Time in special relativity

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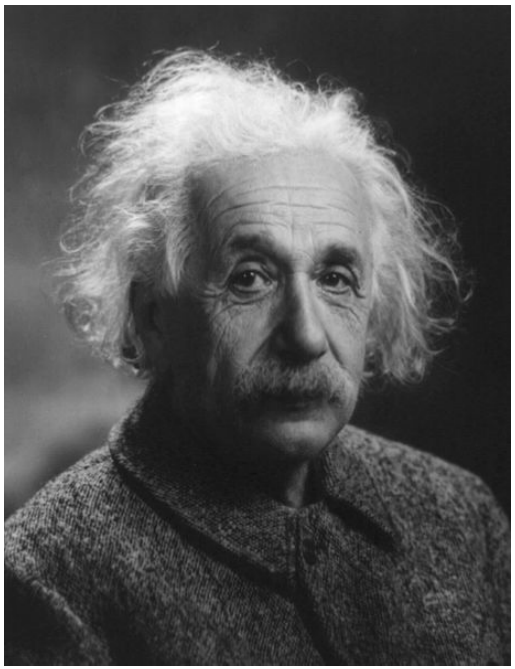
Introduction to Philosophy of Physics

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)

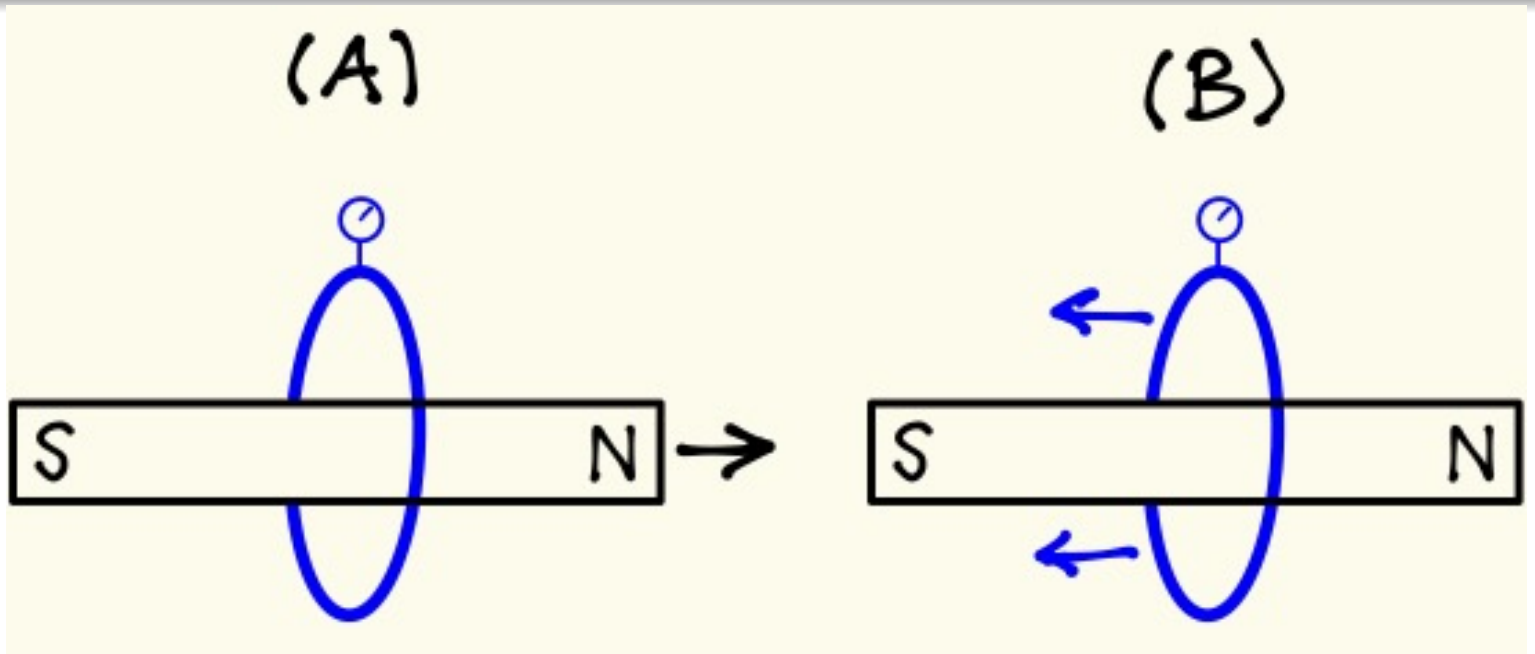
It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon 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.

$\Rightarrow$ 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

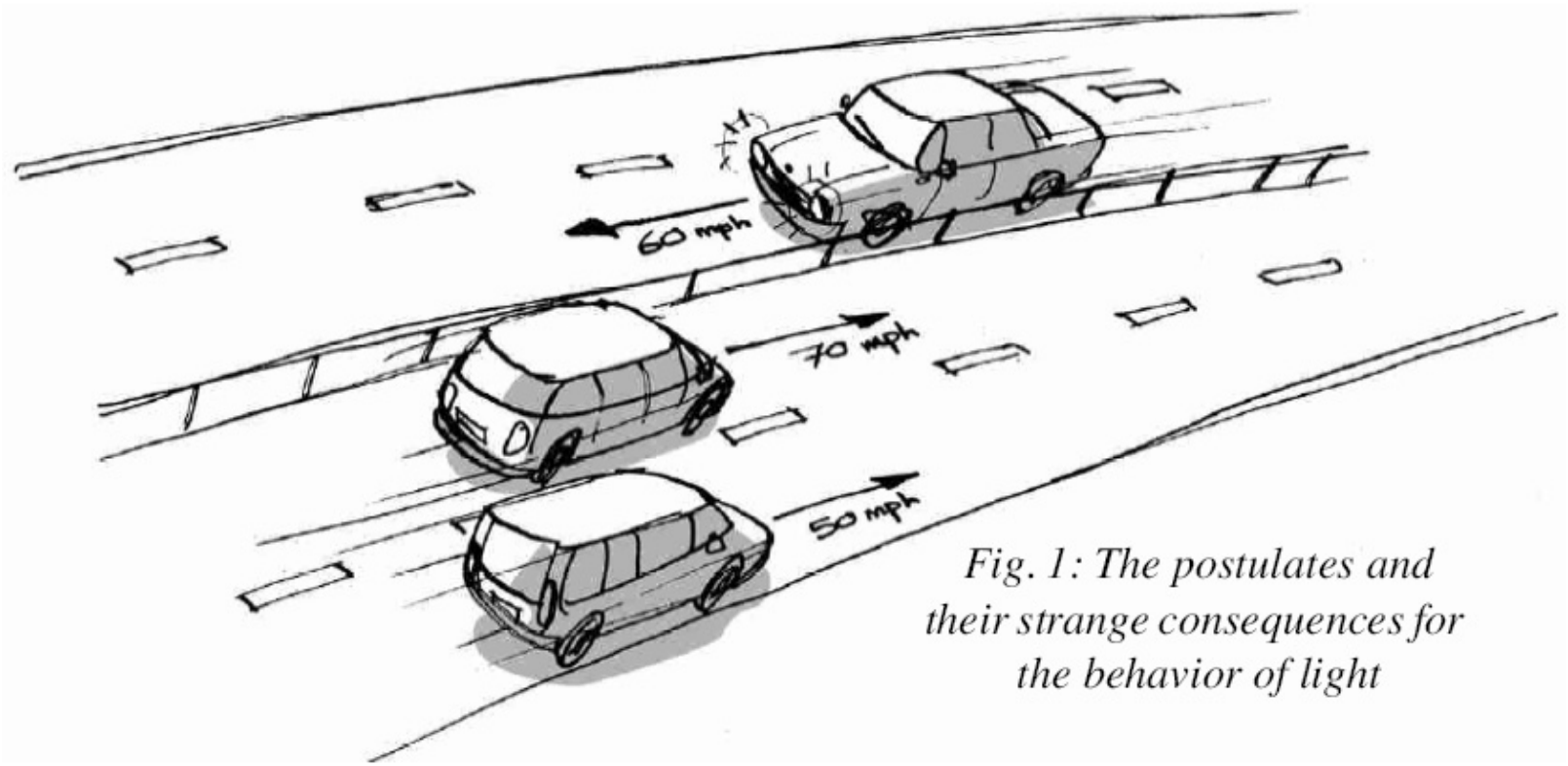


Fig. 1: The postulates and their strange consequences for the behavior of light

How fast is the oncoming vehicle for the two SUVs?

Intuitively: 60 + 70 = 130mph and 60 + 50 = 110mph, 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 first consequence

Our expectation leads to a violation of at least one of the postulates:

Tim Maudlin. *Philosophy of Physics: Space and Time*. Princeton University Press (2012).

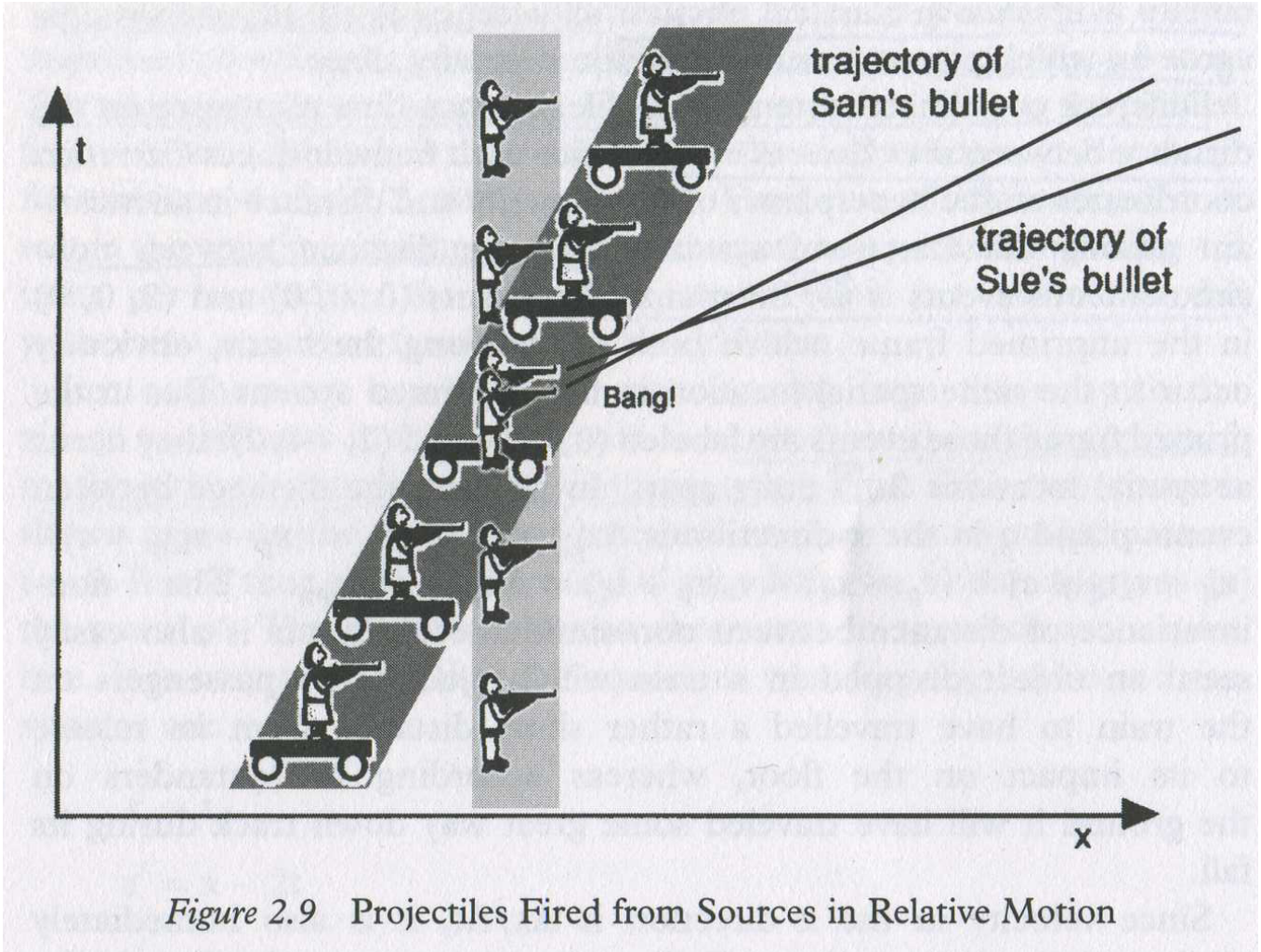


Figure 2.9 Projectiles Fired from Sources in Relative Motion

The first consequence

What the postulates imply about the motion of photons shot from laser guns:

Tim Maudlin. *Philosophy of Physics: Space and Time*. Princeton University Press (2012).

