Space, time, and spacetime, part I: from Newton's bucket to Einstein's hole

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Organization of talk

1. Philosophy of space from Newton to Mach
   - The classical debate: substantivalism and relationalism
   - Leibniz's shifts and Newton's bucket
2. Philosophy of spacetime: Minkowski and Einstein
   - Classical spacetime: General relativity
   - The hole argument

St Augustin (354-430), Bishop of Hippo

"What, then, is time? If no one asks me, I know what it is. If I wish to explain it to him who asks me, I do not know. (*Confessions*, 11.xiv.17)

Do space and time exist?

- Do space and time have independent existence from objects they “contain”?
- inaccessible by direct observation
- this in itself doesn’t imply that they don’t exist: neutrinos and force fields are not directly observable either, but many believe they exist
- Philosophy of space(-time): substantivalism vs relationism
- There are of course also questions regarding their structure:
  - 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?

Space: the classical debate

Substantivalism vs. Relationalism

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.

Position (Relationism)

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.

Sir Isaac Newton (1643-1727)

- English physicist, mathematician, astronomer, natural philosopher, theologian, and alchemist
- education at Trinity College, Cambridge
- Lucasian Professor of Mathematics in 1669 at Cambridge
- *Principia Mathematica* (published in 1687)
- synthesis of mechanical results by Galileo, Kepler, etc

Newton: infinite absolute space

"Space is eternal in duration and immutable in nature... Although space may be empty of body, nevertheless it is itself not a void: and *something* is there, because spaces are there, although nothing more than that." (*De Gravitatione*, as quoted by Dainton, 133)

"Absolute space, in its own nature, without relation to anything external, remains always similar and immovable." (*Principia*, as quoted by Huggett, 118)

Barry Dainton, *Time and Space*, McGill-Queen's, 2001.
Nick Huggett, *Space from Zeno to Einstein*, MIT Press, 1999.

Gottfried Wilhelm Leibniz (1646-1716)

- German polymath (mathematician, natural philosopher, legal scholar, theologian, political advisor, historian)
- rationalism: reason as ultimate arbiter of justification of knowledge
- optimism: God created the best of all possible worlds
- calculus, binary numeral system, etc
- Leibniz-Clarke correspondence (1715-16)

Relationism: a closer look

- sustantivalism inserts an unobservable and redundant intermediary bw objects

$\Rightarrow$ most economical way: objects are directly related to one another via spatial relations (which are not material objects, but relational properties of material objects)

$\Rightarrow$ space is constituted by complex relational structure of material objects and their parts and the spatial relations in which all these stand to one another

- relationism not cost-free: there must be spatial relations *over and above* the material objects that exist

The problem of empty space

- empty space: relationism is committed to non-existence of unoccupied places and regions, whereas substantivalist account entails possibility of empty places

$\Rightarrow$ How can we meaningfully speak of mid-point between Earth and Mars?

- Relationist response: since objects can change in their spatial relations, we can give map/representation that reflects these possibilities $\Rightarrow$ modal aspect of position
- at any given time, only objects and their actual distance relations exist, all remaining points on map do not correspond to anything real
- relations operate across, rather than through space, i.e. they relate objects directly, without passing through intervening empty space (whose reality is denied)

Positive arguments for relationism: 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
3. dynamic shift: subject all material bodies in universe to 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 and inertial motion

- 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 (but we'll get back to dynamic shifts shortly)

The argument from indiscernability

Principle (of the Identity of Indiscernibles (PII))

