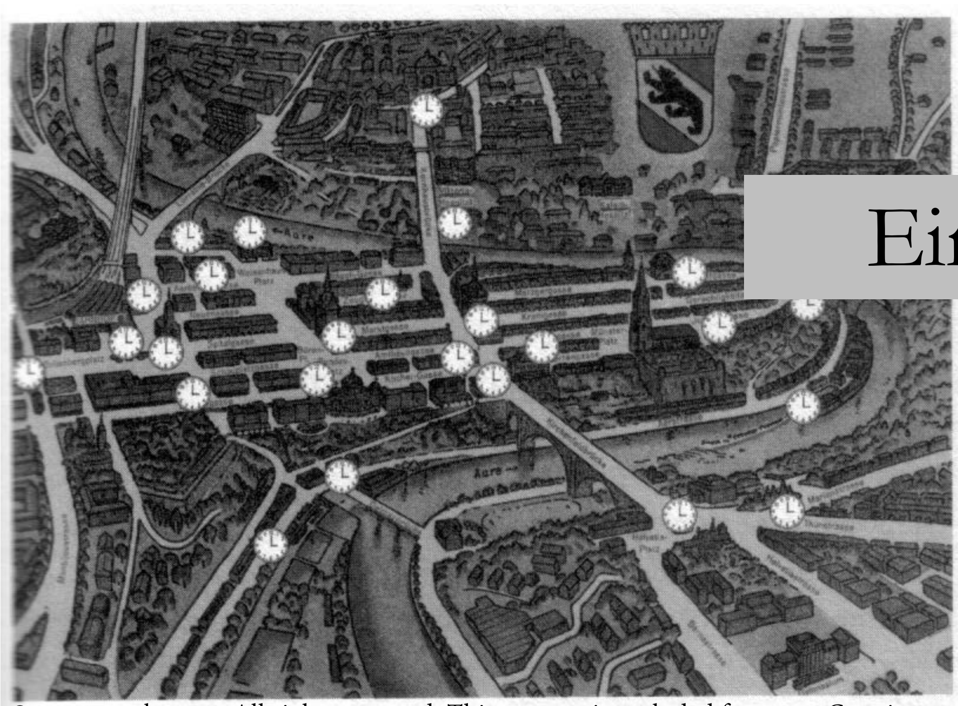


Einstein and Experiment

8.225 / STS.042, Physics in the 20th Century

Professor David Kaiser, 21 September 2020

1. Einstein in 1905:
Kinematics before Dynamics

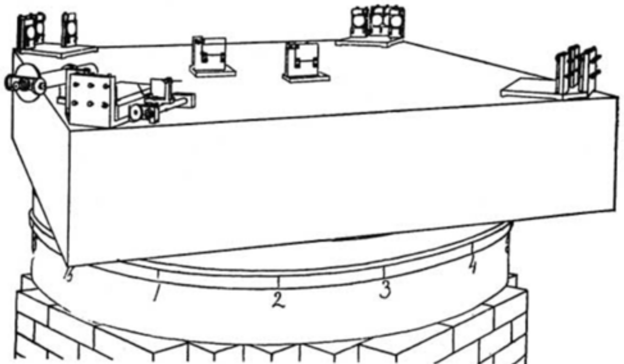
2. Relativity of Simultaneity*

3. Einstein's Experimental Context

* See *Lecture Notes* on "$E = mc^2$"

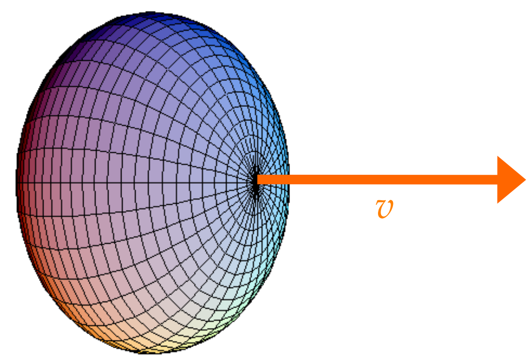
Waves in the Ether: Recap

We saw in the last lecture that questions about light waves in the ether, and efforts to detect the Earth's motion through the ether, were at the center of mainstream physics in the late 19th century: *the electrodynamics of moving bodies*.



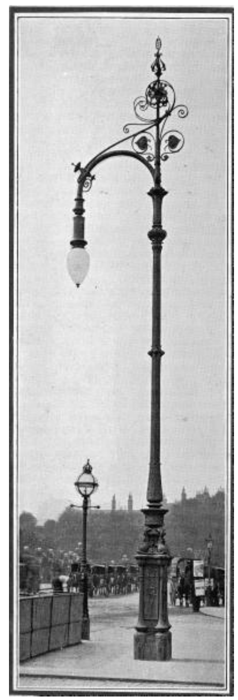
Albert Michelson and Edward Morley used a large *interferometer* to try to measure changes in the relative speed of light, depending on whether it moved directly into an "ether head wind" or perpendicular to it. Their "null result" remained a lifelong disappointment for (Nobel laureate) Michelson.

Mathematical physicists like Hendrik Lorentz accounted for the null result by considering the *force* exerted on the apparatus by the physical, elastic ether: *length contraction*. Lorentz and his peers began with *dynamics* (study of forces) in order to account for *kinematics* (motion of objects).



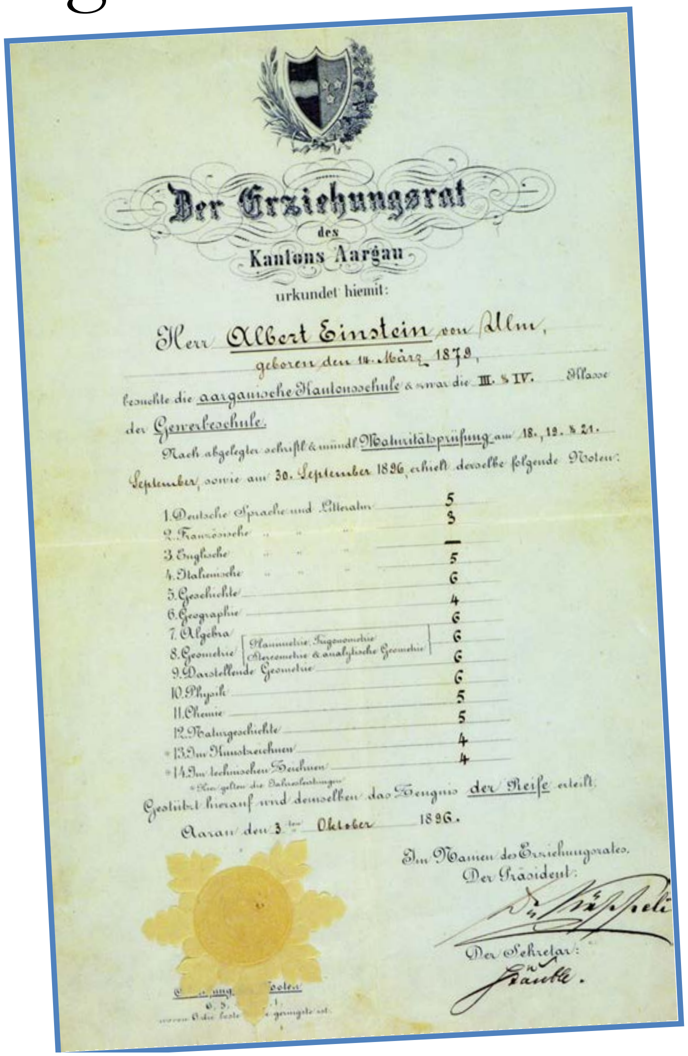
Young Albert

Albert Einstein (1879 – 1955) was born in Ulm, Germany. He dreamed of joining his father's and uncle's business in electrical engineering.