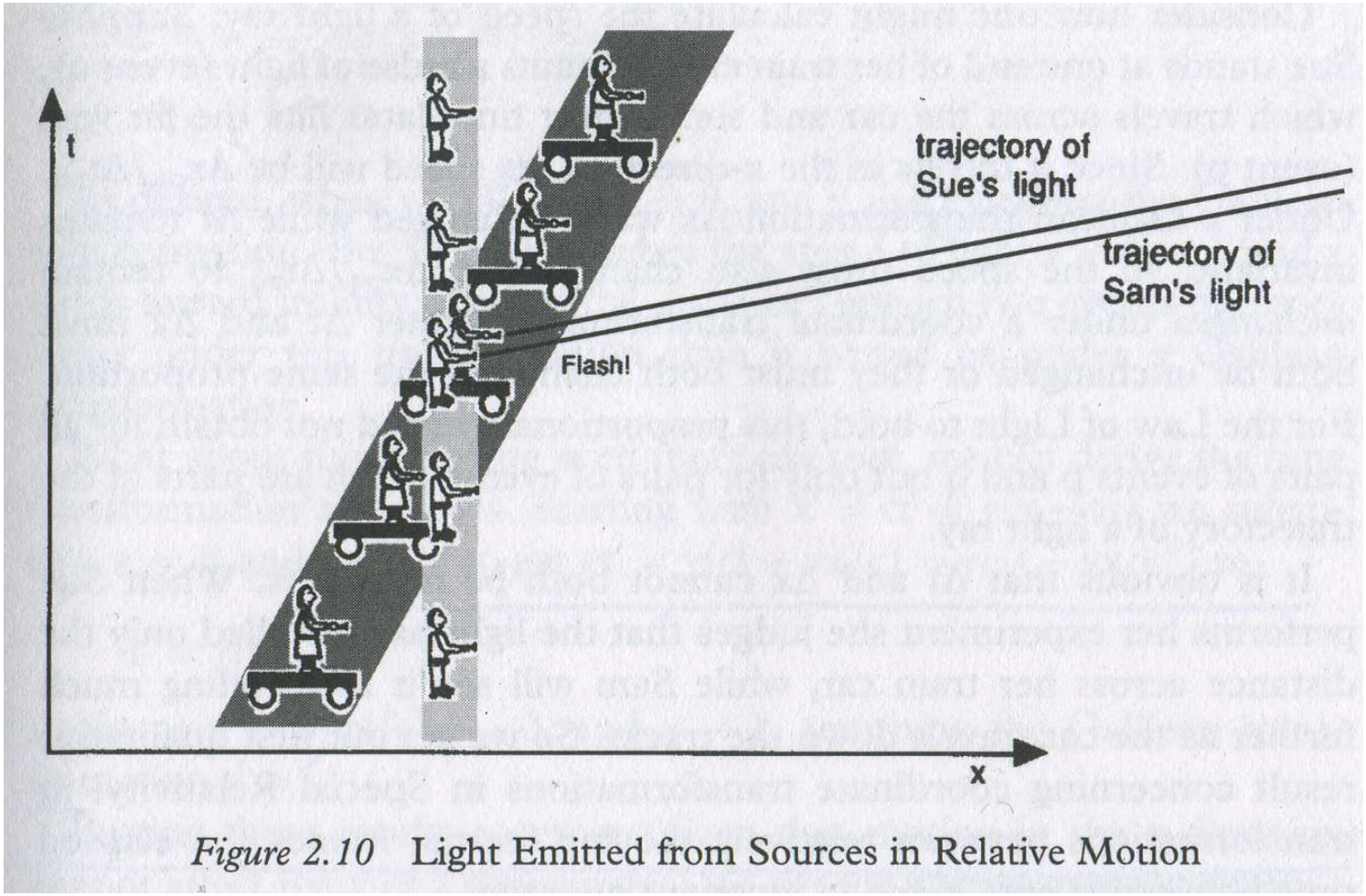


Figure 2.10 Light Emitted from Sources in Relative Motion

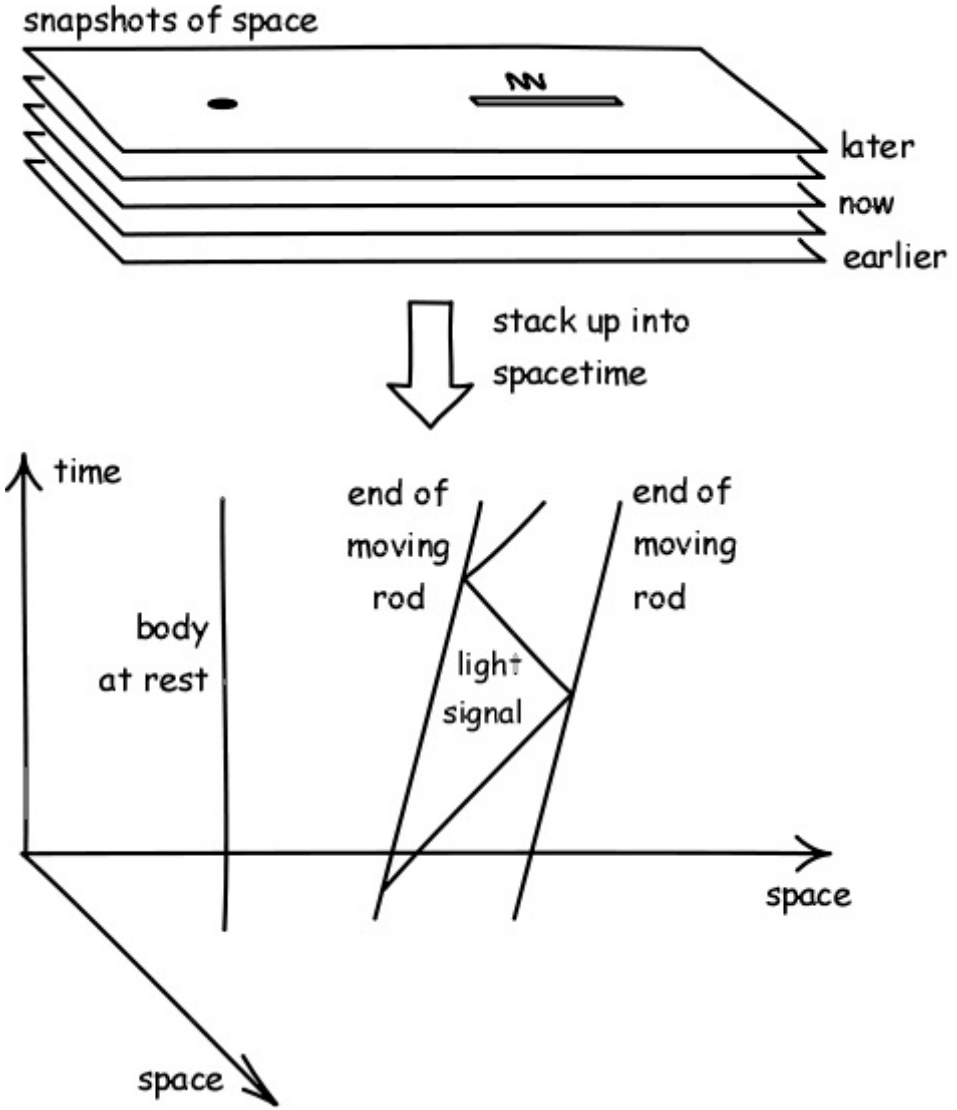
Hermann Minkowski (1864-1909)

- German mathematician
- taught at Bonn, Göttingen, Königsberg, ETH Zürich

To the 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.