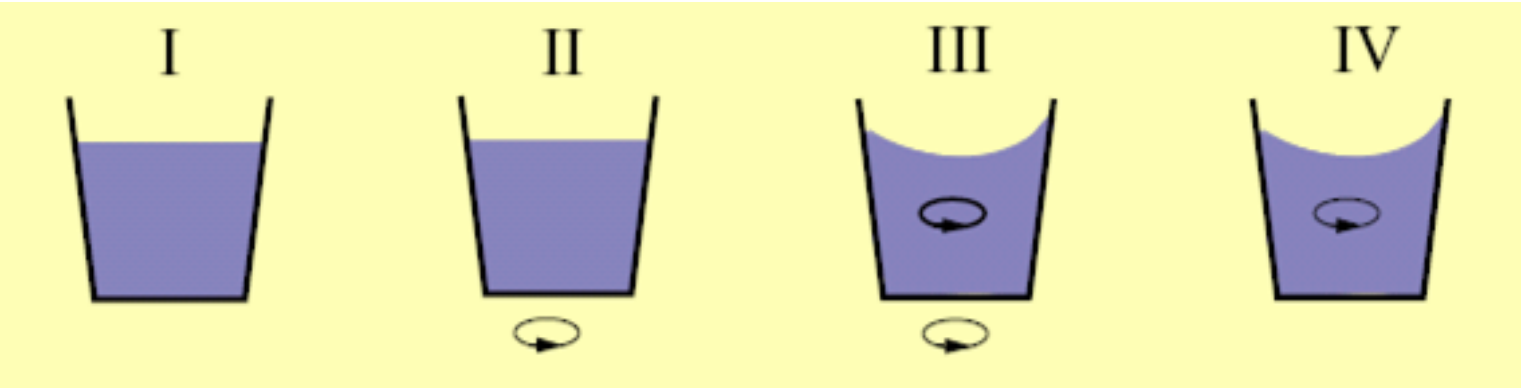
Any two entities which have the same genuine properties are identical.

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.

$\therefore$ From (1) and (4), substantivalism is false.

- There are philosophical objection to PII, so a substantivalist may not need to accept this argument. But Newton does accept it, but turns the table using dynamic shifts...

A substantivalist argument from inertial effects: Newton's bucket



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

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

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

John Earman's reconstruction of the bucket

Abductive inference schema:

(1) p
(2) q is the best explanation of p

∴ q

Reconstruction of bucket experiment:

(1) There are mechanical phenomena such as the bucket experiment.
(2) Absolute acceleration (and absolute rotation in particular) is the best explanation for these phenomena.

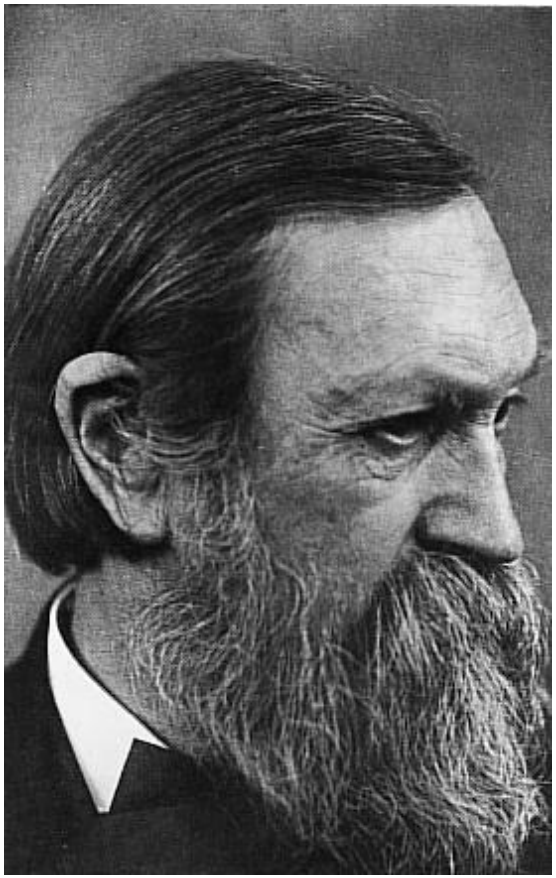
(3) There is absolute acceleration. (from 1 and 2)
(4) Absolute acceleration must be understood as acceleration relative to absolute space.

∴ Absolute space exists.