Electric street lighting, ca. 1900

Young Albert



Der Erziehungsrat des Kantons Aargau urkundet hiemit:

Herr Albert Einstein von Ulm,
geboren den 14. März 1879,
besuchte die aargauische Kantonsschule & zwar die III. & IV. Klasse der Gewerbeschule.

Nach abgelegter schriftl. & mündl. Maturitätsprüfung am 18., 19. & 21. September, sowie am 30. September 1896, erhielt derselbe folgende Noten:

1. Deutsche Sprache und Litteratur	5
2. Französische	3
3. Englische	—
4. Italienische	5
5. Geschichte	6
6. Geographie	4
7. Algebra	6
8. Geometrie (Planimetrie, Trigonometrie, Stereometrie & analytische Geometrie)	6
9. Darstellende Geometrie	6
10. Physik	6
11. Chemie	5
12. Naturgeschichte	5
13. Im Kunstzeichnen	4
14. Im technischen Zeichnen	4

Gestützt hierauf wird demselben das Zeugnis der Reife erteilt.

Aarau, den 3ten Oktober 1896.

Im Namen des Erziehungsrates,
Der Präsident:

Der Sekretär:

He dropped out of high school, took the entrance exam for the ETH* in Zürich in 1895 – and failed. He passed the second time.

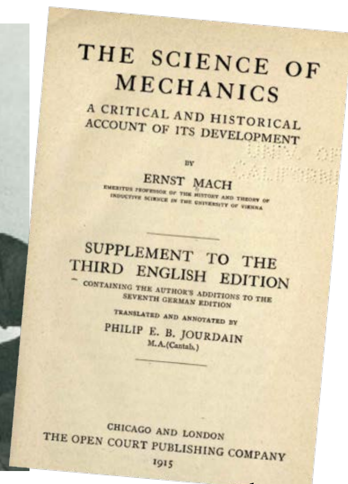
He then proceeded to cut classes to read on his own: Maxwell, Boltzmann, etc.

*Eidgenössische Technische Hochschule: Federal Polytechnic Institute

Patent Officer, 3rd Class

Einstein had so annoyed his professors that upon graduation he couldn't get a job. With help from his friend's father, he finally landed a position in the patent office in Bern, Switzerland.

"Olympia Academy": Solovine, Habicht, Einstein, ca. 1905



THE SCIENCE OF MECHANICS

A CRITICAL AND HISTORICAL ACCOUNT OF ITS DEVELOPMENT

BY

ERNST MACH

SUPPLEMENT TO THE THIRD ENGLISH EDITION

CONTAINING THE AUTHOR'S ADDITIONS TO THE SEVENTH GERMAN EDITION

TRANSLATED AND ANNOTATED BY

PHILIP E. B. JOURDAIN M.A.(Cantab.)

CHICAGO AND LONDON

THE OPEN COURT PUBLISHING COMPANY

1915

Einstein at the Patent Office, 1905

Even for Einstein, it's not *what* you know, but *who* you know…

Patent Officer, 3rd Class

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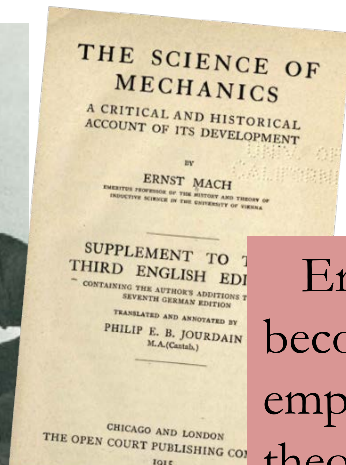

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1915

Einstein at the Patent Office, 1905

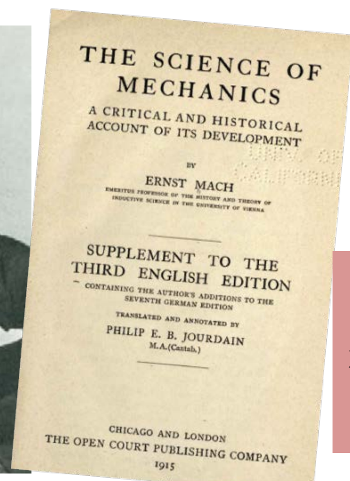
Ernst Mach: "positivism." Only quantities that could become "objects of positive experience" — subject to empirical measurement — belonged in physical theories. Anything else would lead to empty metaphysics and confusion. E.g.: Newtonian "absolute space" and "absolute time" had no meaning.

Patent Officer, 3rd Class

Einstein had so annoyed his professors that upon graduation he couldn't get a job. With help from his friend's father, he finally landed a position in the patent office in Bern, Switzerland.

Einstein at the Patent Office, 1905

Inspired by Mach, Einstein pursued a critical re-evaluation of *kinematics*, before worrying about *dynamics*.



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1915

Not a Bad Year…

While working at the patent office, Einstein submitted several papers to the *Annalen der Physik*.

March 1905: light quanta
May 1905: Brownian motion
June 1905: special relativity
September 1905: $E = mc^2$

3. ***Zur Elektrodynamik bewegter Körper;***
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen

"On the Electrodynamics of Moving Bodies": the title sounded conventional, but Einstein's approach was distinct.

In conclusion, let me note that my friend and colleague M. Besso steadfastly stood by me in my work on the problem discussed here, and that I am indebted to him for several valuable suggestions.

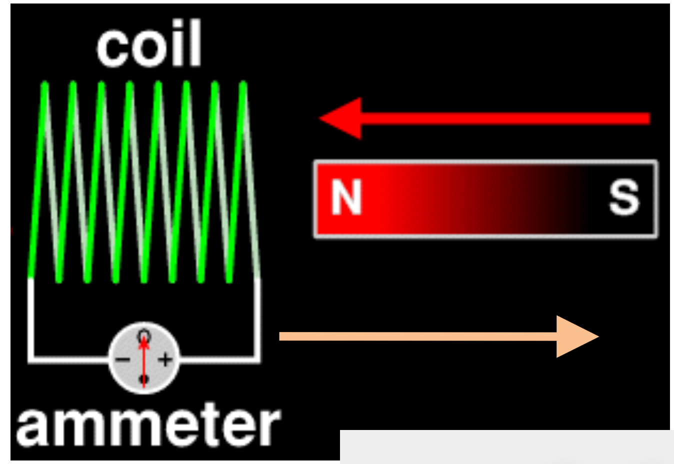
(*Annalen der Physik* 17 [1905]: 891–921)

Questions?

