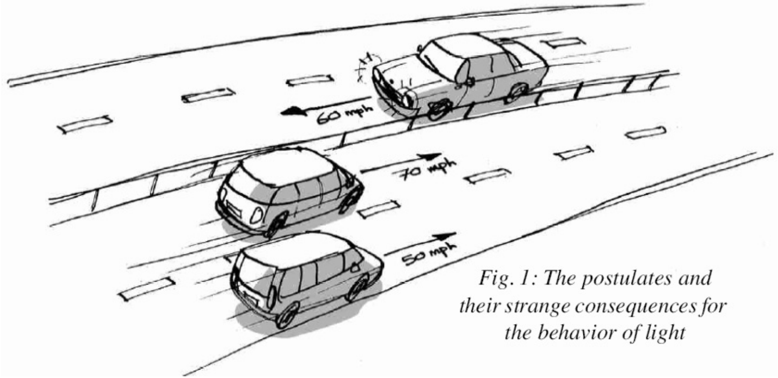


Fig. 1: The postulates and their strange consequences for the behavior of light

How fast is the oncoming vehicle for the two SUVs?

Intuitively: $60 + 70 = 130$mph and $60 + 50 = 110$mph, respectively.

Addition of velocities

- Question: what's the velocity of light emitted by the headlight of the oncoming car for the two SUVs?
- Assume a wave theory of light $\Rightarrow$ velocity of light with respect to the medium is always c, independently of the speed of the source
- Intuitive answer: c + 70mph and c + 50mph, respectively
- But the contradiction between the postulates is only apparent!

$\Rightarrow$ We must revise our intuitions of space and time.

- Most fundamental revision: relativity of simultaneity

$\Rightarrow$ 'at the same place' and 'at the same time' become observer-dependent.

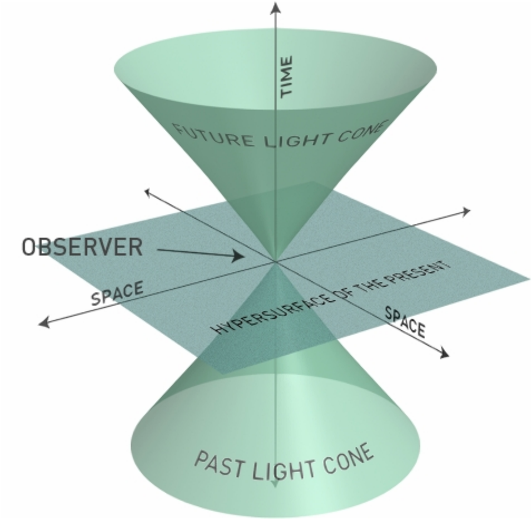
- But we are getting ahead of ourselves...

Two consequences of the postulates

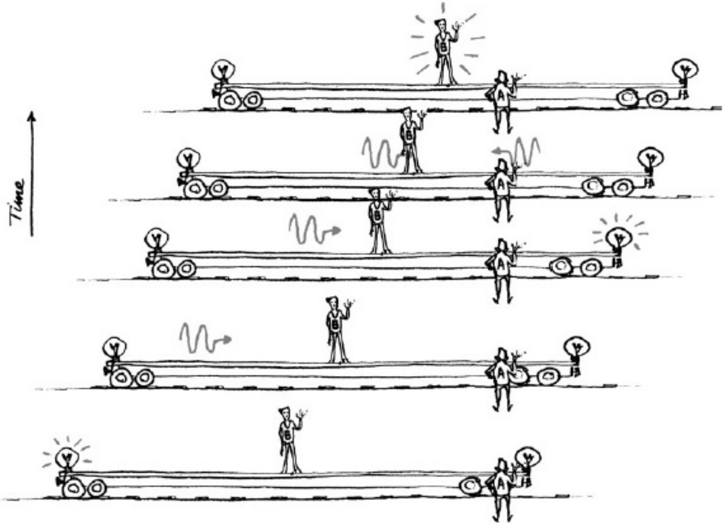
1. The velocity of light must be unaffected by the state of motion of its source $\Rightarrow$ structure which determines light trajectories must be built into spacetime
2. The velocity of light must be independent of the inertial frame of reference in which c is measured.