Ernst Mach (1838-1916)

- Austrian physicist and philosopher
- contributions to optics, acoustics, aerodynamics, hydrodynamics
- Mach number, Mach's Principle
- arch empiricist
- dominating influence on Vienna circle and logical positivism

Mach's Principle (according to Einstein)



"The [metric] field is *completely* determined by the masses of the bodies [in the universe]. Since mass and energy are equivalent according to special relativity and the energy is formally described by the symmetric energy tensor ($T_{\mu\nu}$), this means that the [metric] field is caused and determined by the energy tensor." (My translation)

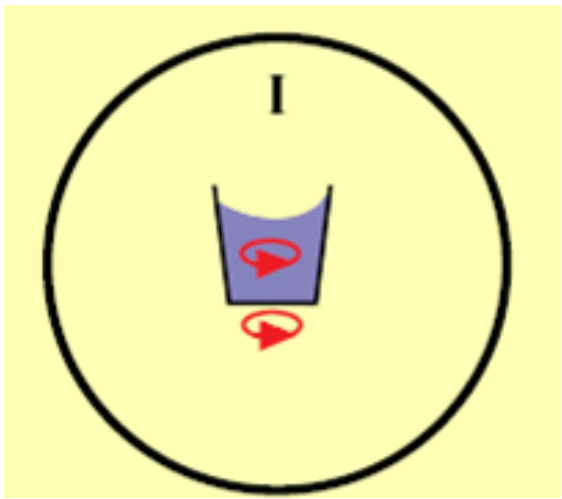
Albert Einstein, "Prinzipielles zur allgemeinen Relativitätstheorie", *Annalen der Physik* **55** (1918): 241f

Mach's interpretation of Newton's bucket

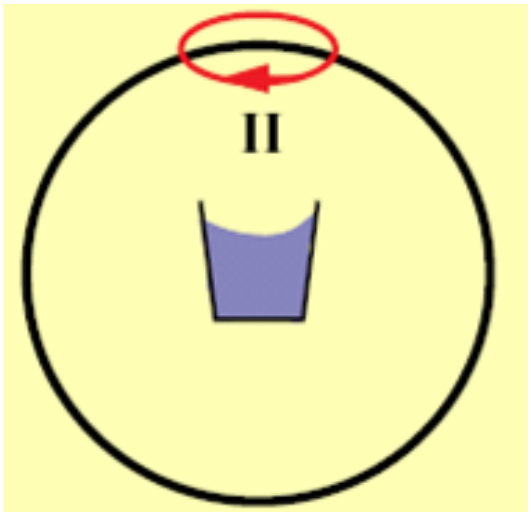
Surface of water concave bc of motion of bucket and water relative to shell of distant masses

$\Rightarrow$ 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 fusion of space and time: Minkowski spacetime

Hermann Minkowski (1864-1909)

Assembly of German Natural Scientists and Physicians in Köln in 1908: “The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.”

Hermann Minkowski, “Raum und Zeit”, *Jahresberichte der Deutschen Mathematiker-Vereinigung* (1908/9): 75-88.

The debate in general relativity

Question

How does the debate transpose into the currently best physical theory of space and time—General Relativity (GR)?

General relativity in one slide

John Wheeler's gloss on the heart of GR

John A Wheeler (1911-2008)

- Einstein's field equations: spacetime geometry $\Leftrightarrow$ distribution of mass and energy
- In Wheeler's slogan, in GR, mass grips spacetime, telling it how to curve, and spacetime grips mass, telling it how to move.

$\Rightarrow$ GR: gravity as curvature of spacetime

What is classical spacetime?

Semantically, classical general relativity (GR) can be considered a set of triples $\langle \mathcal{M}, g_{ab}, T_{ab} \rangle$ ("models"), which satisfy the so-called Einstein equations (and perhaps other local conditions).