Learning how to draw spacetime diagrams



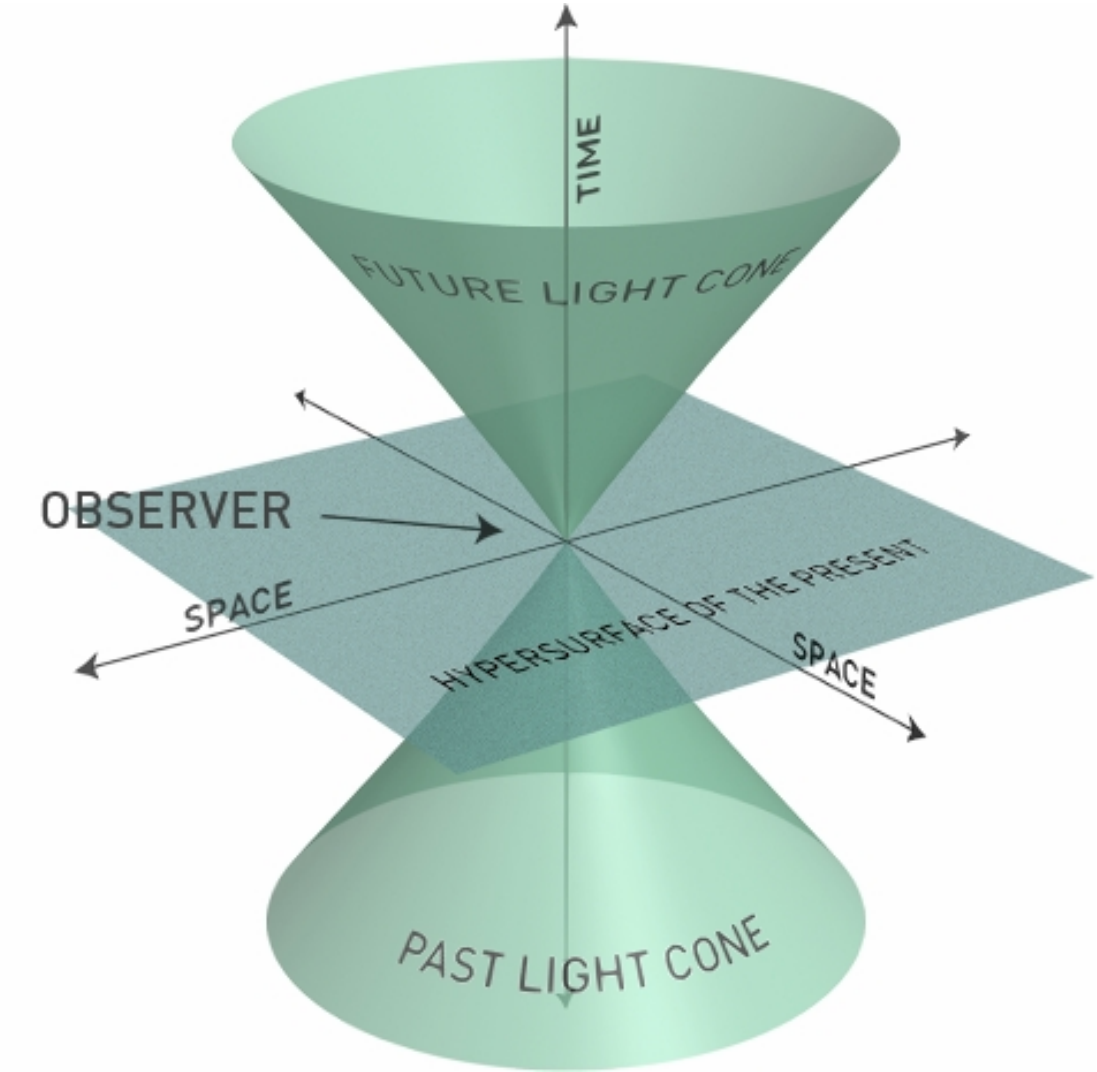
Construction of Minkowski spacetime

- Goal: to construct a spacetime with the structure encoding constraints as given by special relativity
- Spacetime structure becomes absolute, but separation of spacetime into space and time depends on kinematic state of observer.
- manifold of 'events' (= dimensionless spacetime points)

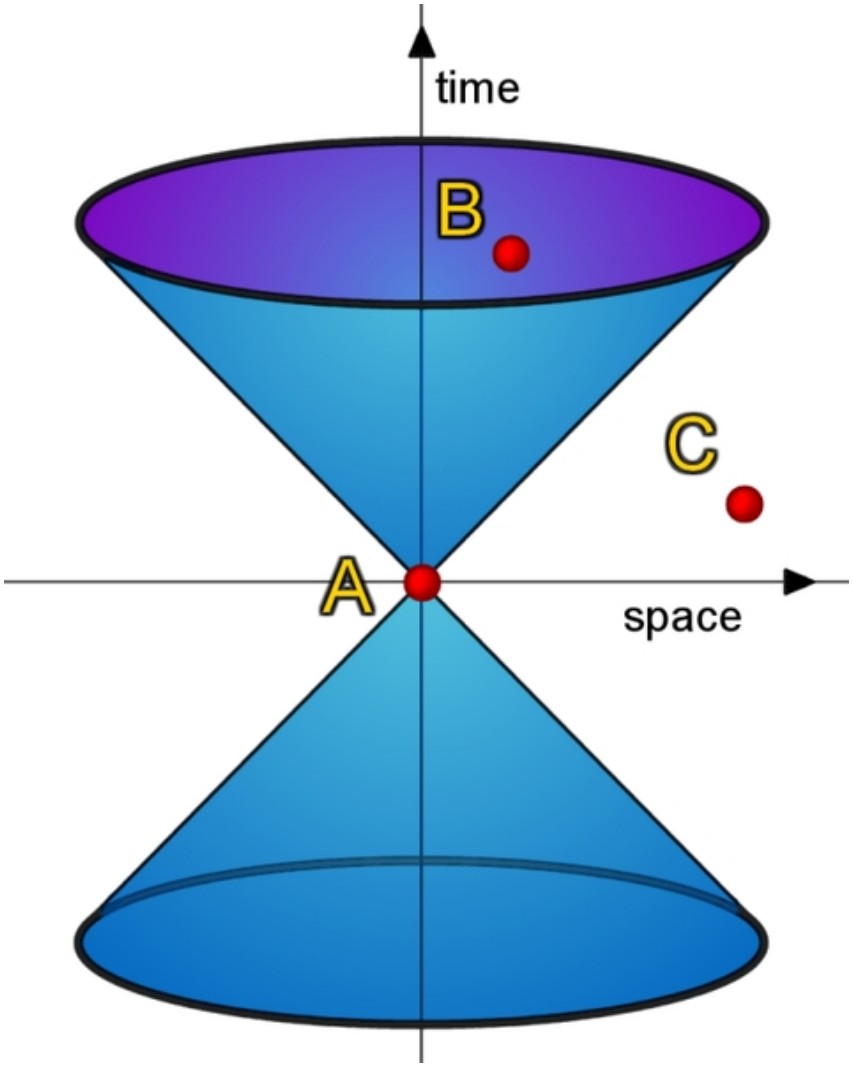
$\Rightarrow$ we can smoothly label events by four numbers ('coordinates')

- add additional structure: time orientation, metric structure
- The so-called Lorentz transformations (to be discussed soon) constitute the symmetries of the Minkowski spacetime, so the latter's geometry perfectly captures the postulates of SR.

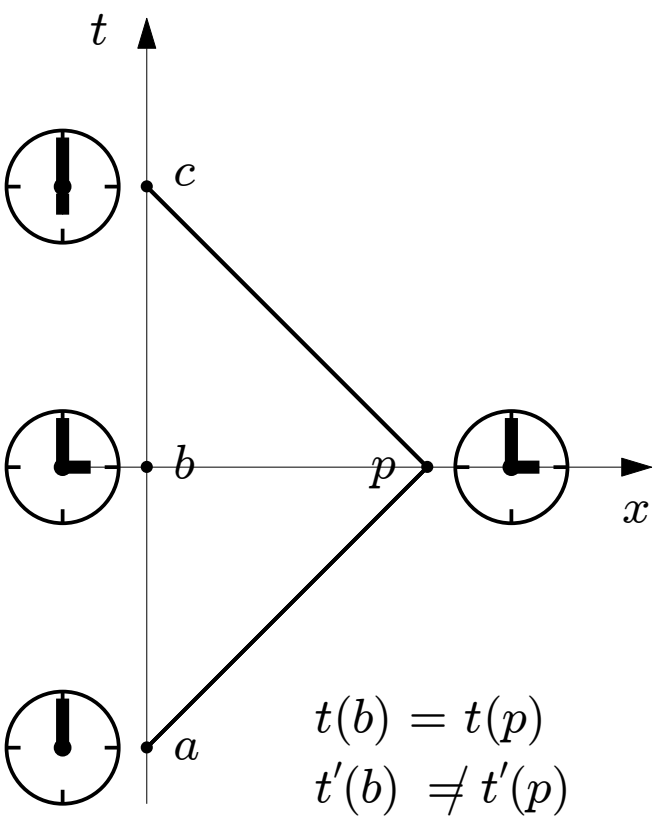
The light cone structure



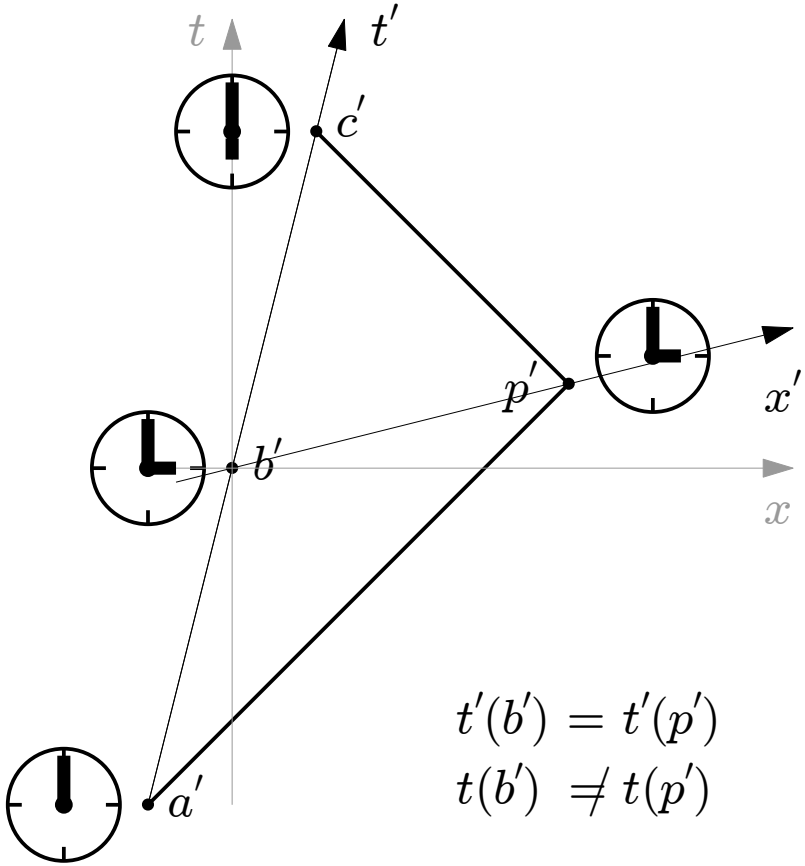
Timelike-, spacelike-, and null-related event