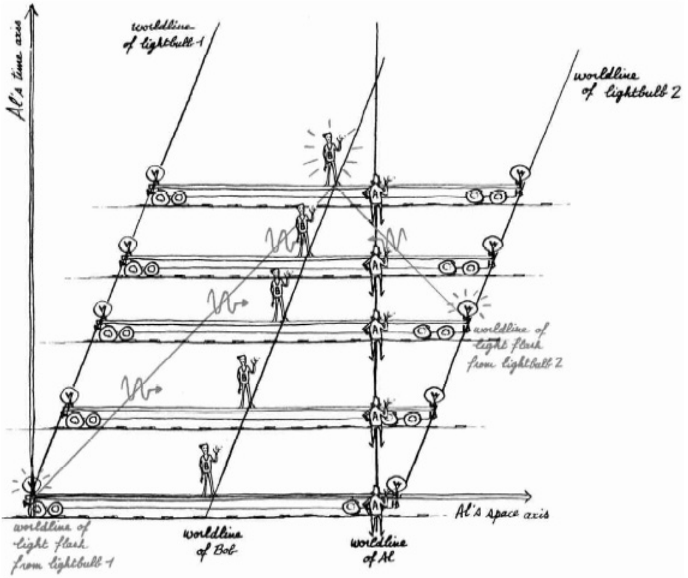
But note that this is not at all in accordance with what we intuitively think is the usual behaviour of moving bodies or projectiles...

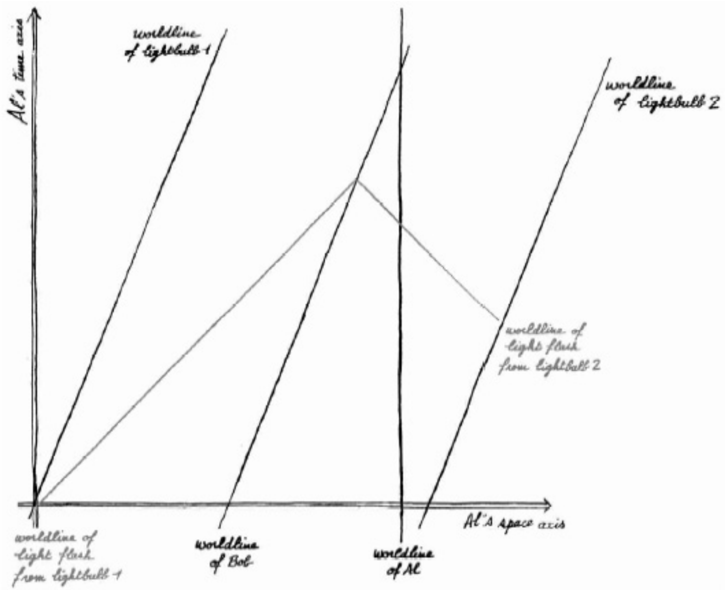
The light cone structure

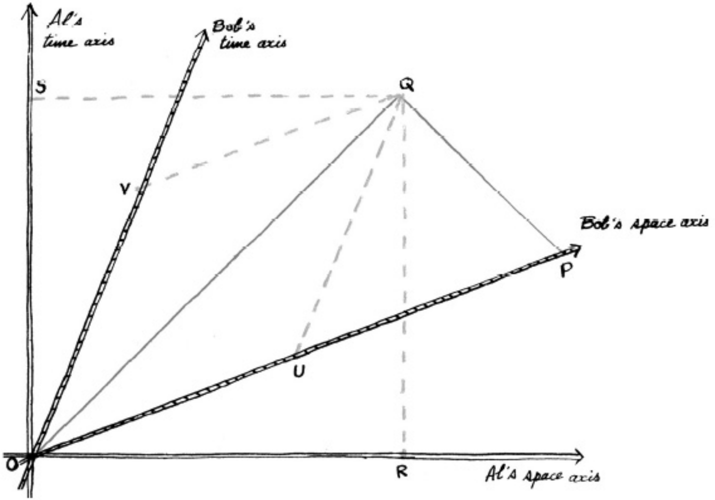


Relativity of simultaneity geometrically constructed




Al's time axis
worldline of lightbulb 1
worldline of lightbulb 2
worldline of light flash from lightbulb 2
Al's space axis
worldline of light flash from lightbulb 1
worldline of Bob
worldline of Al