“An Asymmetry in the Explanation”

When the magnet and coil were in relative motion, an electric current was produced.

Physicists had given two completely different explanations for the effect, depending on which item was moving.



Case 1: Magnet moving, coil at rest

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\longrightarrow \mathbf{F} = q\mathbf{E}$$

The time-varying **B** field induces an **E** field, which exerts a force on the charges in the coil, pushing them along the coil and generating a current.

“An Asymmetry in the Explanation”

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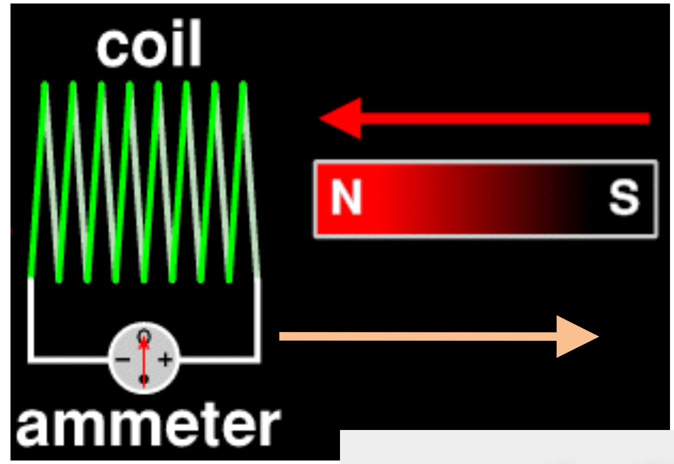
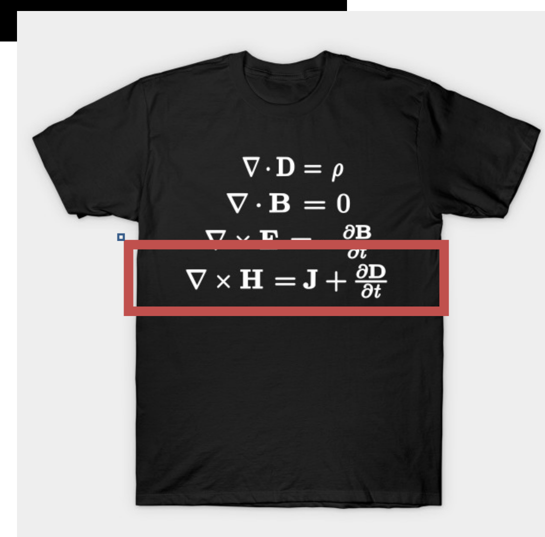


Case 2: Coil moving, magnet at rest

$$\nabla \times \mathbf{B} = \epsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t}\,,$$
$$\mathbf{F} = q\,(\mathbf{v} \times \mathbf{B})$$

The static magnetic field varies in space, generating a “displacement current.” By virtue of their motion **v**, the charges in the coil experience a force from **B** and are pushed along the coil, generating a current.



“An Asymmetry in the Explanation”

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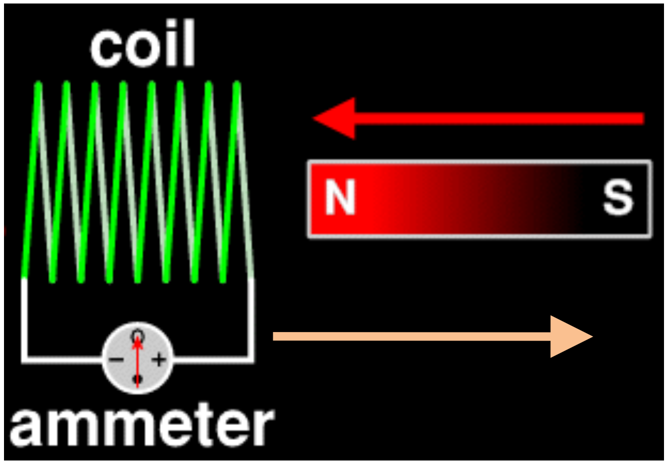


Einstein insisted that physicists had been too clever by half. There was only *one phenomenon* — magnet and coil in relative motion, current generated — so there should only be *one explanation*.

Two Postulates

1. The laws of physics are valid in any frame of reference moving at a constant speed (*inertial* frames of reference).
2. The speed of light *c* is constant, independent of the motion of the source.

3. Zur Elektrodynamik bewegter Körper;
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fälle

for every reference system in which the laws of mechanics are valid*, the laws of electrodynamics and optics are also valid.

We will raise this conjecture (whose intent will from now on be referred to as the "Principle of Relativity") to a postulate, and moreover introduce another postulate, which is only apparently irreconcilable with the former: 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 in order to obtain a simple and consistent theory of the electrodynamics of moving bodies taking as a basis Maxwell's theory for bodies at rest. The introduction of a "luminiferous ether" will prove to be superfluous because the view here to be developed will introduce neither an "absolutely resting space" provided with special properties, nor associate a velocity-vector with a point of empty space in which electromagnetic processes occur.

Why Postulate Two?

Einstein began to wonder at age 16: what would happen if you could catch up to a light wave?

Like a surfer riding along a wave on the ocean, the wave would look *static*: frozen in space, not changing over time.

But from Maxwell's equations, if there were no sources nearby ($\rho = J = 0$), there could be no *static* field configurations, with **E** and **B** frozen in space.

How could one avoid that contradiction? *Make sure no one could ever catch up with a light wave!*

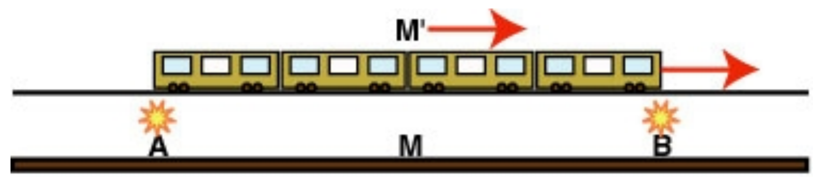
Kinematics First

Inspired by Mach, Einstein *began* with kinematics, not dynamics: What we can *observe* are bodies in motion through space and time.

If we wish to describe the *motion* of a material point, we give the values of its coordinates as functions of the time. Now we must bear carefully in mind that a mathematical description of this kind has no physical meaning unless we are quite clear as to what we will understand by "time". We have to take into account that all our judgments in which time plays a role are always judgments of *simultaneous events*. If, for instance, I say, "That train arrives here at 7 o'clock," I mean something like this: "The pointing of the small hand of my watch to 7 and the arrival of the train are simultaneous events."

Relativity of Simultaneity

If there is no absolute time, how can we compare times associated with different events? By sending *light signals*, since c = constant.