$\mathcal{M}$: four-dimensional manifold (of certain kind), serves as "canvass" for physical fields

g_{ab}: metric; contains information about spatiotemporal relations among elements of $\mathcal{M}$

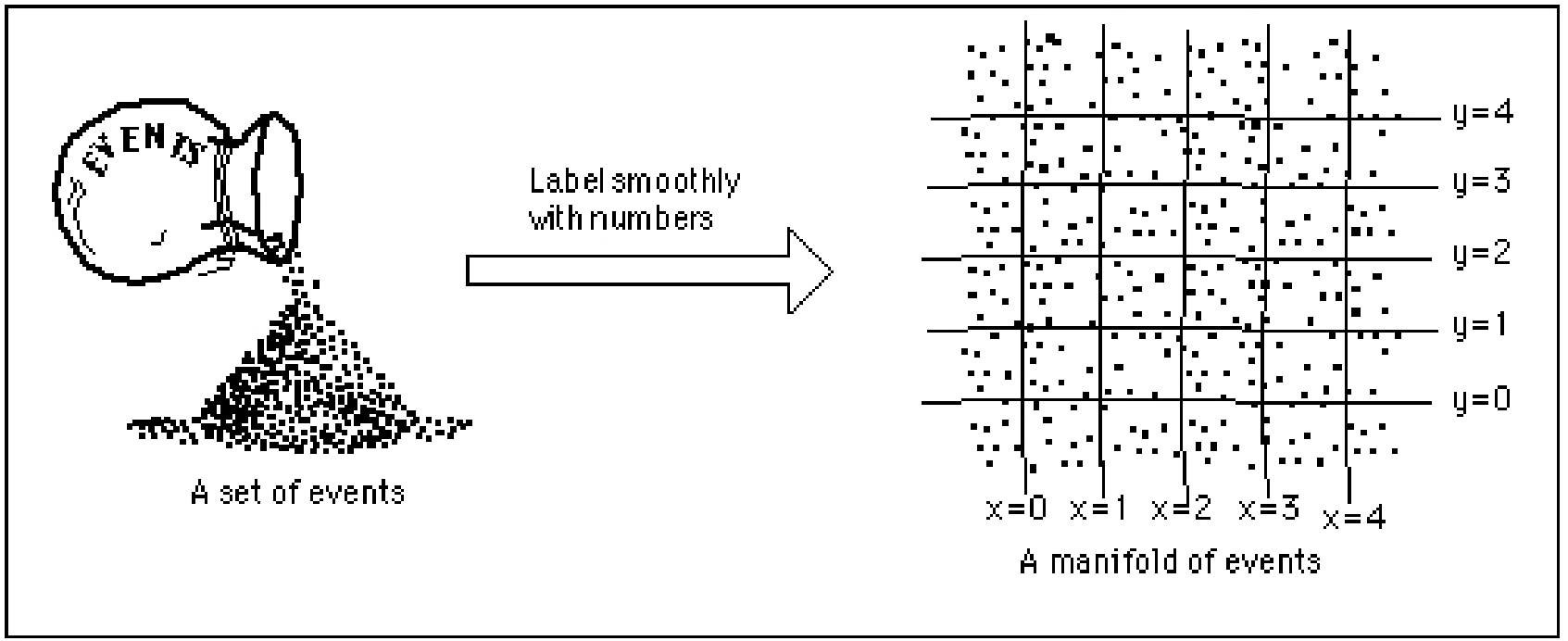
T_{ab}: mass-energy density; describes distribution of (energy and) matter in universe