Al's time axis
worldline of lightbulb 1
worldline of lightbulb 2
worldline of light flash from lightbulb 2
Al's space axis
worldline of light flash from lightbulb 1
worldline of Bob
worldline of Al


Al's time axis
Bob's time axis
S
Q
V
Bob's space axis
P
U
O
R
Al's space axis

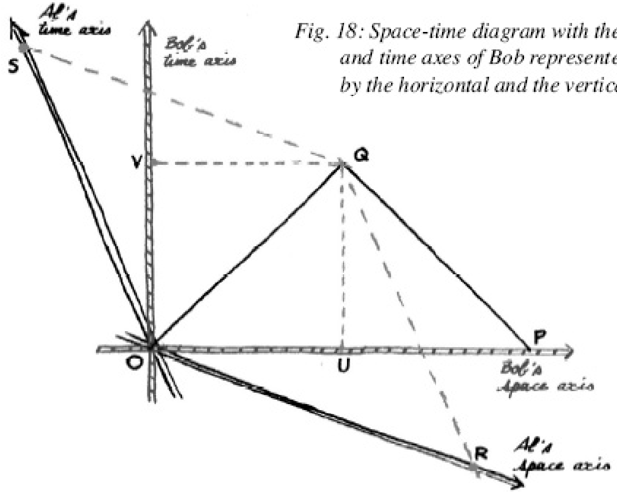


Fig. 18: Space-time diagram with the space and time axes of Bob represented by the horizontal and the vertical

Relativity of simultaneity again

- geometry of Minkowski spacetime $\Rightarrow$ The parsing of the spatio-temporal separation between events into spatial and temporal components highly non-unique.
- This has profound implications for the metaphysics of time: the time order between events depends on frame of reference and is not objectively given.

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'."

$\Rightarrow$ 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

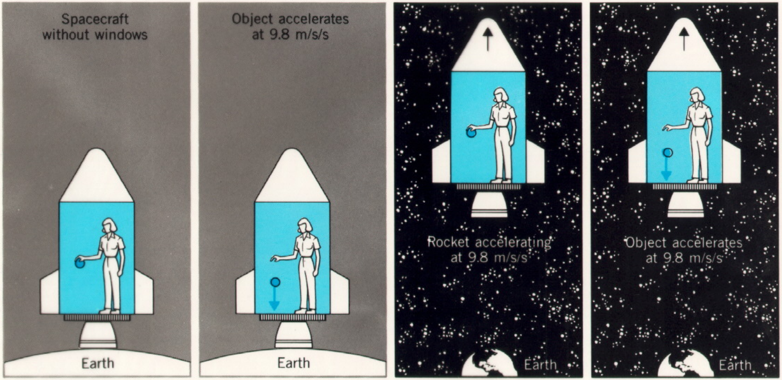
Principle (Principle of Equivalence (roughly))

"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.

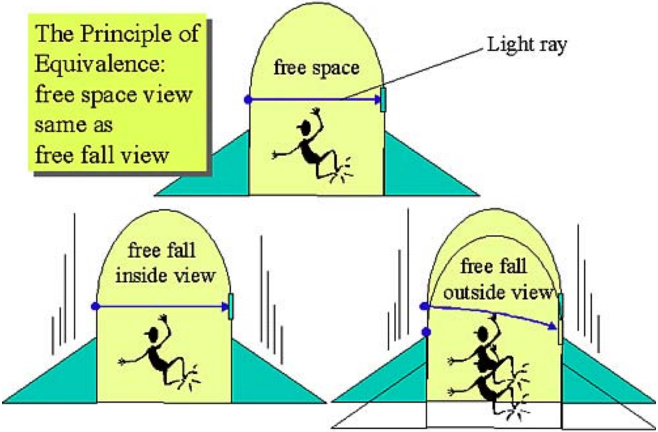
Principle (Strong Equivalence Principle (SEP))