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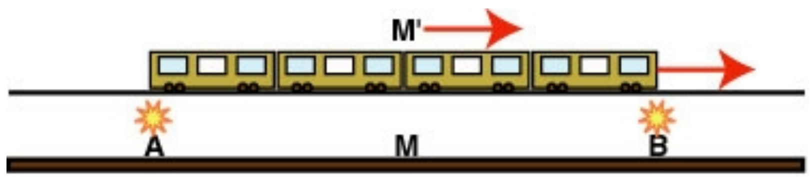
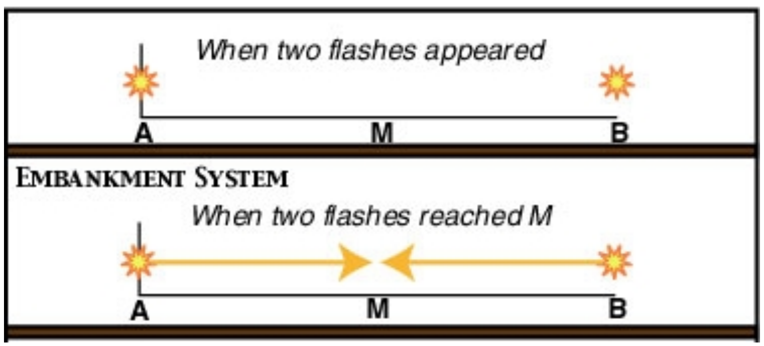
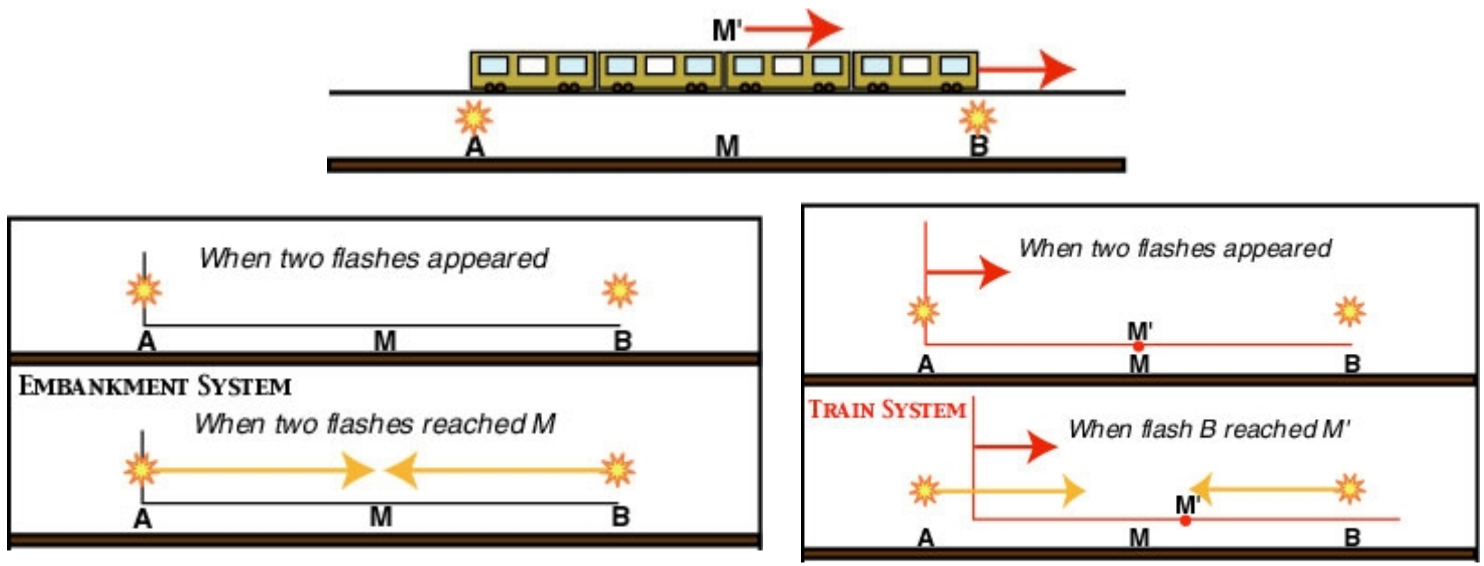




The observer on the train platform at M was an equal distance from locations A and B, and she received light waves from A and B at the same time. Thus, she concludes, the flashes were emitted *simultaneously* from A and B.

Relativity of Simultaneity

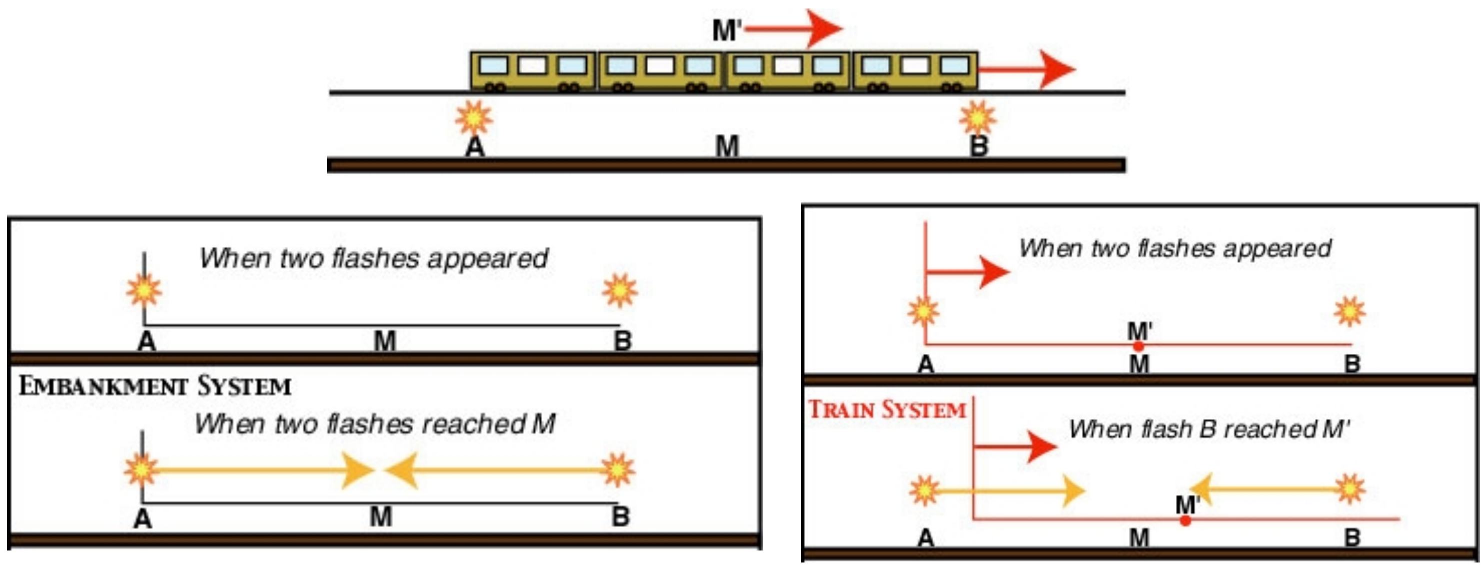
If there is no absolute time, how can we compare times associated with different events? By sending *light signals*, since c = constant.