Question

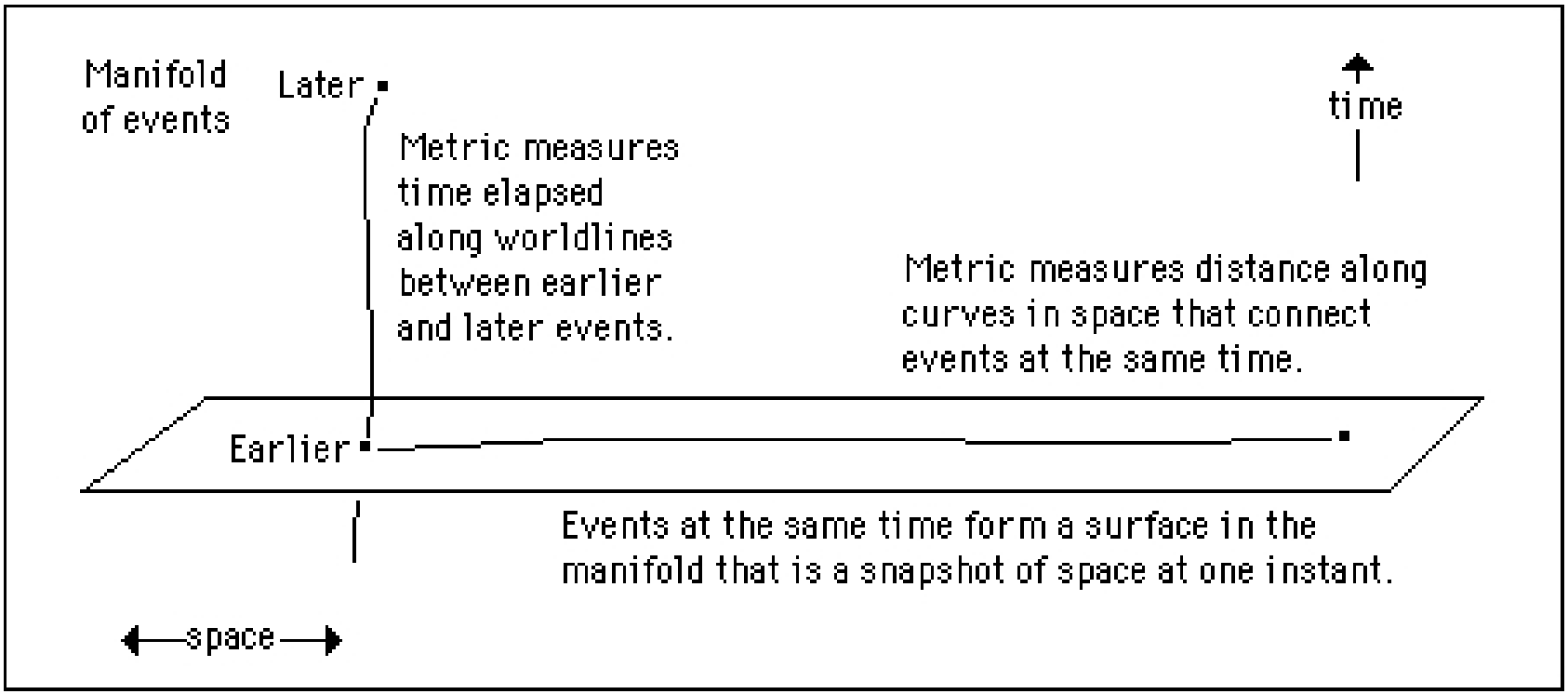
What exactly is a "spacetime" in GR?