Einstein-Poincaré convention for synchronizing distant clocks

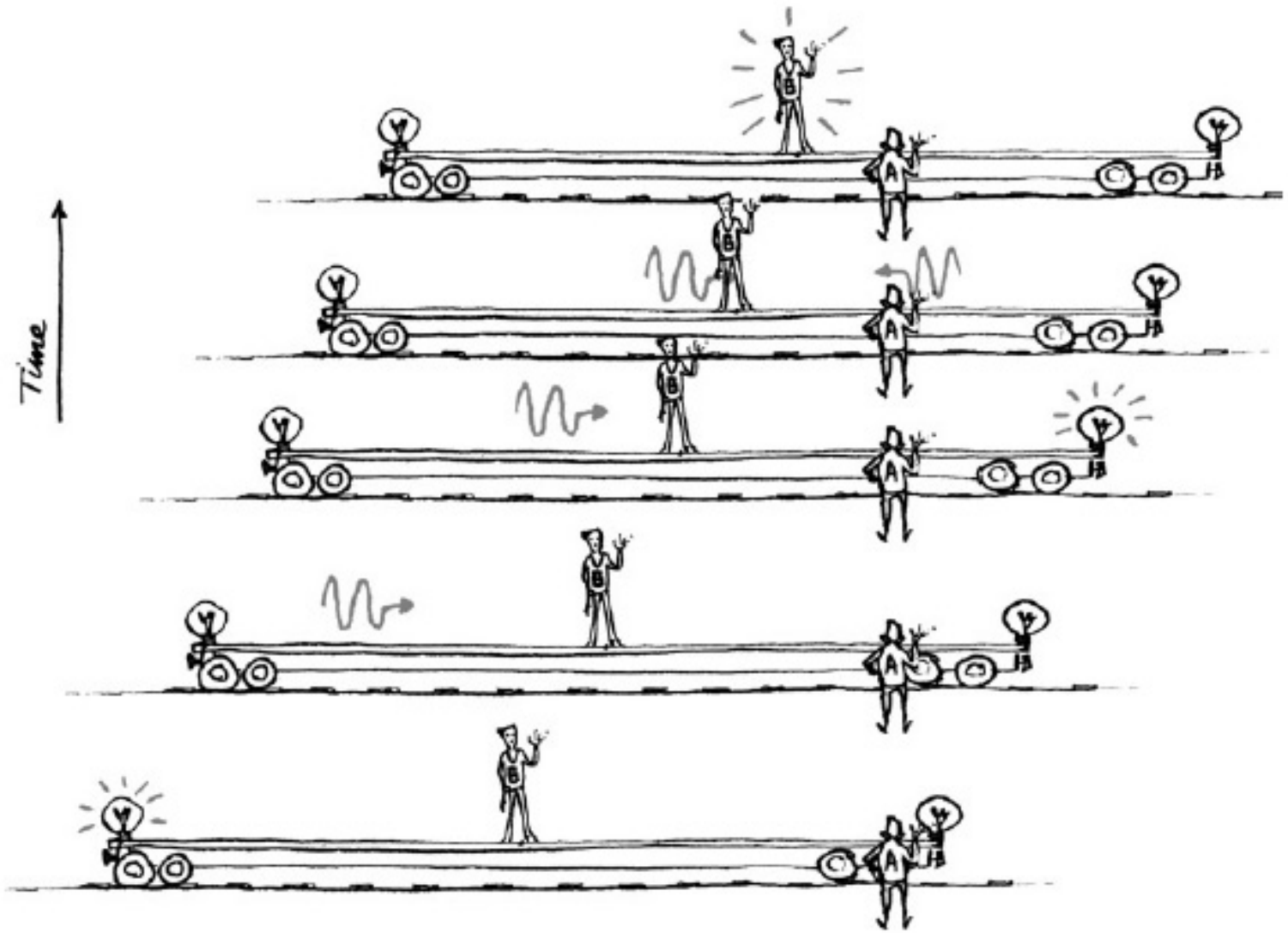


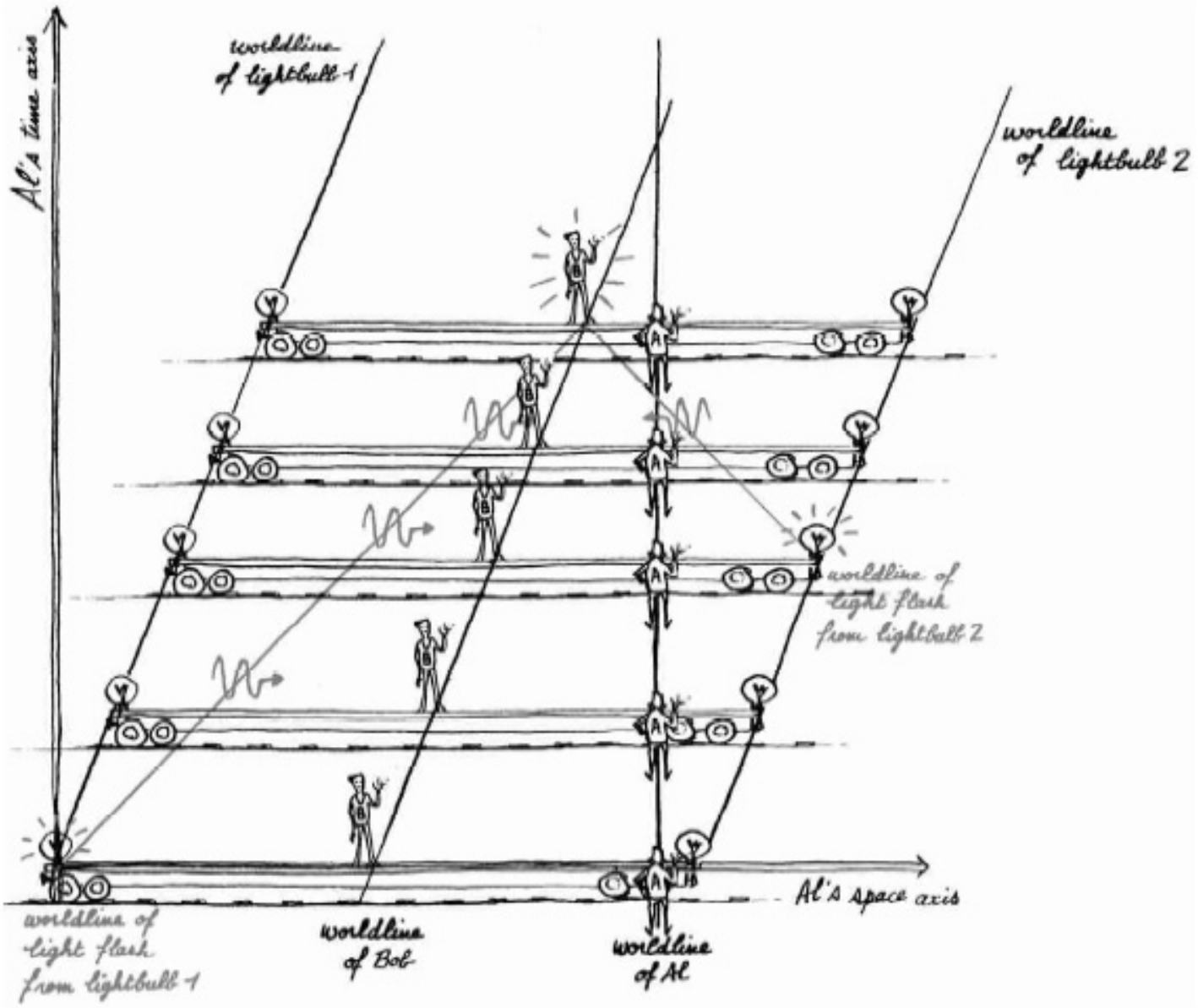
$$t(b) = t(p)$$
$$t'(b) \neq t'(p)$$

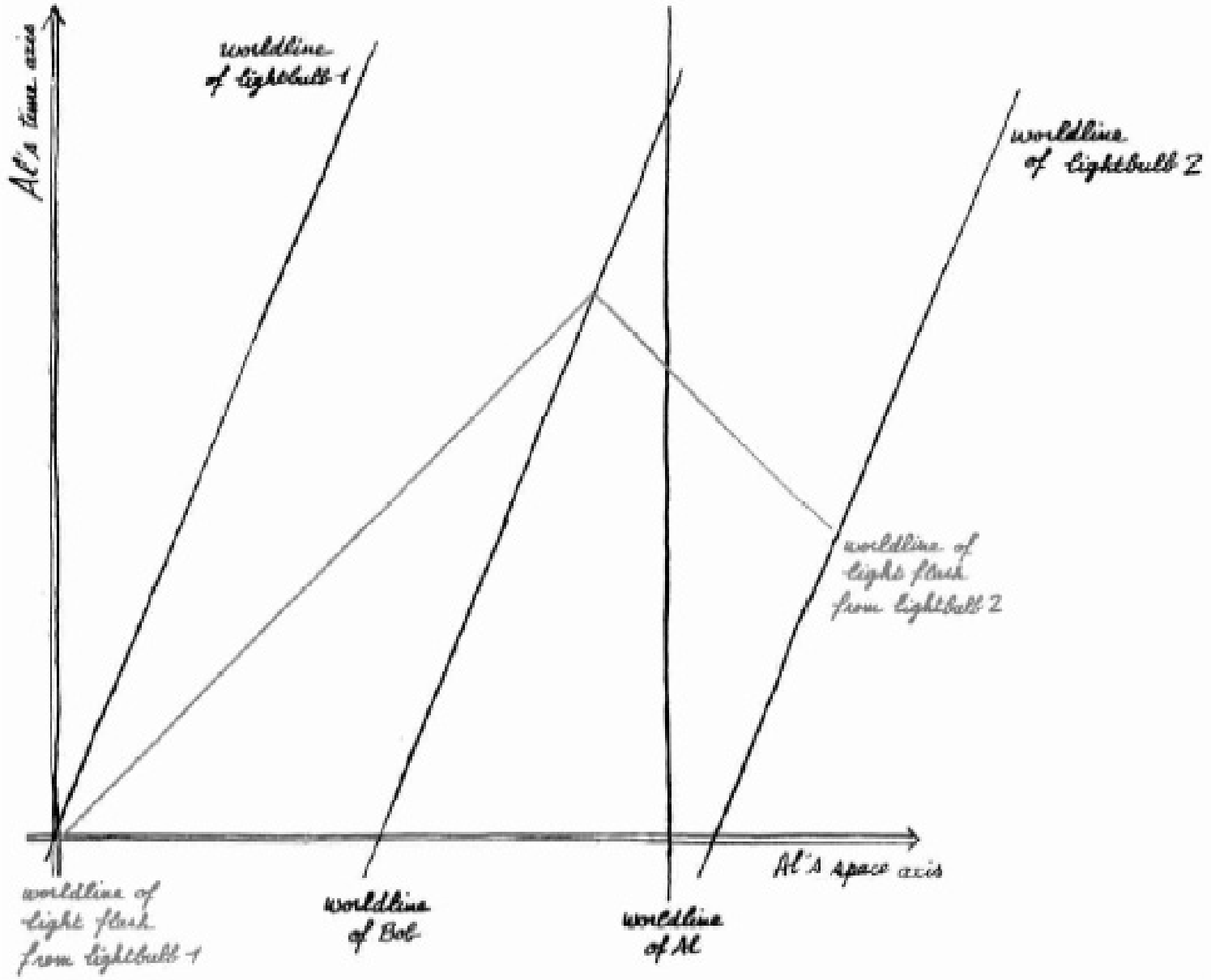


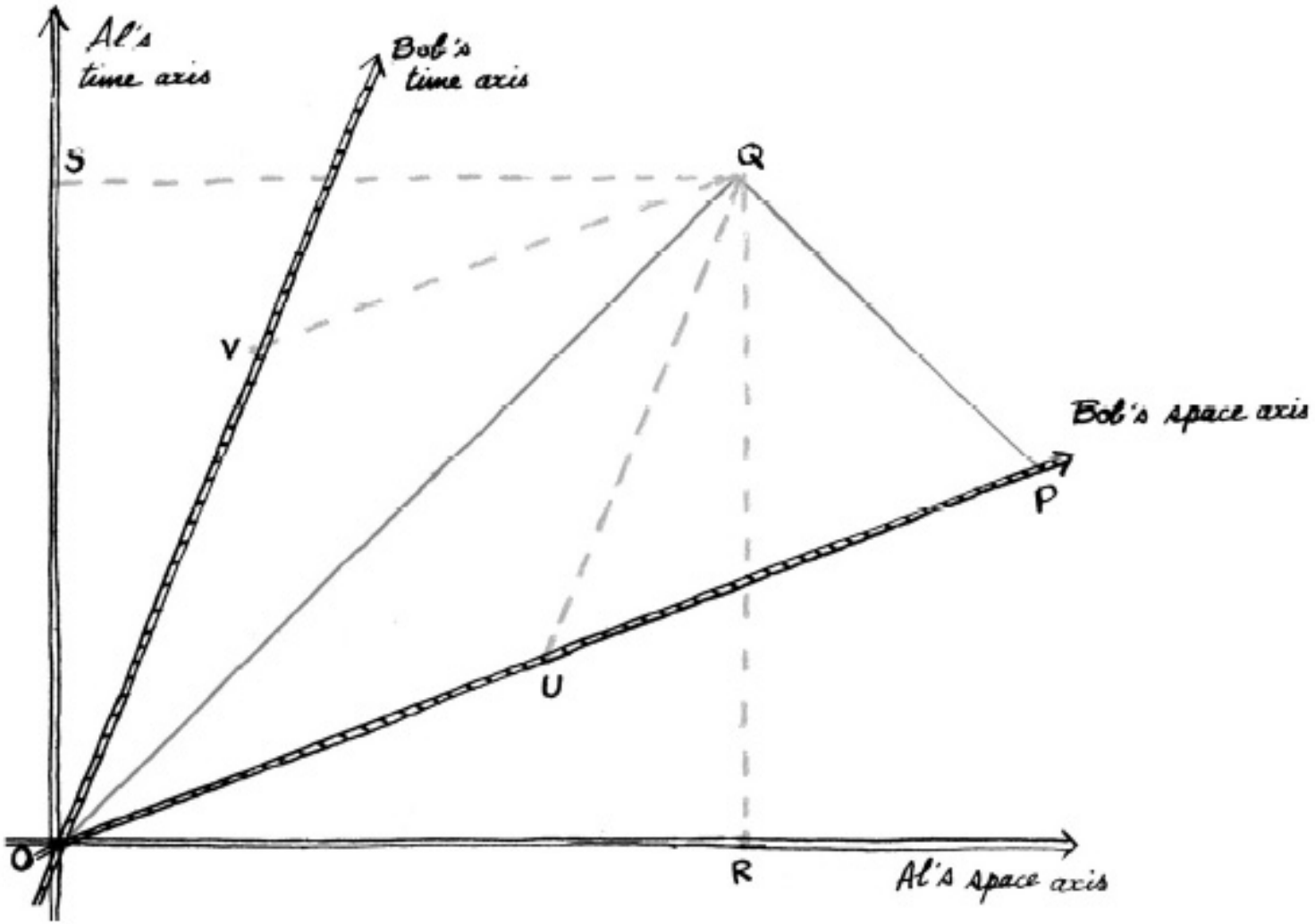
$$t'(b') = t'(p')$$
$$t(b') \neq t(p')$$

Geometry of Minkowski spacetime




worldline of lightbulb 1
worldline of lightbulb 2
Al's time axis
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

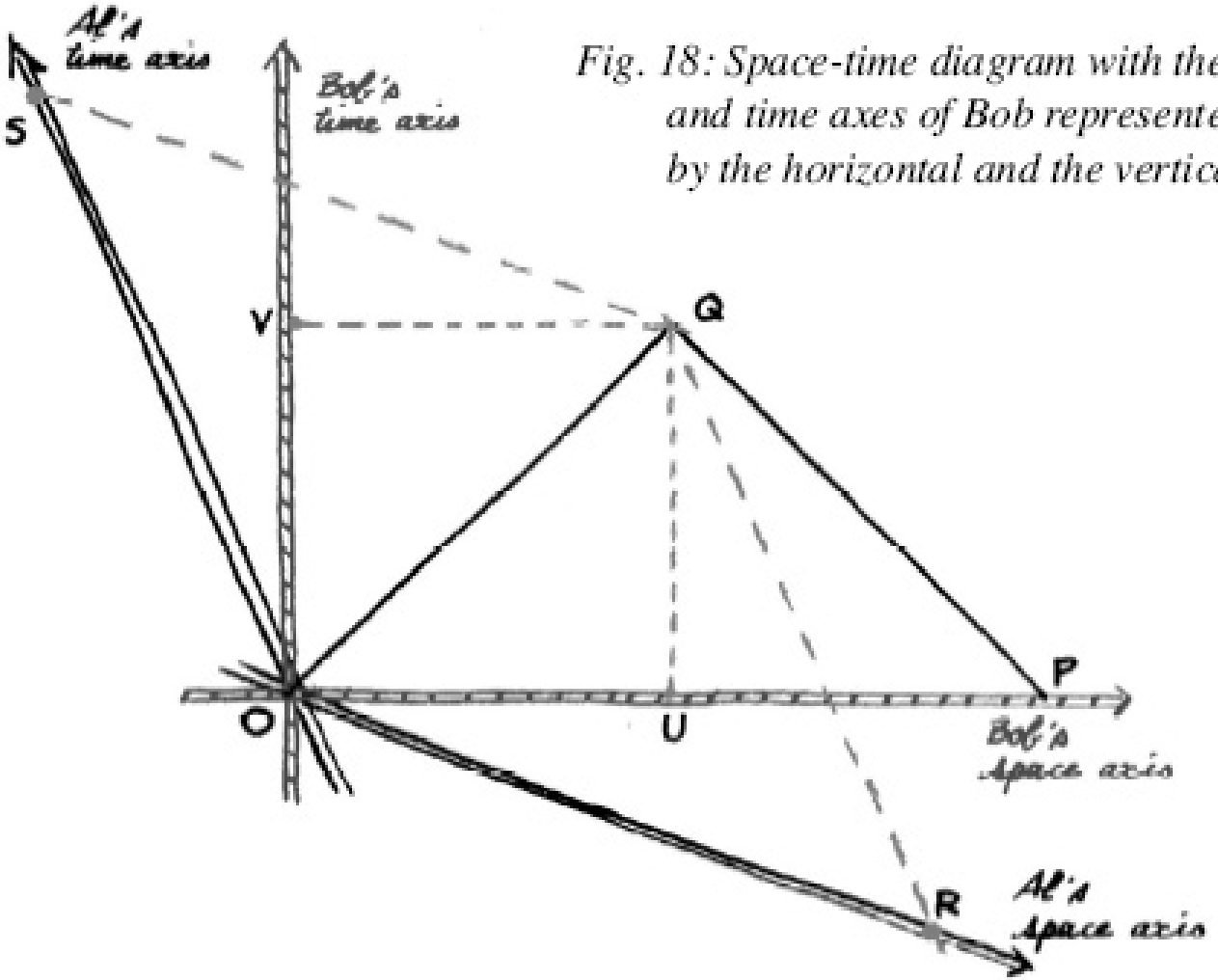


Fig. 18: Space-time diagram with the space and time axes of Bob represented by the horizontal and the vertical

Important principles of drawing spacetime diagrams

Principle

Since light propagates with the same velocity in all frames (Light Postulate), its worldlines have the same slope in all frames. Conventionally, we choose the units such that their slope is $+1$ or -1. Thus, we draw them as the angle bisectors between the axes.

Principle

The previous principle determines how the time-axis of a different inertial frame must be drawn given its space-axis: the angle between the time-axis and the worldlines of light must be the same as the angle between the corresponding space-axis and the worldlines of light. Always, for all frames, as represented in any other frame.

Principle

An inertial frame's planes of simultaneity (i.e., set of events which are simultaneous in this frame) are parallel to the space-axes of this frame.