The observer on the train at M' was an equal distance from locations A and B, but she received the light wave from B *before* she received the light wave from A. Thus, she concludes, the flashes were *not* emitted simultaneously from A and B.

Relativity of Simultaneity

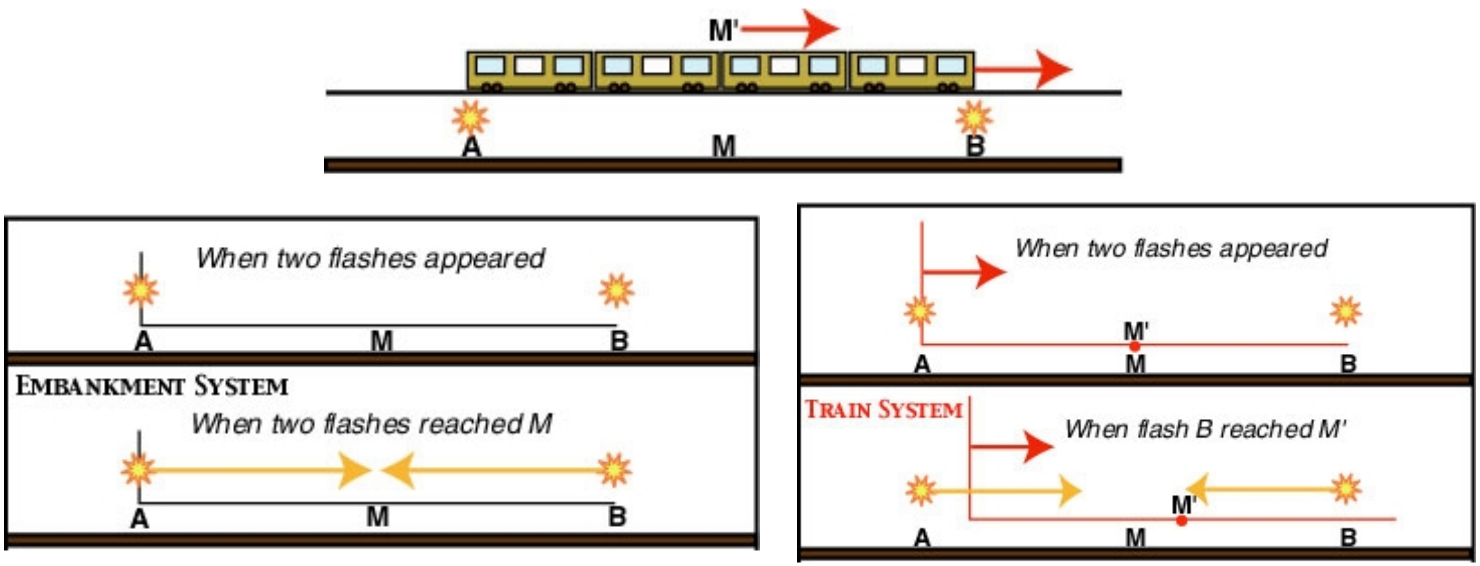
If there is no absolute time, how can we compare times associated with different events? By sending *light signals*, since c = constant.



Who was correct? *Both!* Recall postulate 1: The laws of physics are valid in *any* frame of reference moving at a constant speed (*inertial* frames of reference).

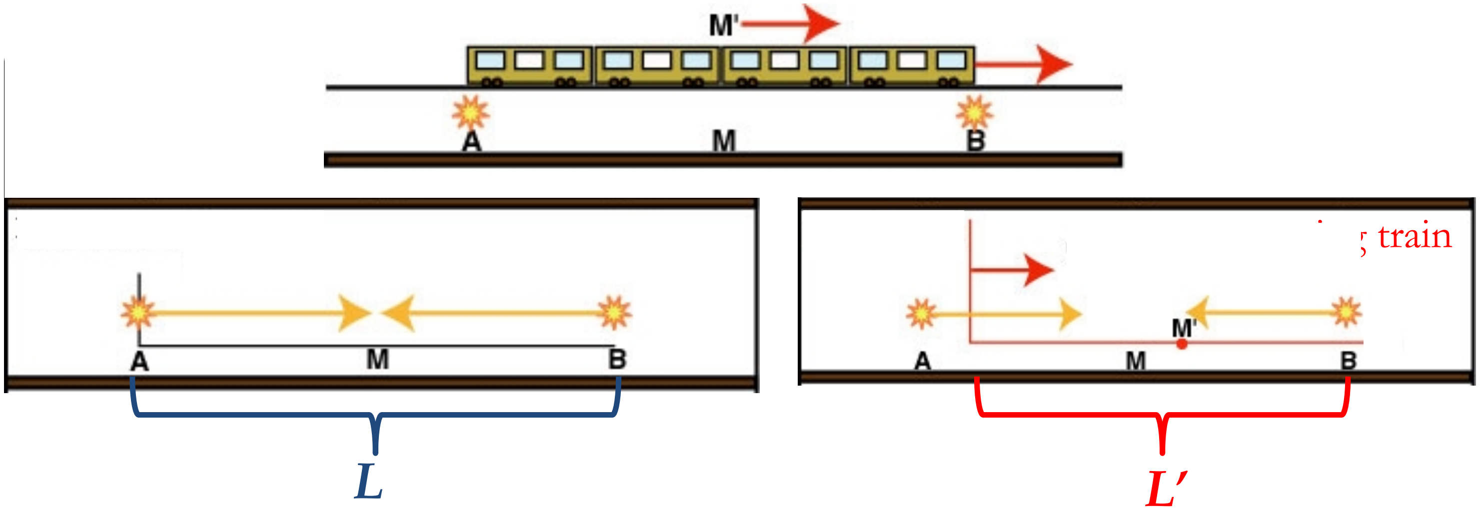
Relativity of Simultaneity

If there is no absolute time, how can we compare times associated with different events? By sending *light signals*, since c = constant.



Thus we see that we can attribute no *absolute* meaning to the concept of simultaneity, but that two events which, examined from a coordinate system, are simultaneous, can no longer be interpreted as simultaneous events when examined from a system which is in motion relatively to that system.