Construction of spacetimes in GR: A manifold of events

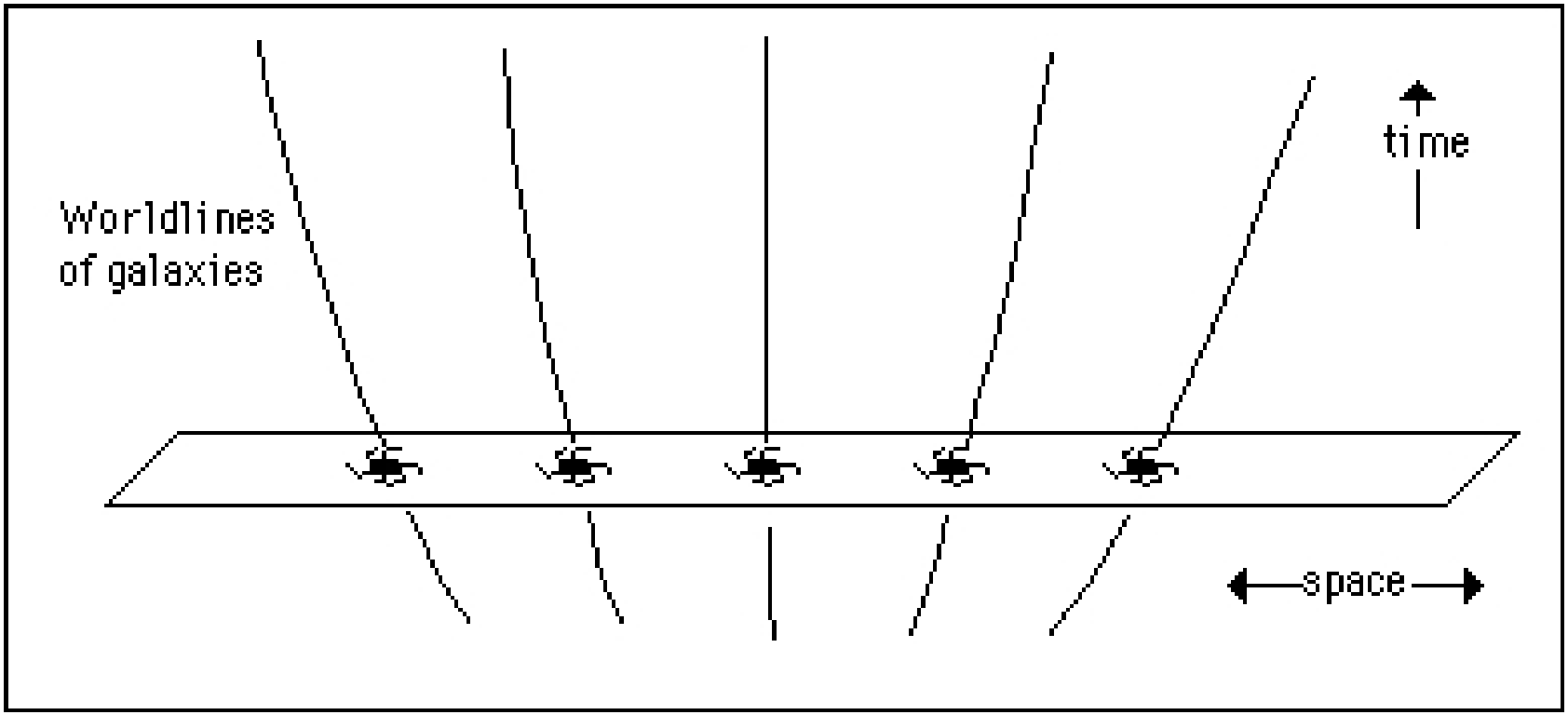
Figures from: J. Norton, “The hole argument”, in E. Zalta (ed.), *Stanford Encyclopedia of Philosophy*, 1999/2008.