Relativity of simultaneity in spacetime diagrams

Simultaneity in first inertial frame

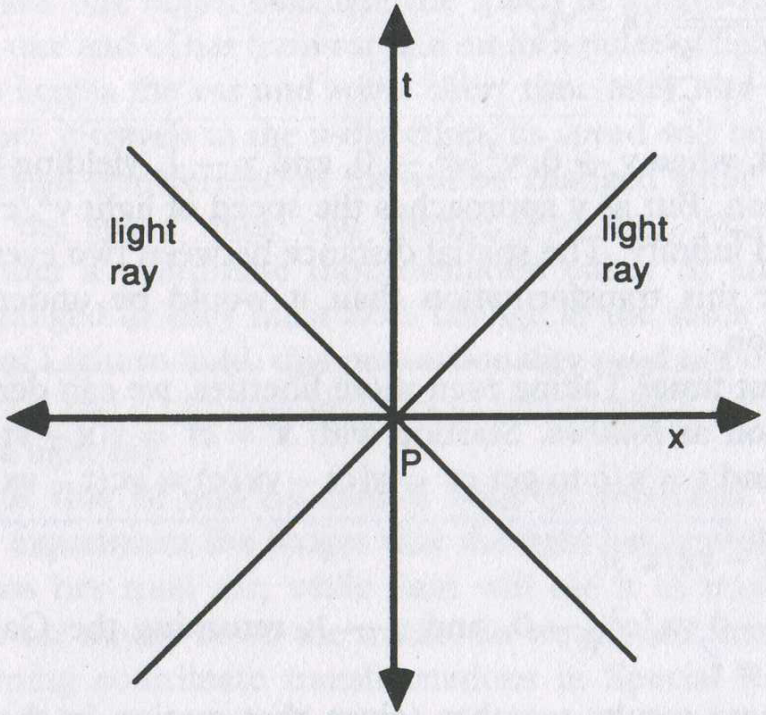


Figure 2.11 The Light Cone in the x – t Frame

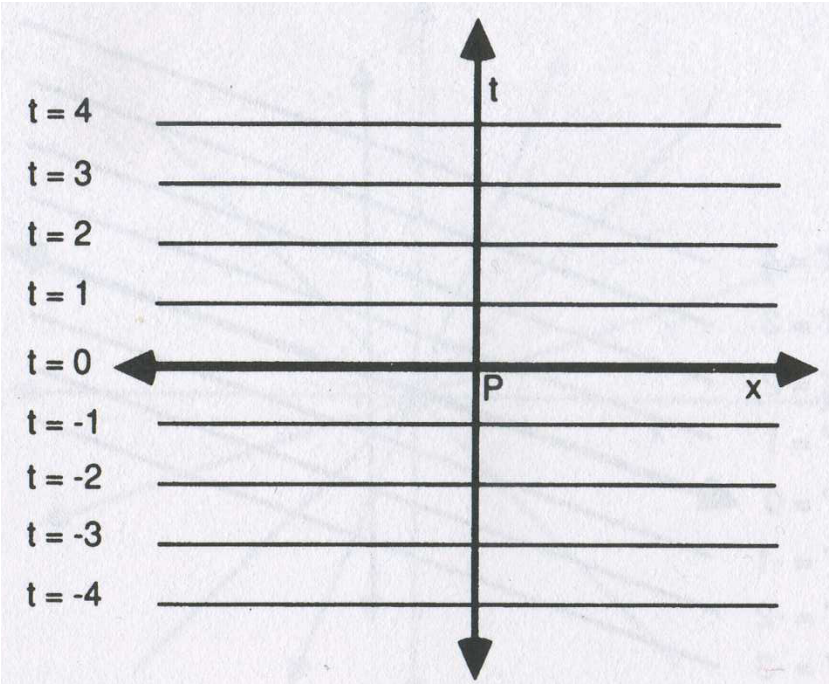


Figure 2.12 Simultaneity Slices in the x – t Frame

Relativity of simultaneity in spacetime diagrams

Simultaneity in second inertial frame

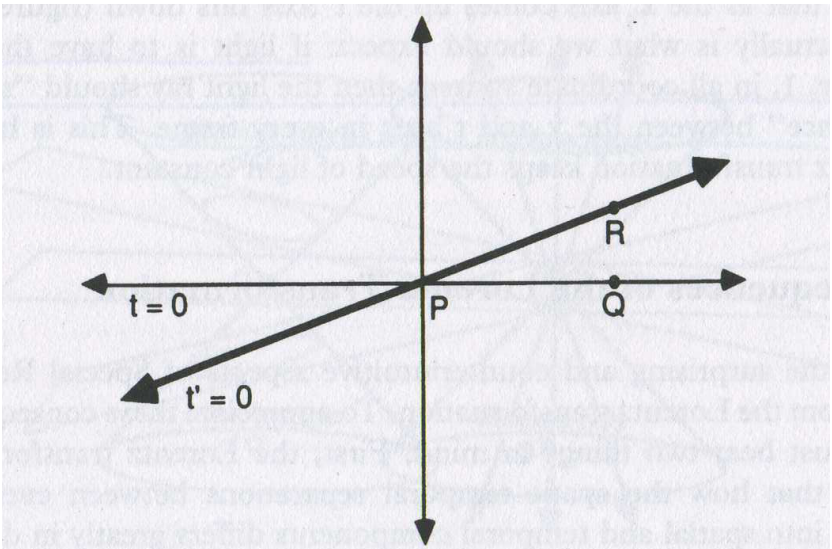


Figure 2.13 Points Simultaneous with P in the $x' - t'$ Frame

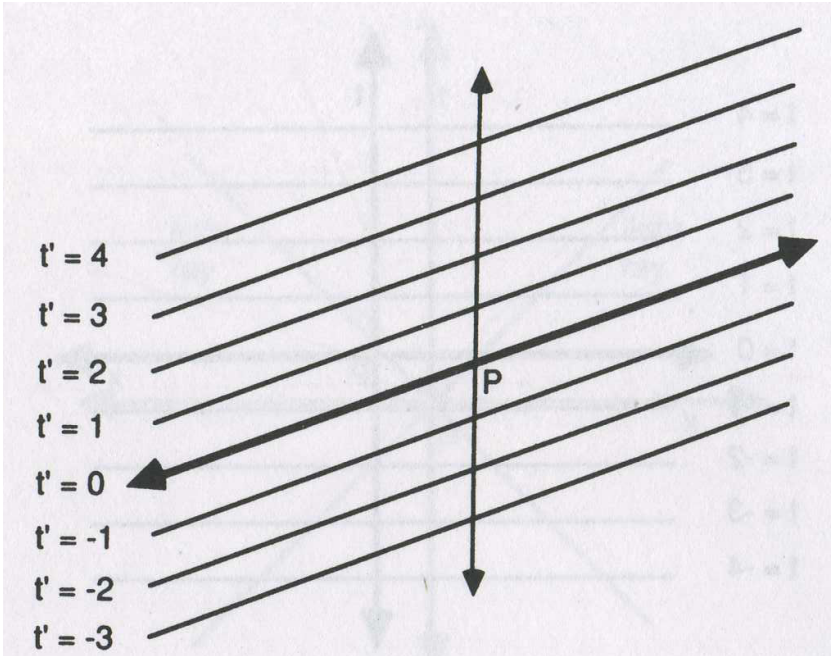


Figure 2.14 Simultaneity Slices in the $x' - t'$ Frame

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, as we will soon discuss: the time order between events depends on frame of reference and is not objectively given.

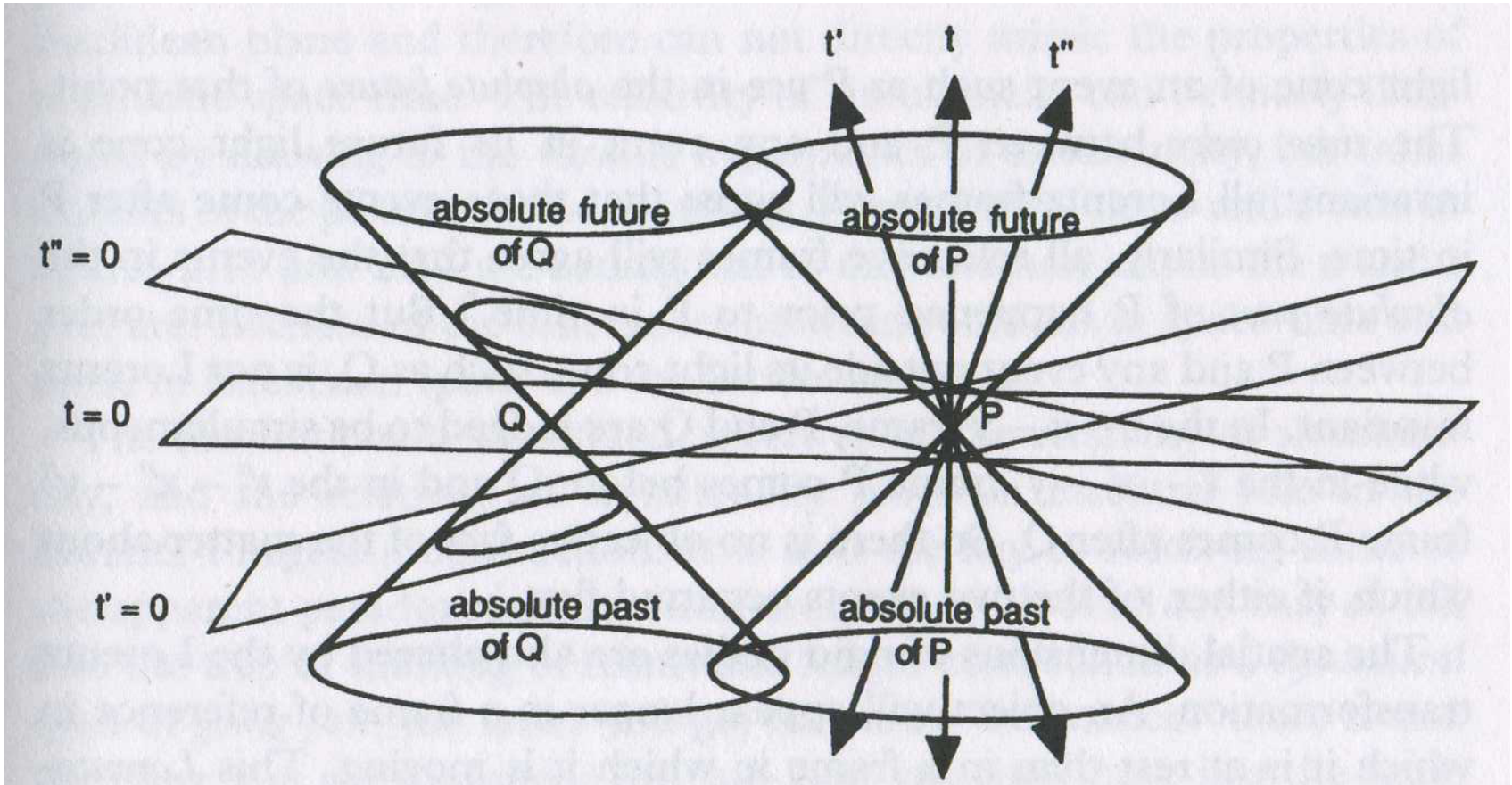
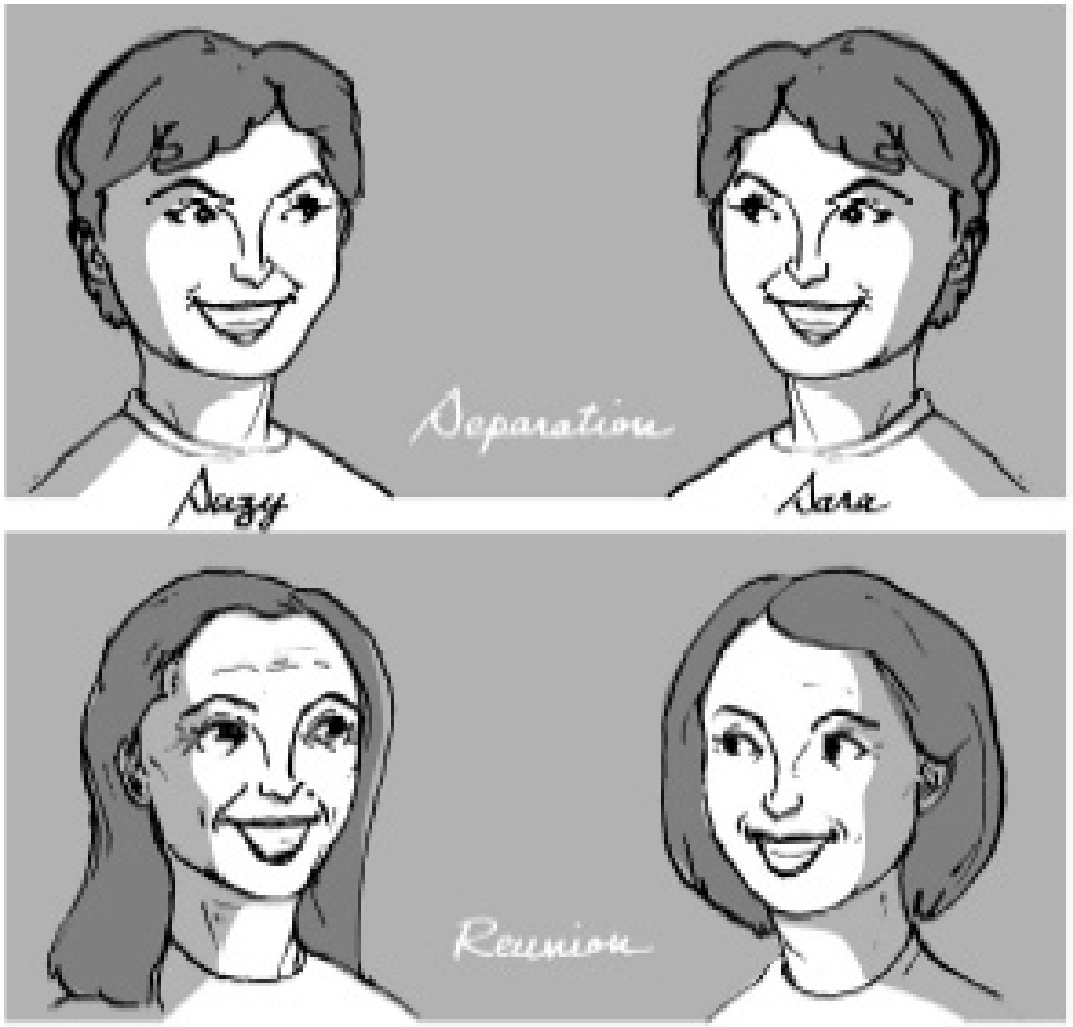


Figure 2.16 Light Cones of Two Events

Time dilation and length contraction

- time dilation: the apparent going slower of clocks moving relative to observer
- length contraction: the apparent being shorter of physical objects in the direction moving relative to observer
- path-relativity of proper time: elapsed times of non-co-moving clocks will in general differ
- If you are interested, I recommend you read this up in Janssen's wonderful article.