Length Contraction

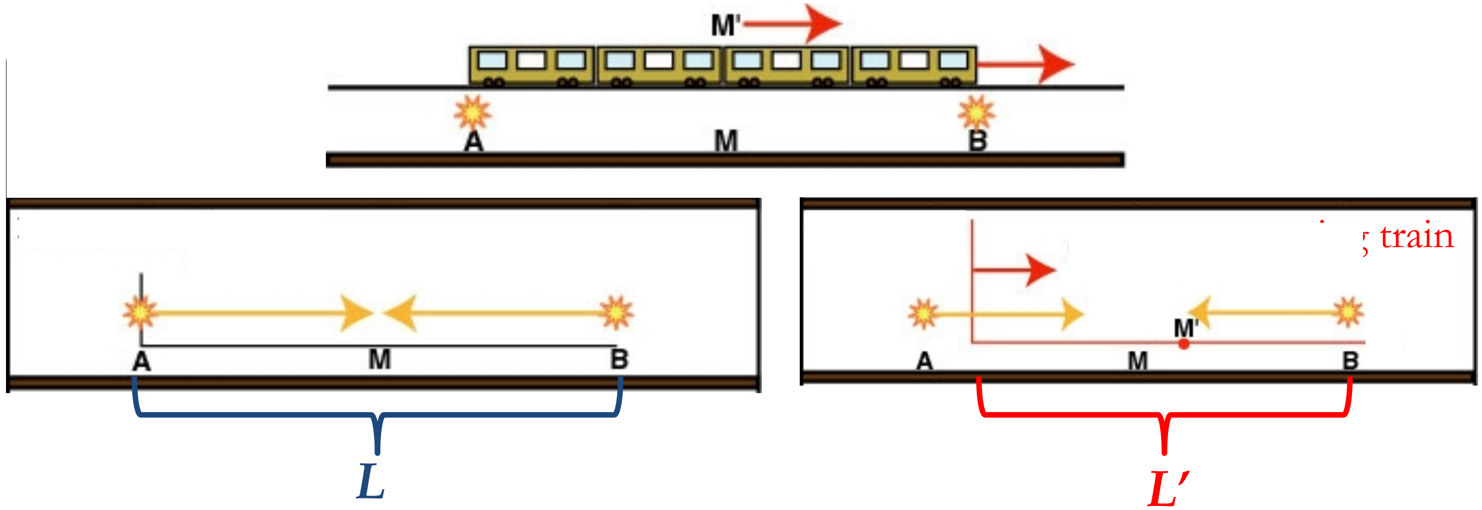


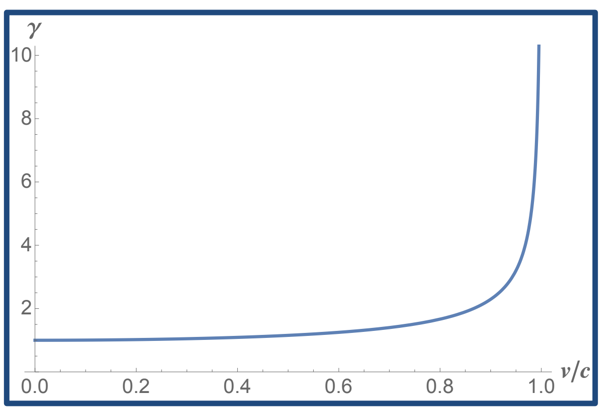
The passenger on the train says that the person on the platform *first* measured the location of the front, then *waited* while the train moved, and only *later* measured the location of the back — so of course their measurement was *too short*.

How do we measure the *length* of an object? *At the same time*, measure the locations of the front and the back of the object, and take the difference.

If we disagree about simultaneity, then we will disagree about lengths!

Length Contraction



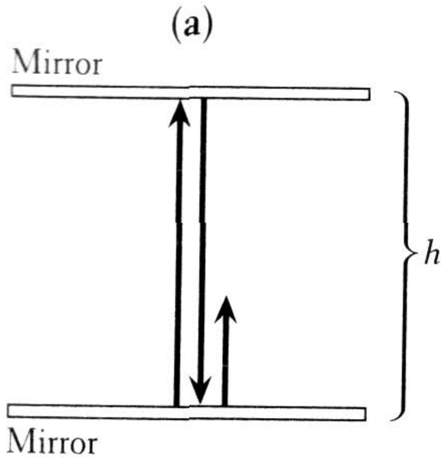


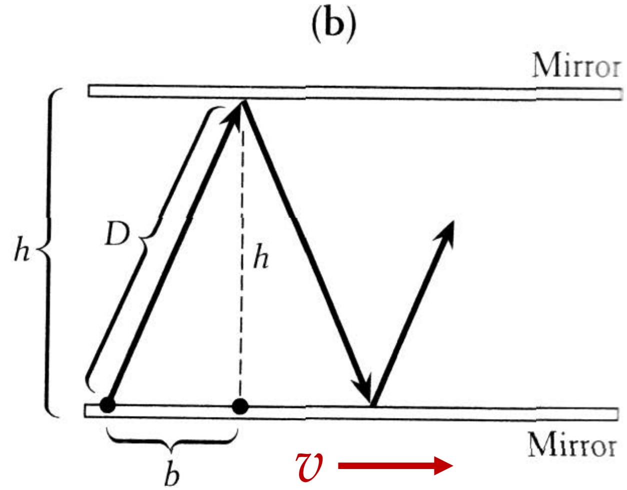
$$L' = L/\gamma$$

A moving object *shrinks* along its direction of motion.

To Einstein, length contraction had *nothing to do with forces exerted by an ether (dynamics)*; it was simply a consequence of *kinematics*.

Time Dilation





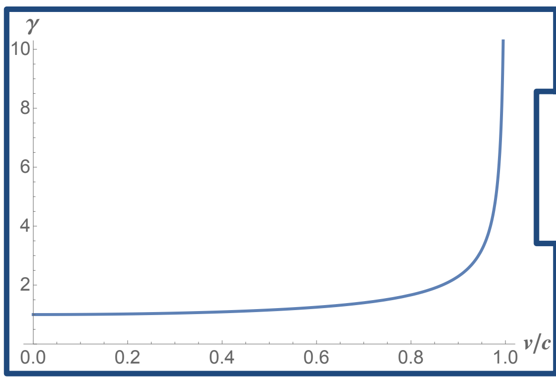
$$\Delta t = \frac{h}{c}$$

$$D^2 = b^2 + h^2$$

$$(c\Delta t')^2 = (v\Delta t')^2 + h^2$$

$$= (v\Delta t')^2 + (c\Delta t)^2$$

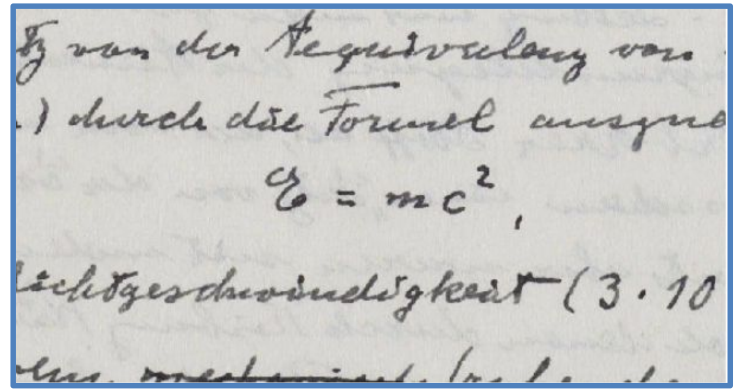
$$\Delta t' = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\Delta t$$