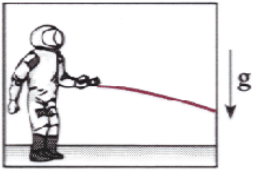
(i) An experiment carried out in 'free fall' in a uniform gravitational field will have the same outcome when carried out 'at rest' in an inertial laboratory in empty space. (ii) An experiment carried out 'at rest' in a uniform gravitational field will have the same outcome as if carried out in a uniformly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

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

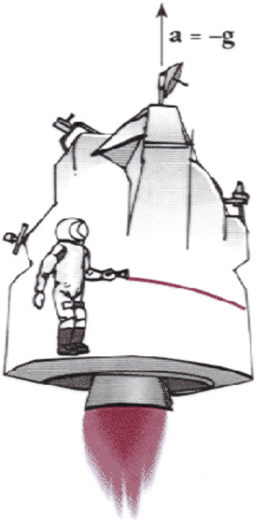
Prediction of the Principle of Equivalence:

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 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 as 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

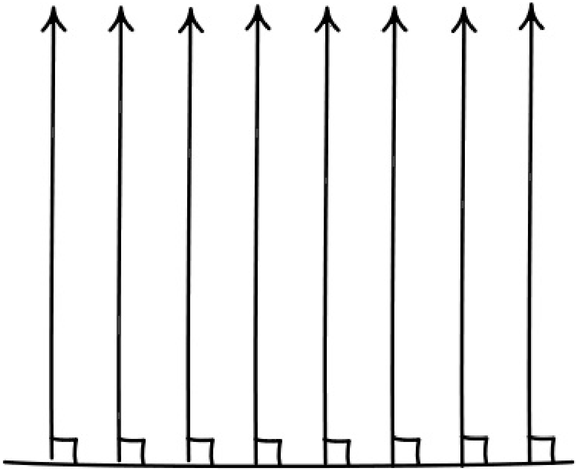
- geometry of spacetime is dynamic rather than static: changes as material objects move through spacetime
- In a curved spacetime, the equivalent of straight lines in Euclidean space are geodesics (= paths of shortest length).
- Mass affects the shape of geodesics.

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

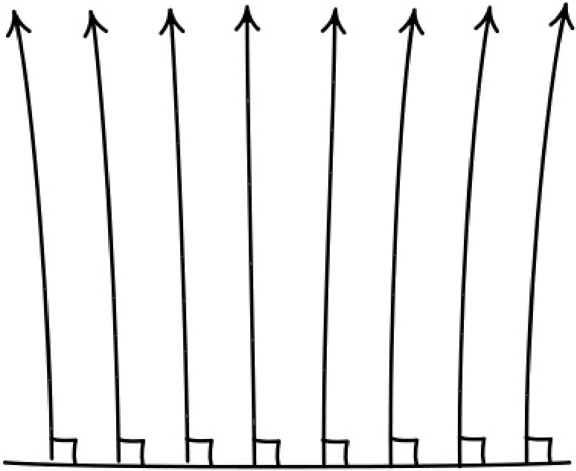
- Deviations from straight lines are due to the non-Euclidean nature of geometry, not to a universal force such as gravity.

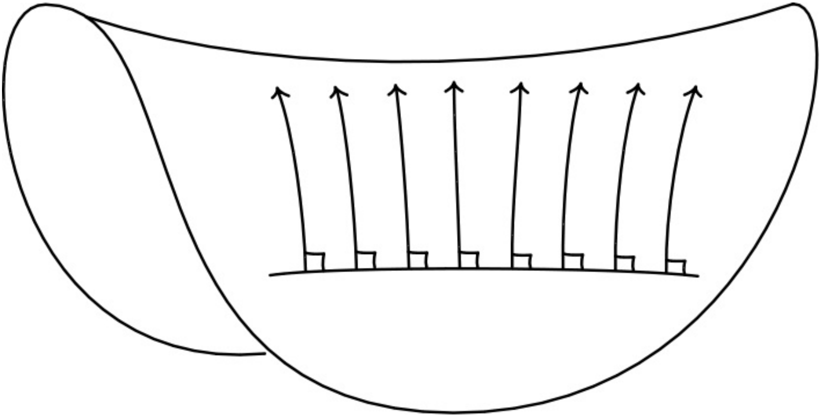
How geometry replaces force

Deviation in flat spacetime:

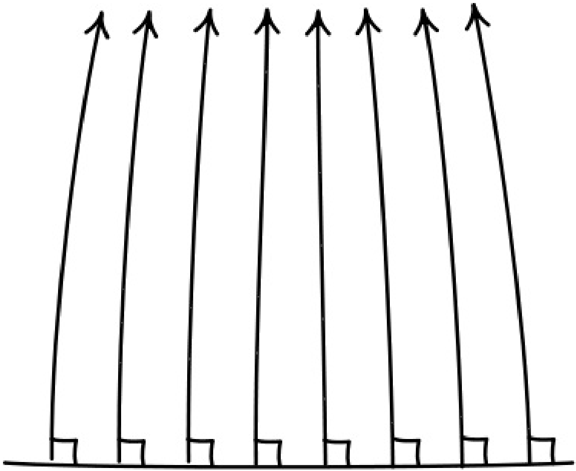


Deviation in negatively curved region of spacetime:





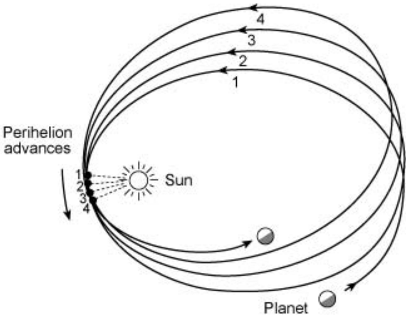
Deviation in positively curved region of spacetime:



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)

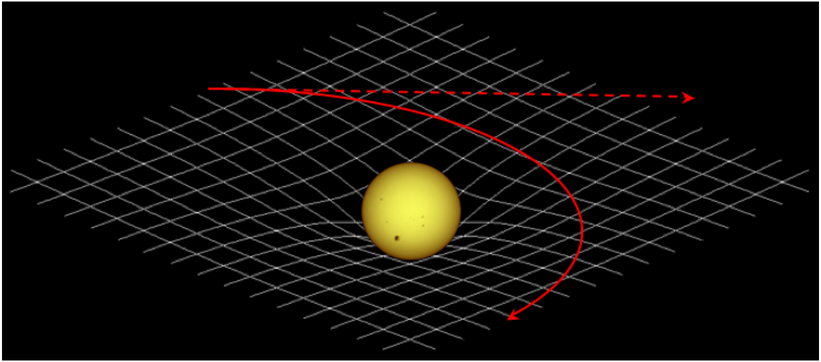
The precession of Mercury's perihelion



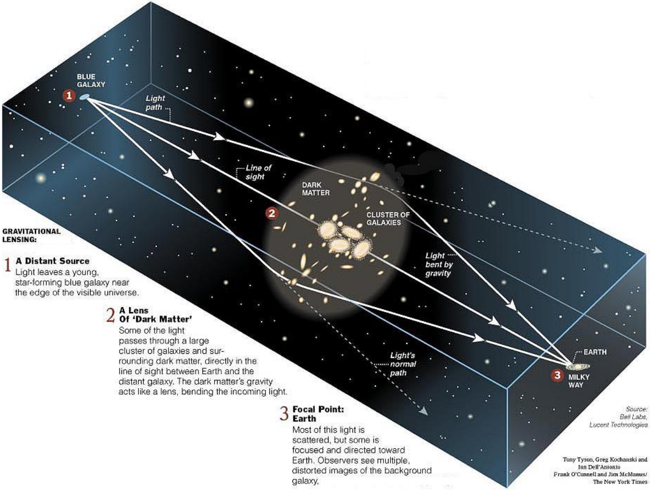
- Newton's theory could not (fully) account for precession of Mercury's perihelion
- Einstein correctly derived the precession from his field equations in 1916 ("I was beside myself with ecstasy for days")

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