A final oddity: Twin paradox



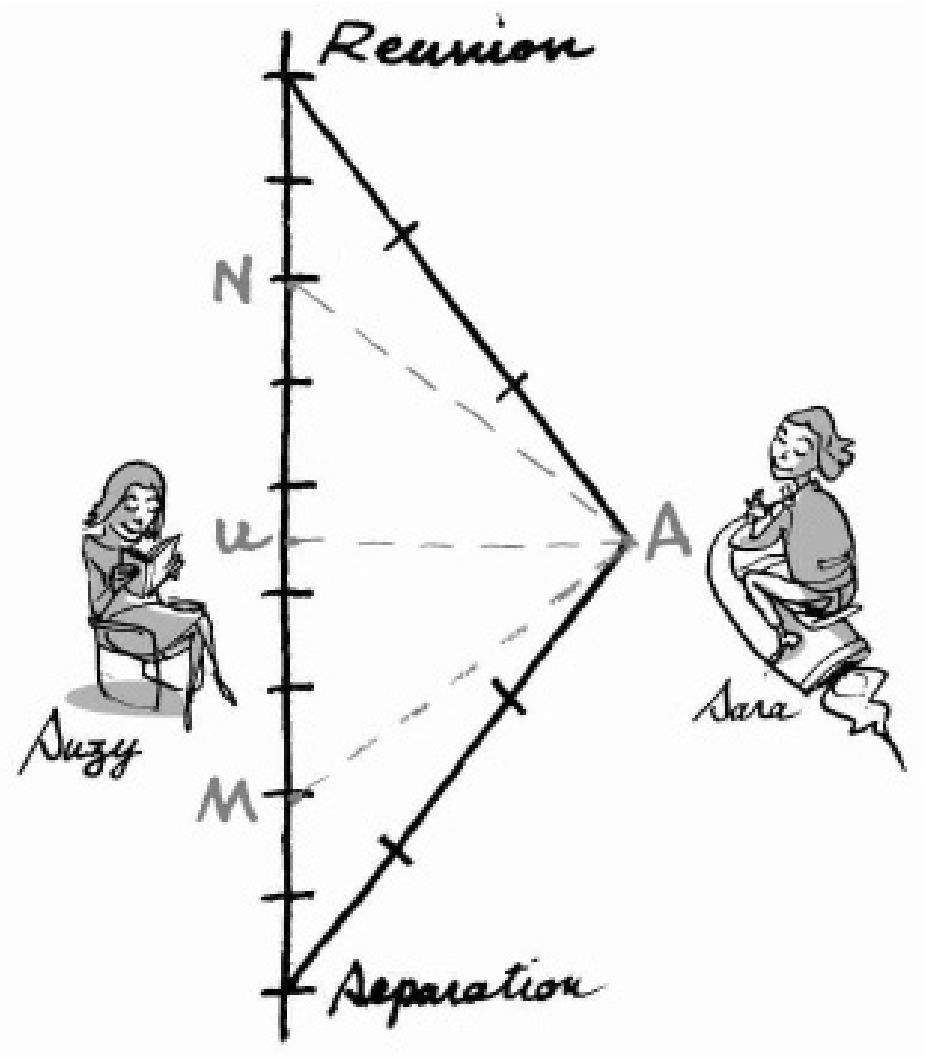


Fig. 29: Space-time diagram for the twin paradox

A spatial analogue to the twin paradox

Fig. 31: A spatial analogue of the twin paradox in space-time.

Lorentz-invariant quantities

- So-called Lorentz transformations relate different inertial frames; thus, we are interested in quantities that do not change under Lorentz transformations.
- Lorentz-non-invariant quantities:
  - spatial distance between events
  - time elapsed between events
  - time order between events which lie outside one another's light cones
  - all velocities other than c
- Lorentz-invariant quantities:
  - c
  - causal structure given by light cones
  - spatiotemporal 'distance'

Presentism

Position (Presentism)

Presentism maintains that only present events and objects exist. Furthermore, it is usually assumed that there is a succession of presents, i.e. a moving Now.

Presentists face at least two major challenges:

1. The 'problem of the past': by virtue of what are propositions on past events true?
2. It seems to be incompatible with contemporary physics.

The threat from SR

Definition (Present-centric models (PCMs))

A model of time is a present-centric model just in case it posits an absolute and universal present, and thus an absolute and universal front of becoming or annihilation.

- 'absolute': not relative to a frame of reference or observer
- 'universal': fullest spatial extent, not spatially local or restricted
- Examples of PCMs: presentism, growing block universe
- spatially extended present: set of all spacetime points ('events') which are simultaneous with the *here-now*
- The problem is that PCMs require a metaphysically robust, objectively valid concept of 'a spatially extended present' which is under serious pressure from SR given the latter's relativity of simultaneity.

The initial pressure from SR

- PCMs: division between what is present and non-present bears ontological significance
- SR: what is present (i.e. simultaneous with *here-now*) and non-present (not simultaneous with *here-now*) depends on an arbitrary choice of reference frame

$\Rightarrow$ It seems as if SR implied that an advocate of a PCM is committed to a relativization of reality: what's real depends on observer.

$\Rightarrow$ Kit Fine's fragmentalism

The pressure from SR: Putnam-Rietdijk argument


Hilary Putnam (1967). Time and physical geometry. *Journal of Philosophy* 64: 240-247.


C W Rietdijk (1966). A rigorous proof of determinism derived from the special theory of relativity. *Philosophy of Science* 33, 341-344.


Howard Stein (1991). On relativity theory and openness of the future. *Philosophy of Science* 58: 147-167.

In a nutshell

Putnam (1967) and Rietdijk (1966, see also Stein (1991)) proposed an argument that puts presentism, and similarly classical dynamical theories of time, under significant pressure. I think presentists do have a response to this sort of argument. But it is difficult for the presentist to escape the general thrust of the Putnam-Rietdijk argument without serious harm.

- What follows is my version of the argument, which I dub the relativistic argument against the fundamentality of the present. Boxes indicate substantive assumptions or premises in the argument.

The relativistic argument against the fundamentality of the present

Premise (Point)

The fundamental ontological units are pointlike events, i.e., events without any temporal or spatial extension ('here-nows').

- If we take extended regions as starting point, then the situation is even worse for PCMs.

Premise (SR)

Minkowski spacetime correctly captures the spatiotemporal relations between pointlike events.

Premise (Present)

There is a fundamental present consisting in at least one event.

- Call this event p.
- Question: which other events stand in the relation of being co-present to p?

The relativistic argument against the fundamentality of the present (2)

Premise (Equivalence)

The binary relation R of 'being co-present with' is an equivalence relation, i.e., it is

1. *reflexive:* $\forall x, Rxx$, *i.e., an event is co-present with respect to itself*
2. *symmetrical:* $\forall x, y$, *if* Rxy, *then* Ryx
3. *transitive:* $\forall x, y, z$, *if* Rxy *and* Ryz, *then* Rxz

- Now the next question is how we should interpret the relation of being co-present with in terms of the geometry of Minkowski spacetime. There seem to be three viable options:

Premise (Simultaneity)

The relation of being co-present with is interpreted in the context of SR as the relation of being simultaneous with either (i) in all inertial frames, or (ii) in some inertial frame or other, or (iii) in some particular, but fixed inertial frame.

The relativistic argument against the fundamentality of the present (3)

- Let us consider these three options in turn.

Fact (1)

Given Point, SR, Present, Equivalence, and Simultaneity (i), the relation of being co-present with is the identity relation.

- For numerically distinct events, they must be spacelike-related in order to be simultaneous in some inertial frame.
- But only the identity relation is a candidate for co-presentness as it satisfies the premises if we demand that co-presentness means simultaneity in all inertial frames. Any spacelike-related events will be simultaneous in some, but not all, inertial frames.

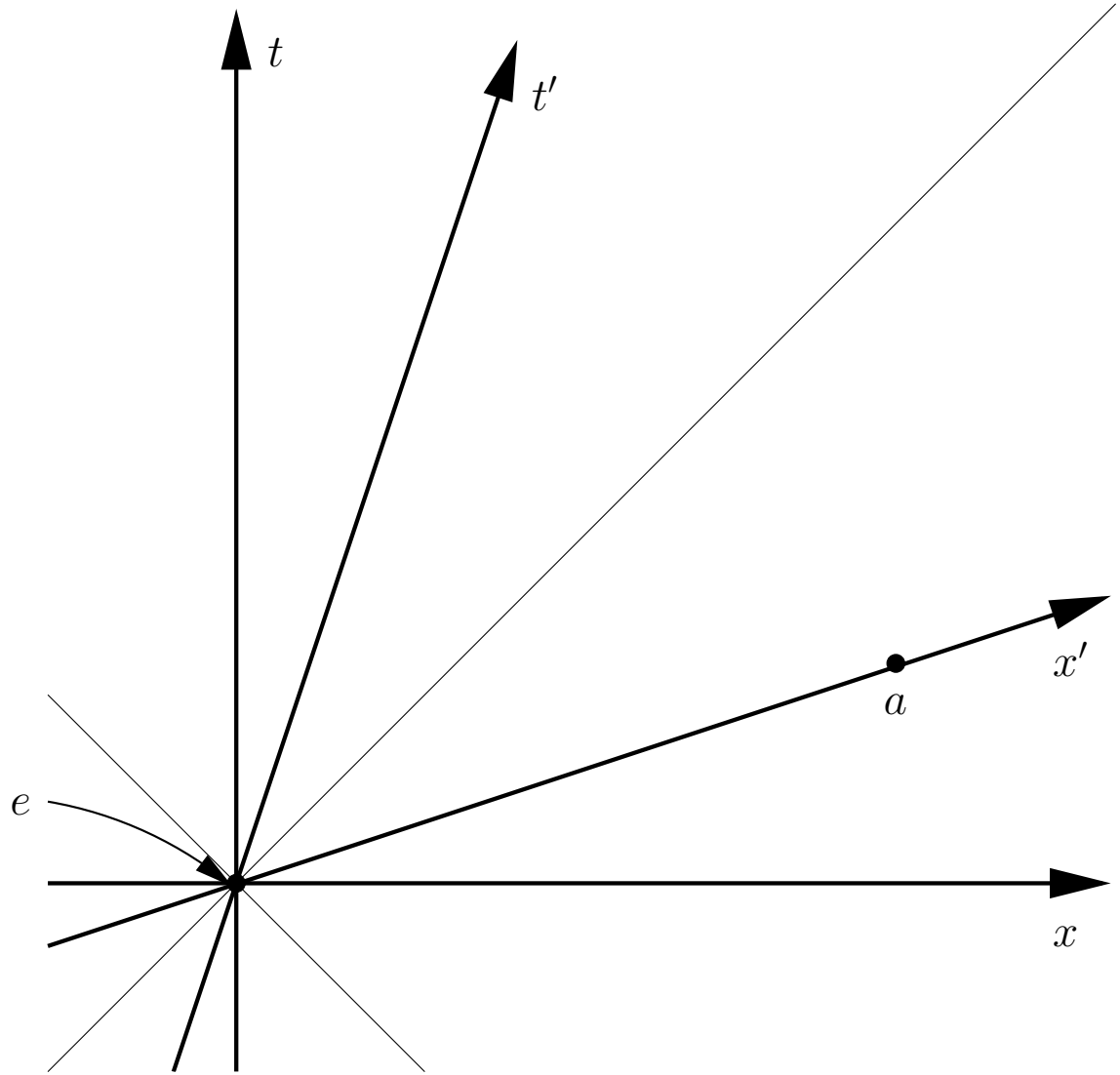
The relativistic argument against the fundamentality of the present (4)