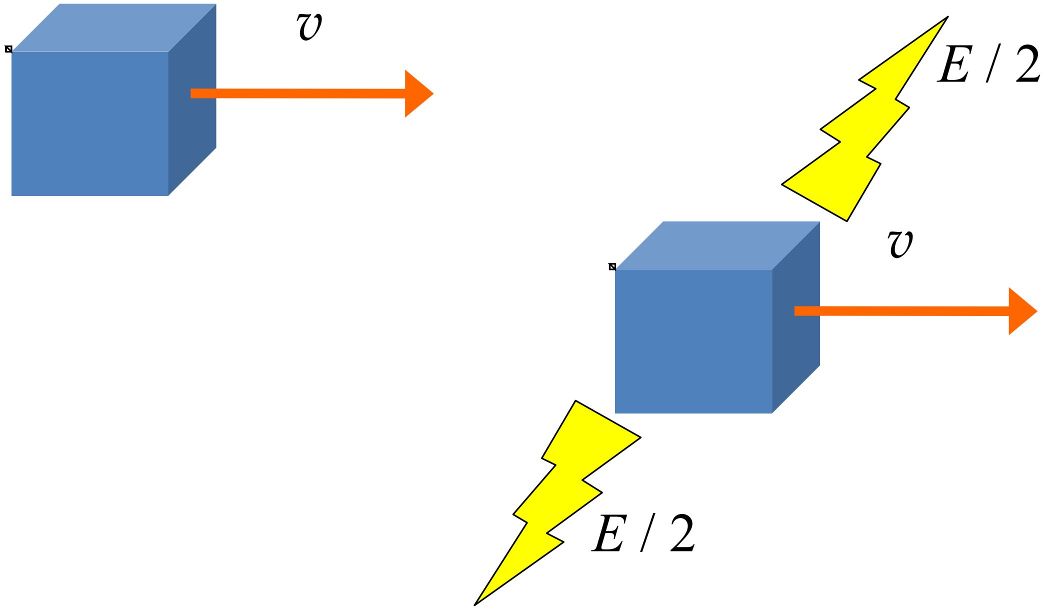


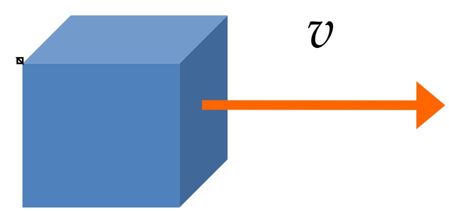
$$\boxed{\Delta t' = \gamma \Delta t}$$

A moving clock *ticks slowly*.

Mass and Energy







* See *Lecture Notes* on "$E = mc^2$"

Einstein argued: the *velocity* of the box did not change, so to *conserve energy*, the *mass* of the box must have changed: $\Delta m = E/c^2$, or $E = (\Delta m)\, c^2$ (for small v). For arbitrary v, $E = \gamma\, (\Delta m)\, c^2$.

Questions?

Einstein and Experiment

For a long time, physicists, philosophers, and historians read Einstein's relativity as a direct response to the Michelson-Morley experiment.

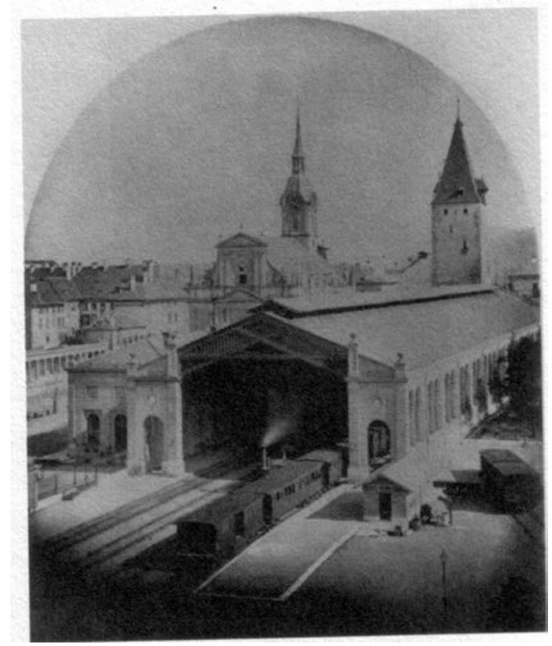
Yet it's not clear whether Einstein even *knew* about the results at the time. Either way, they don't seem to have played much role in his thinking.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," lead to the conjecture that to the concept of absolute rest there correspond no properties of the phenomena, neither in mechanics, nor in electrodynamics, but rather that as has already been shown to quantities of the first order, for every reference system in which the laws of mechanics are valid*, the laws of electrodynamics and optics are also valid.

Does that mean that Einstein was uninterested in experiments?

Train Time

Until the late 19th century, there were no coordinated time zones. Each town kept local time, based on a clock in its town square.



Bern train station, ca. 1860
Image is in the public domain.

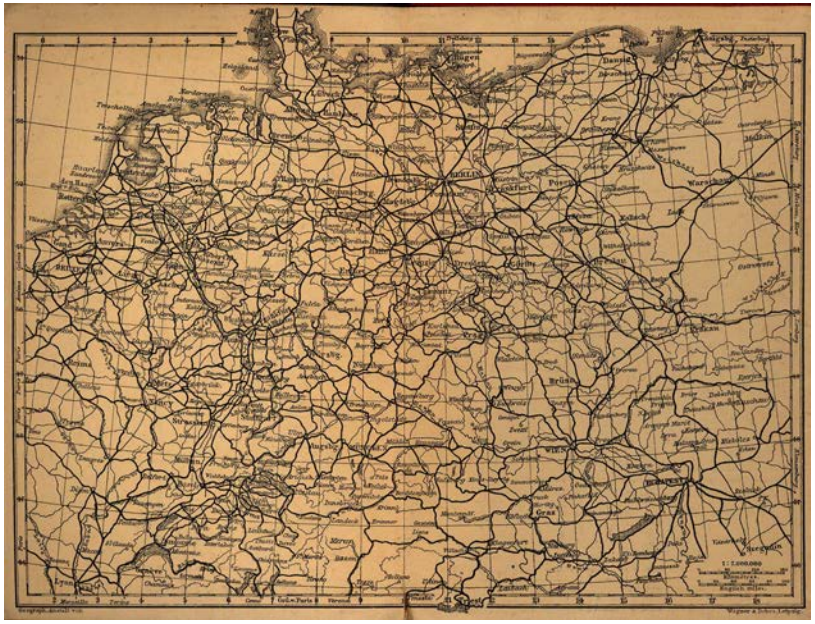
French train wreck, 1895
Image is in the public domain.

Passengers riding from Boston to New York City had to change their watches by 37 minutes after their trip.