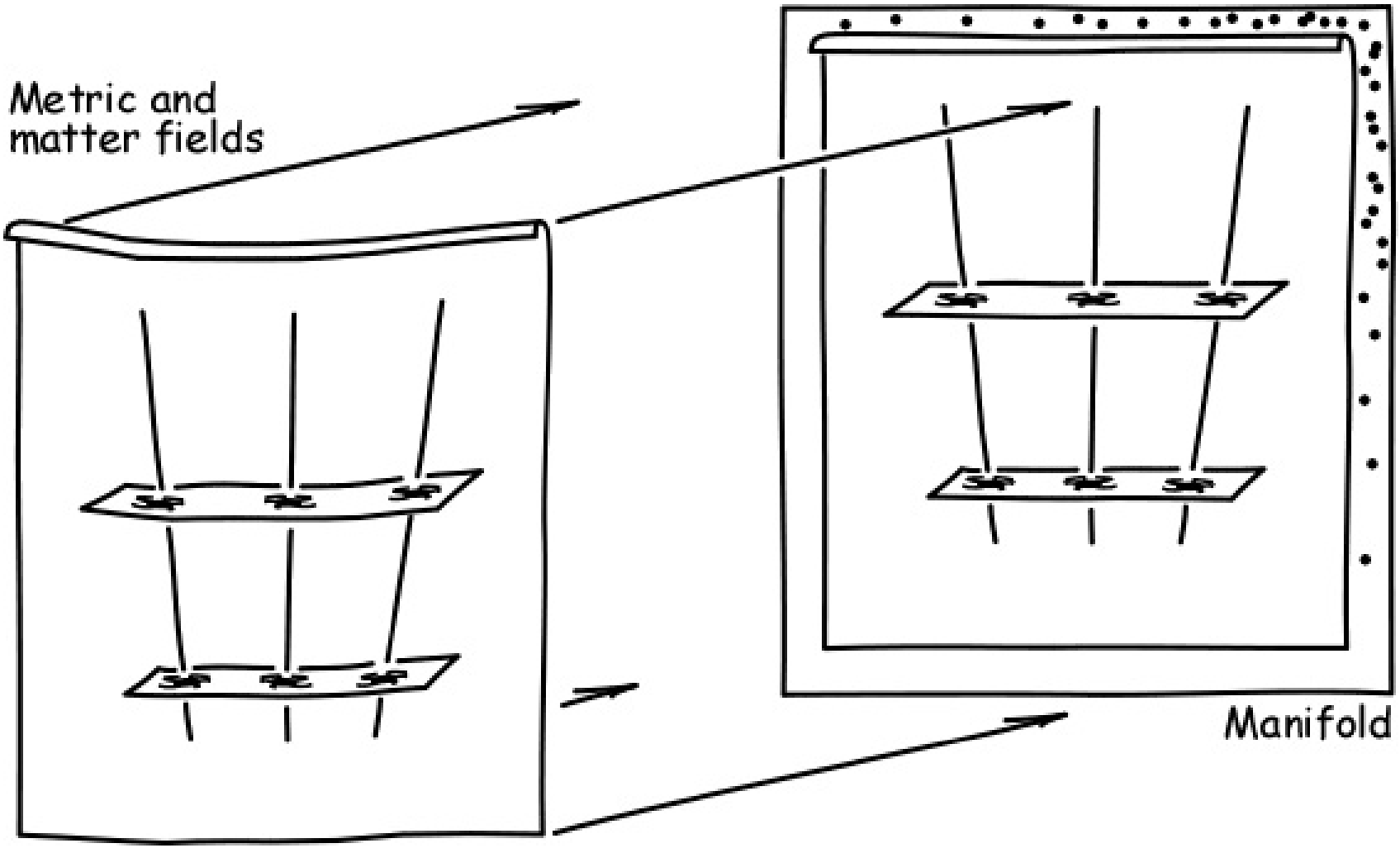
The function of the metric field



Worldlines:
Galaxies in an expanding universe



Spreading of metric (and matter fields) on $\mathcal{M}$



Does GR arbitrate between substantivalism and relationism?

In the literature, it is contended that GR

- establishes substantivalism, since GR is a field theory.
- proves substantivalism, as Mach's Principle is invalid in GR.
- shows that relationism is true, because GR doesn't care which spacetime points "carry" which field values and "hence" no spacetime points are needed.
- demonstrates that relationism is true, for otherwise an unpalatable form of indeterminism results (the "hole argument").
- provides evidence that the entire debate is misguided.

The hole argument

Principle (Einstein Equivalence)

Inertial and gravitational effects are both manifestations of the same structure. This structure is the inertio-gravitational field.

Einstein's Principle of Equivalence motivates a generalization to non-inertial systems of the Principle of Relativity, which is given in special relativity as

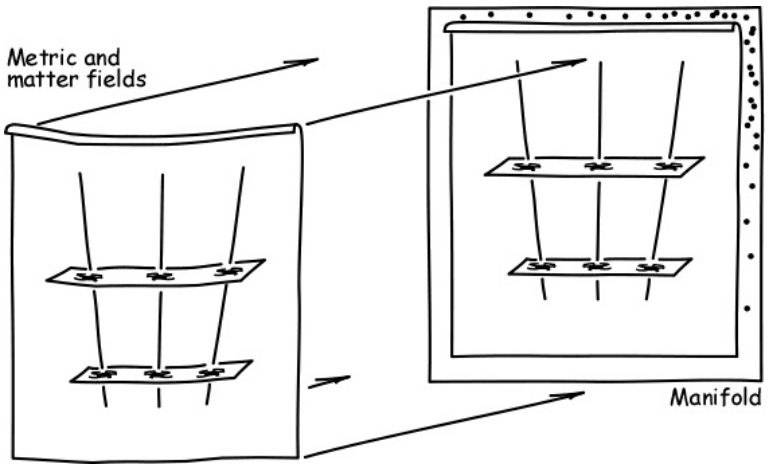
Principle (Relativity)