Fact (2)

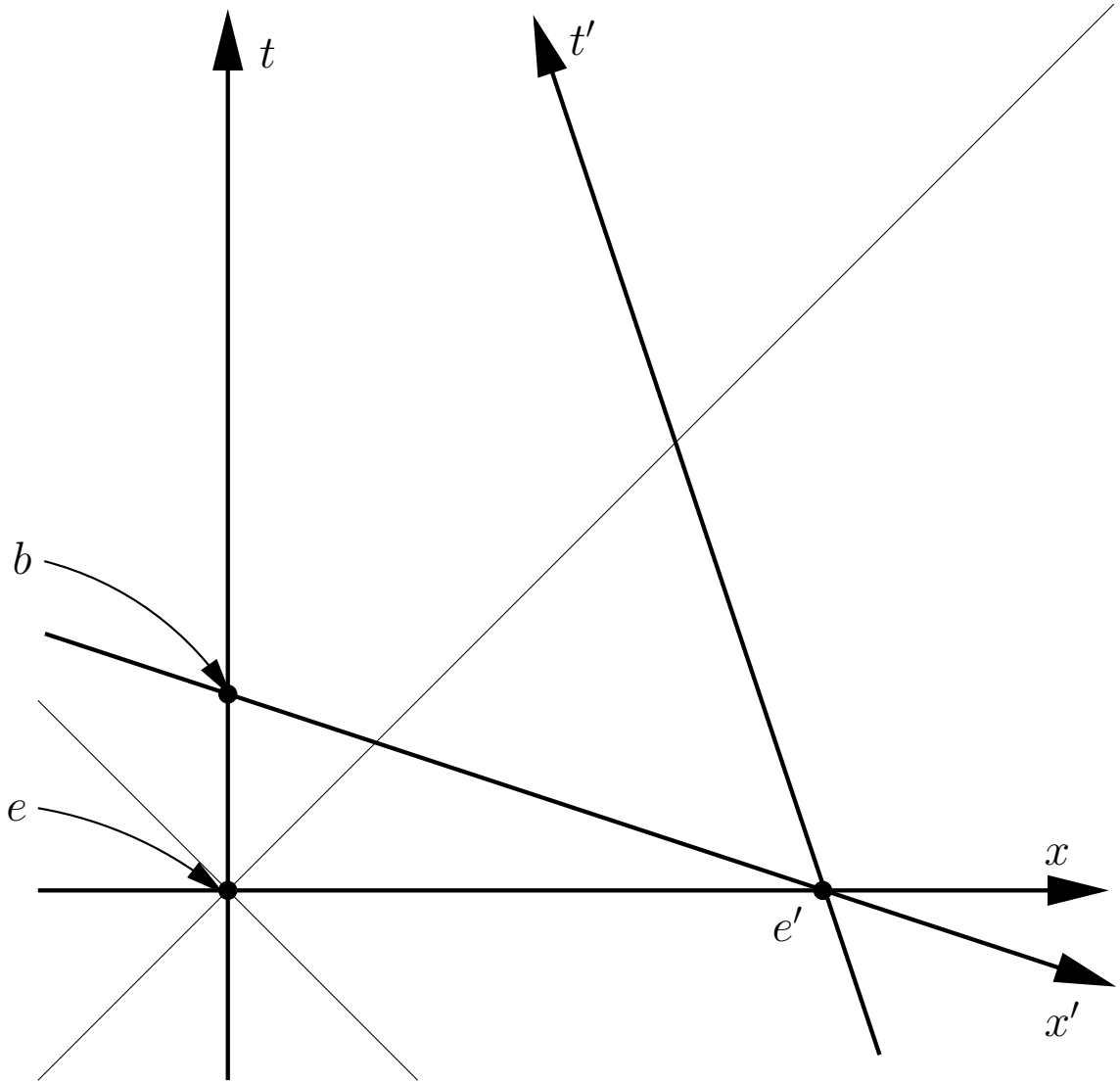
Given Point, SR, Present, Equivalence, and Simultaneity (ii), the relation of being co-present with is the universal relation.

- Any two (possibly timelike-related) events in Minkowski spacetime can be related by a sequence of two simultaneity relations (generally in different frames).
- Let's look at this geometrically:

For any spacelike-related events e and a



For any timelike-related events e, e', and b



The relativistic argument against the fundamentality of the present (5)

Fact (3)

Given Point, SR, Present, Equivalence, and Simultaneity (iii), the relation of being co-present with depends on a choice of inertial frame.

- This option for a simultaneity relation as the basis for co-presentness thus faces the challenge of justifying the assumption that one particular inertial frame bears special metaphysical weight.
- This inertial frame is neither empirically discernible nor physically special in any way as far as special relativity is concerned.

Fact (4)

The only options for a relation of co-presentness in special relativity that does not depend on a choice of a particular inertial frame, a particular event, or a particular worldline are the identity relation and the universal relation. So an event is co-present either only with itself or with any other event ever.

Putnam's conclusion

Putnam (1967, 247, emphasis in original)

> *I conclude that the problem of the reality and determinateness of future events is now solved. Moreover, it is solved by physics and not philosophy... Indeed, I do not believe that there are any longer any philosophical problems about Time; there is only the physical problem of determining the exact physical geometry of the four-dimensional continuum that we inhabit.*

Why no form of presentism escapes the pressure

In a nutshell

The basic problem for (almost) all forms of presentism is that it requires a metaphysically robust, objectively valid concept of a spatially extended present, and it seems that that can't be had.

- A spatially extended present is the set of all spacetime points which are simultaneous with the here-now.
- But the relativity of simultaneity in special relativity frustrates attempts of introducing an objectively valid concept of a spatially extended present.

$\Rightarrow$ Hence I favour eternalism. But let's see what an advocate of a PCM can say...

Can PCM recover?

Two types of strategies, depending on whether or not they accept premise SR:

1. Compatibilism: try to reconcile the PCM model with SR
2. Non-compatibilism: reject SR, as least in its standard form

(1) Compatibilism

Christian Wüthrich (2013). The fate of presentism in modern physics. In R Ciuni, K Miller, and G Torrengo (eds.), *New Papers on the Present–Focus on Presentism*. Philosophia Verlag, 91-131.

General compatibilist strategies (not necessarily exclusive) for saving PCMs:

1. Deny transitivity (and so reject premise Equivalence) of the relation 'being co-present with'.
2. Accept that co-presentness is either the identity relation ('spacetime solipsism') or the universal relation—but the latter is basically eternalism, so PCM is given up.
3. Modify presentist position: e.g. events on past light cone of p are co-present with p (motivation via their epistemic accessibility, and the invariant character of the light cone structure in SR). PCM is arguably modified.

Howard Stein: light cone becoming, a version of (4)

- Assuming the premises of the relativistic argument against the fundamentality of the present except the symmetry of R (and a time orientation in Minkowski spacetime), only one 'Lorentz-invariant' option remains for reconciling SR with a PCM:
- For any given point p, the only points co-present with p are those on or inside the past light cone of p (and p itself).

$\Rightarrow$ Since every point has a different past light cone, this amounts to a relativization of becoming to individual spacetime points—even spacelike-related ones.

$\Rightarrow$ 'fragmentation' of reality, i.e. for every point in spacetime, a different set of points are co-present and therefore existing

$\Rightarrow$ The relativistic argument does not rule out possibility of becoming entirely, but constrains it.

- Similar position: worldline becoming

Light cone becoming

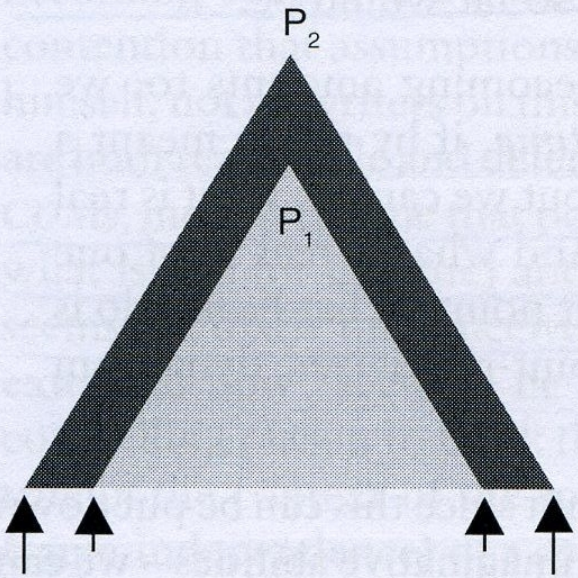


Figure 17.3 The coming-into-being of the distant past.

Light cone presentism

- Stein's light cone becoming is not a congenial home for presentism, since it would include the entire past lightcone at co-present with its apex.

$\Rightarrow$ hollow past light cone: only events on the surface of the past light cone of p are co-present with p

- epistemic accessibility: what's on past light cone is what you see now
- but: symmetry and transitivity of relation 'co-present' must be denied
- symmetry can be regained by extending reality to future light cone; but in what sense would this still be the present?

$\Rightarrow$ We are left with a position quite removed from the original motivations for PCM.

(2) Incompatibilism

- Idea: since there is an absolute and universal present, SR must be wrong, or at least be modified
- but: metaphysical preferences in themselves weak advocates against well-substantiated empirical theory
- Even if SR will be replaced one day, it is unlikely that theory with absolute simultaneity will be able to explain length contraction, time dilation, twin paradox etc.

$\Rightarrow$ relative simultaneity is here to stay

- weaker approach (Michael Tooley): there is absolute simultaneity (in line with Simultaneity (iii)), but it is in principle undetectable—so SR is accepted in some instrumental sense
- Of course, this requires that there is a privileged inertial frame, so Lorentz invariance no longer holds (or only as epistemic, rather than metaphysical invariance).
- But why should anyone believe in such a violation of Lorentz invariance?

The quantum move

Cf. modules 5 and 6

- So-called 'collapse interpretations' of quantum theory (QT) require instantaneous collapse of wave function across the entire universe and must thus rely on absolute simultaneity.
- Problems: few advocates; hard to make relativistic; might soon be experimentally ruled out.
- 'Bohmian mechanics', another interpretation of QT, also assumes (unobservable) absolute simultaneity.
- Problem: also not very popular; also hard to make relativistic.
- The existence of non-local quantum correlations appears to violate SR (but this is not necessarily so).
- More generally, it is acknowledged that it's a problem for QT that it's not Lorentz invariant $\Rightarrow$ quantum field theory (QFT).

The dilemma of any PCM:

Dilemma

Any identification of a present/becoming in special relativity either answers to the PCM theorist's explanatory demands or is compatible with the structure of Minkowski spacetime, but not both. (Callender 2000, Wüthrich 2013)

(This remains true whether or not the additional, non-Lorentz-invariant structure is observable.)

Craig Callender (2000). Shedding light on time. *Philosophy of Science* 67: S587-S599.

Christian Wüthrich (2013). The fate of presentism in modern physics. In Ciuni, Miller, and Torrengo (eds.), *New Papers on the Present–Focus on Presentism*, Philosophia Verlag: 91-131.