Time Zones

"That unity of time is indispensible for the satisfactory operating of railways is universally recognized, and is not disputed. But, *meine Herren*, we have in Germany five different units of time. […] We have thus in Germany five zones, with all the drawbacks and disadvantages which result. These we have in our own fatherland, besides those we dread to meet at the French and Russian boundaries. This is, I may say, a ruin which has remained standing out of the once splintered condition of Germany, but which, since we have become an empire, it is proper should be done away with."

Count von Moltke, 1891



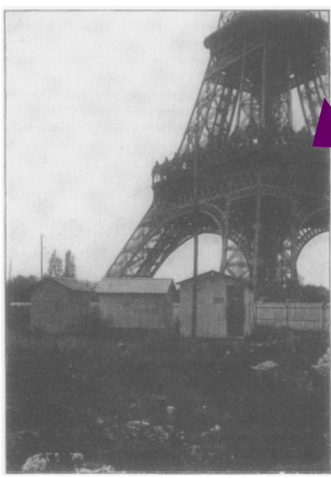
German railway system, 1910
Image is in the public domain.

Especially relevant after 1870 war with France, and 1871 unification of Germany.

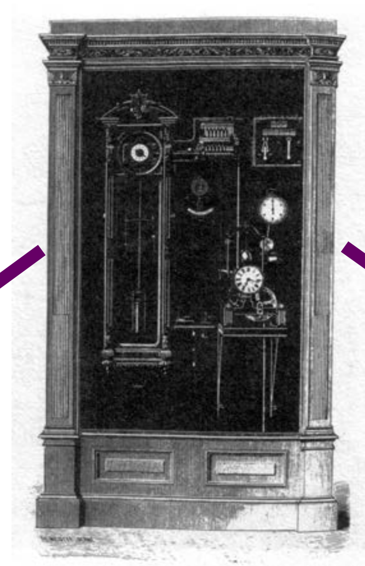
All during Einstein's childhood.

Coordinating Clocks at a Distance

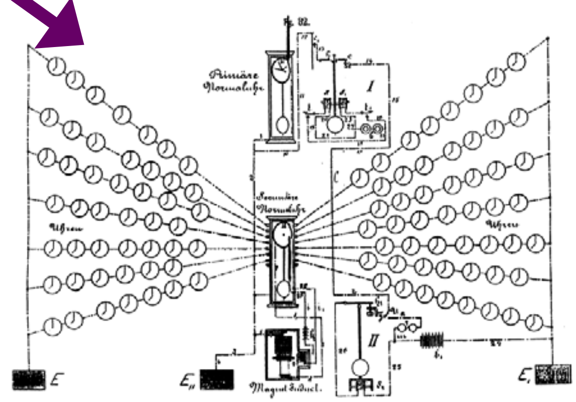
Main idea: install massive "mother clocks" in central train stations, connected to other clocks via telegraph or radio signals.



Eiffel Tower radio station, ca. 1910

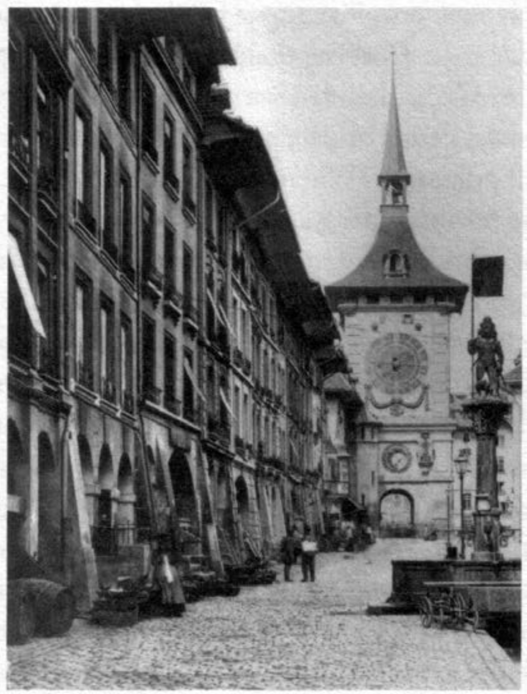


"Mother clock" in Neuchatel, Switzerland, ca. 1920



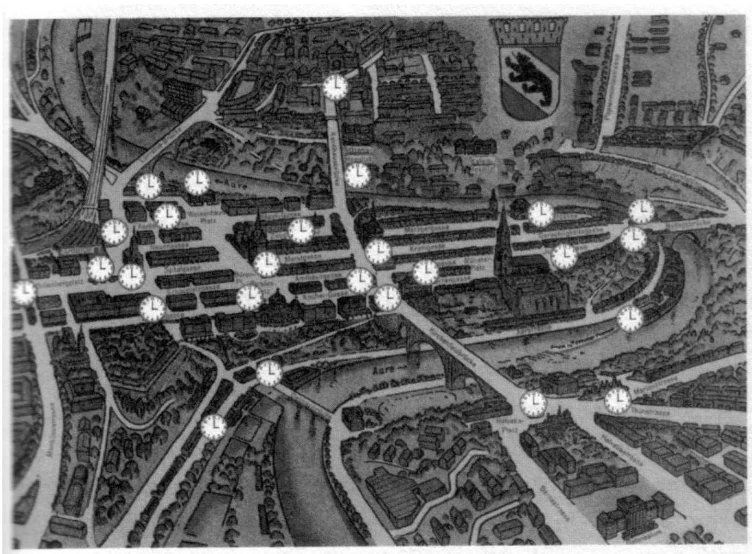
Time synchronization scheme, 1890

Patents and Pathways

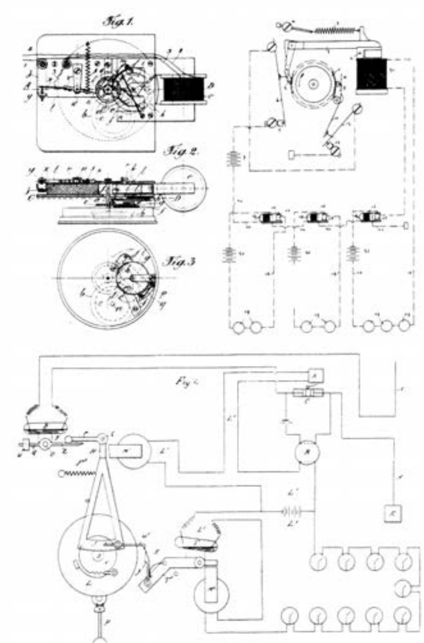


Coordinated clock on Einstein's block, 1905

Einstein was immersed in these devices: at the electro-technical desk at the patent office, and even on his stroll to get to the patent office.



Coordinated clock network throughout Bern, 1905



Patents on clock coordination components, 1903–1905

Re-Reading Einstein

**3. *Zur Elektrodynamik bewegter Körper;*
*von A. Einstein.***

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen

Lack of references: emphasize priority, downplay precedents;

Focus on operational details of measuring space, time, and simultaneity.

Looks like a patent application…

STS.042J / 8.225J Einstein, Oppenheimer, Feynman: Physics in the 20th Century
Fall 2020