# Space, Time, and Spacetime



David Kaiser

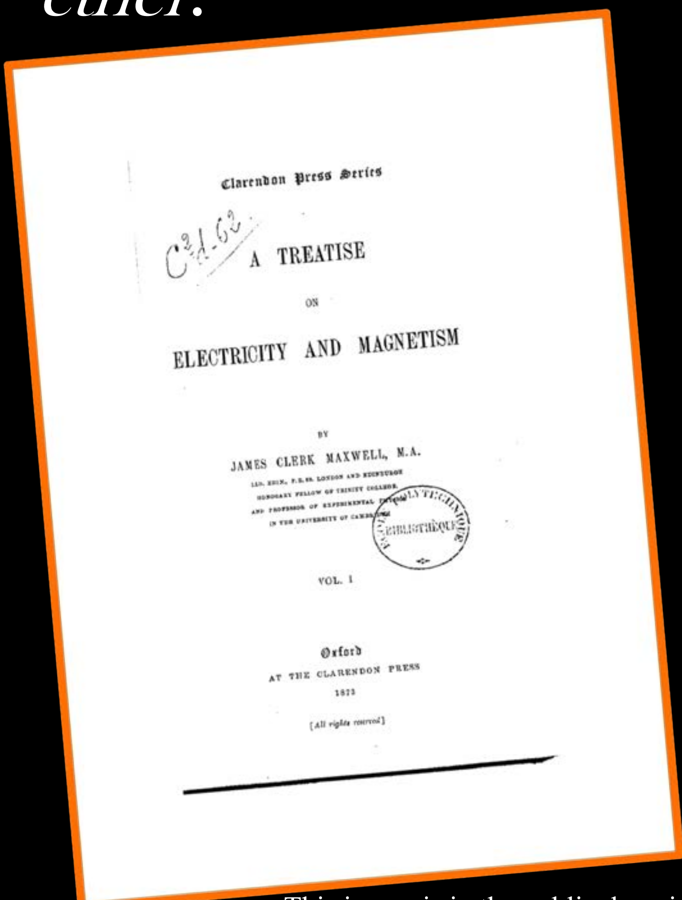
# I. Motion through the Ether

# II. Patent Clerk, Third Class

# III. Clock Coordination

# Maxwell's Medium

Electrical actions are "effected, not by direct action at a distance, but by means of a distribution of stress in a *medium* extending continuously" throughout the universe: the *ether*.



Clarendon Press Series

A TREATISE

ON

ELECTRICITY AND MAGNETISM

BY

JAMES CLERK MAXWELL, M.A.

LLD. EDIN., F.R.SS. LONDON AND EDINBURGH

HONORARY FELLOW OF TRINITY COLLEGE,

AND PROFESSOR OF EXPERIMENTAL PHYSICS

IN THE UNIVERSITY OF CAMBRIDGE

VOL. I

Oxford

AT THE CLARENDON PRESS

1873

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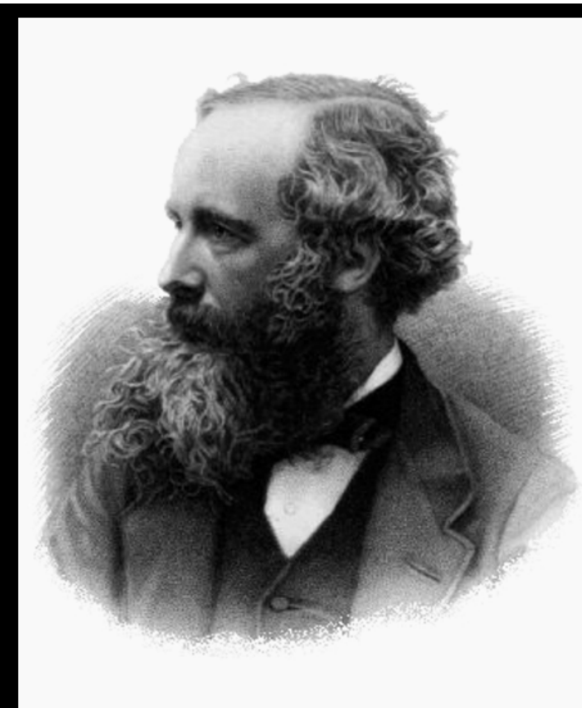

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James Clerk Maxwell (1831 – 1879)