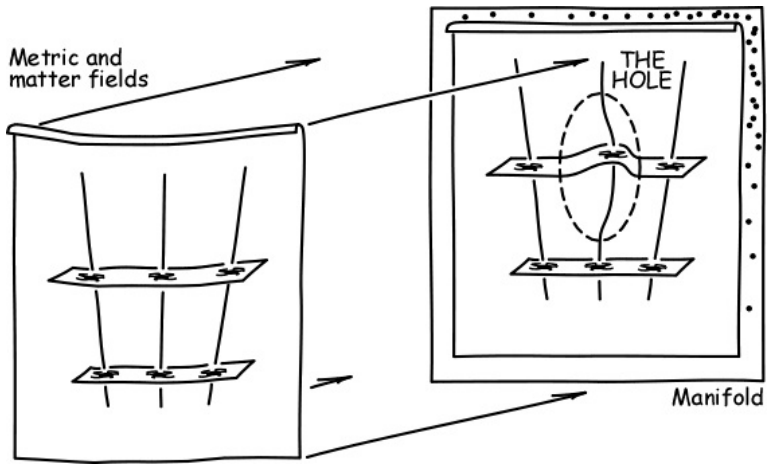
For all reference frames in which the mechanical laws are valid [= inertial systems], the same laws of electrodynamics and optics are valid (cf. Einstein 1905).

Albert Einstein, "Zur Elektrodynamik bewegter Körper", *Annalen der Physik* **17** (1905): 891-921.

A generalization of the Principle of Relativity:
"Diffeomorphism invariance"

Figures: J. Norton, "The hole argument", in E. Zalta (ed.), *Stanford Encyclopedia of Philosophy*, 1999/2008.





models only distinct in how fields are spread on $\mathcal{M}$

Question

Are these two models physically distinct or are we rather confronted with two representations of the same physical possibility?

The hole argument (simplified)

Earman and Norton (1987)

J. Earman and J. Norton, „What price spacetime substantivalism? The hole story", *British Journal for the Philosophy of Science* **38** (1987): 515-525.

P1: In GR, there are models which differ insofar as to which field values are instantiated at different spacetime points within the "hole", but are identical outside the hole.

P2: Substantivalism is committed to the claim that models related in this way represent two physically distinct situations.

$\therefore$ Substantivalism is committed to a form of indeterminism, since from all the information of how the fields are distributed outside the hole, it cannot be determined how they are distributed in the hole.

Possible responses to the hole argument

1. Classic (manifold) substantivalism, i.e. spacetime points have a *haecceitas*, a primitive identity $\Rightarrow$ indeterminism (bite the bullet)
2. Sophisticated substantivalism, i.e. points of manifold have no *haecceitas* (deny P2)
3. Relationism, i.e. spacetime (qua manifold) is no substance (dodge the bullet)
4. Spacetime structuralism...

Spacetime structuralism

Definition (Spacetime structuralism)

Spacetime structuralism is the realist thesis that spacetime is a structural complex consisting of a set of spacetime points (essentially, the manifold) and the spatiotemporal relations in which these points stand (as given by the metric).

Spacetime structuralism thus attempts a third way:

- Just like substantivalism, it is realist about spacetime.
- However, it doesn't conceive of spacetime as a passive container (as does traditional substantivalism), but as a complex of objects standing in spatiotemporal relations, just as does relationism, even though these objects are not material, but spacetime points.

$\Rightarrow$ resolves traditional debate (but it's not without problems, cf. Wüthrich 2009)

Christian Wüthrich, "Challenging the spacetime structuralist", *Philosophy of Science* **76** (2009): 1039-1051.

State of debate after GR

- Crude forms of substantivalism are eliminated by the hole argument.
- Conversely, considerations involving rotating bodies show that a crude relationism is equally problematic (cf. also failure of Mach's Principle)
- Central lesson of GR: inertial background and a physical entity—the gravitational field—are one and the same
- What exists according to GR: matter fields and force fields (e.g. gravitational field)