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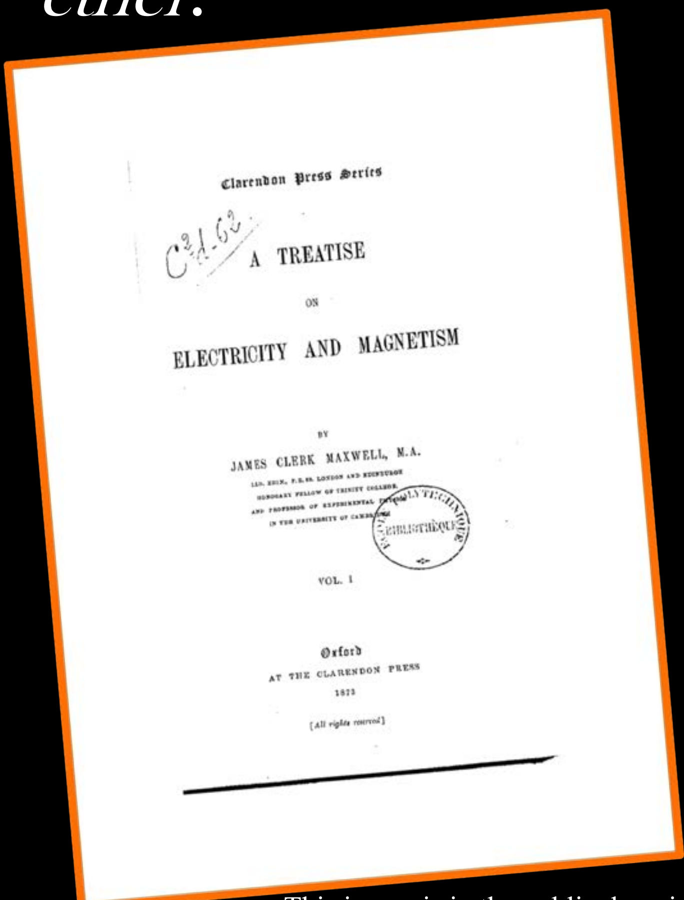

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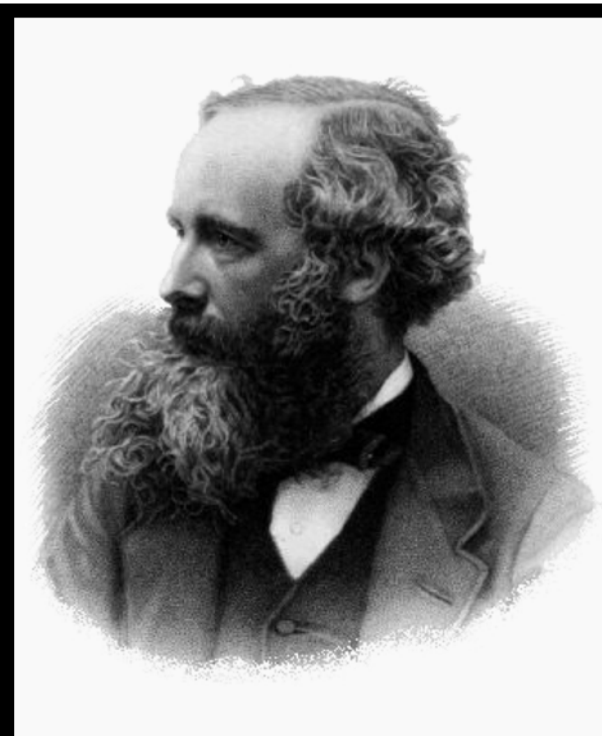
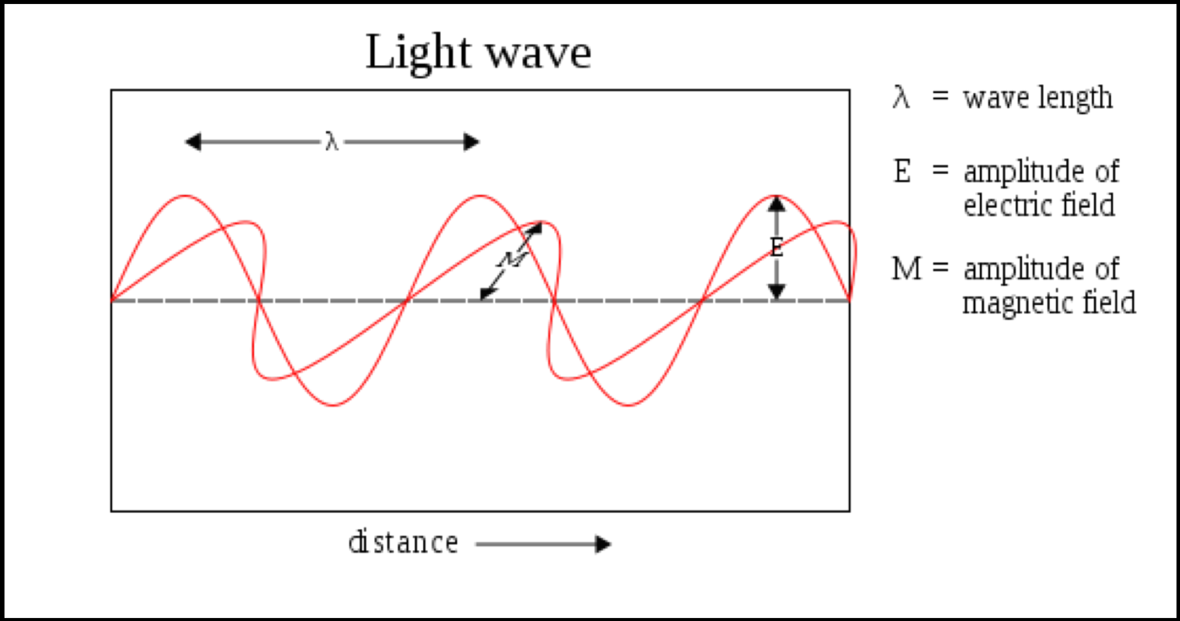


James Clerk Maxwell (1831 – 1879)



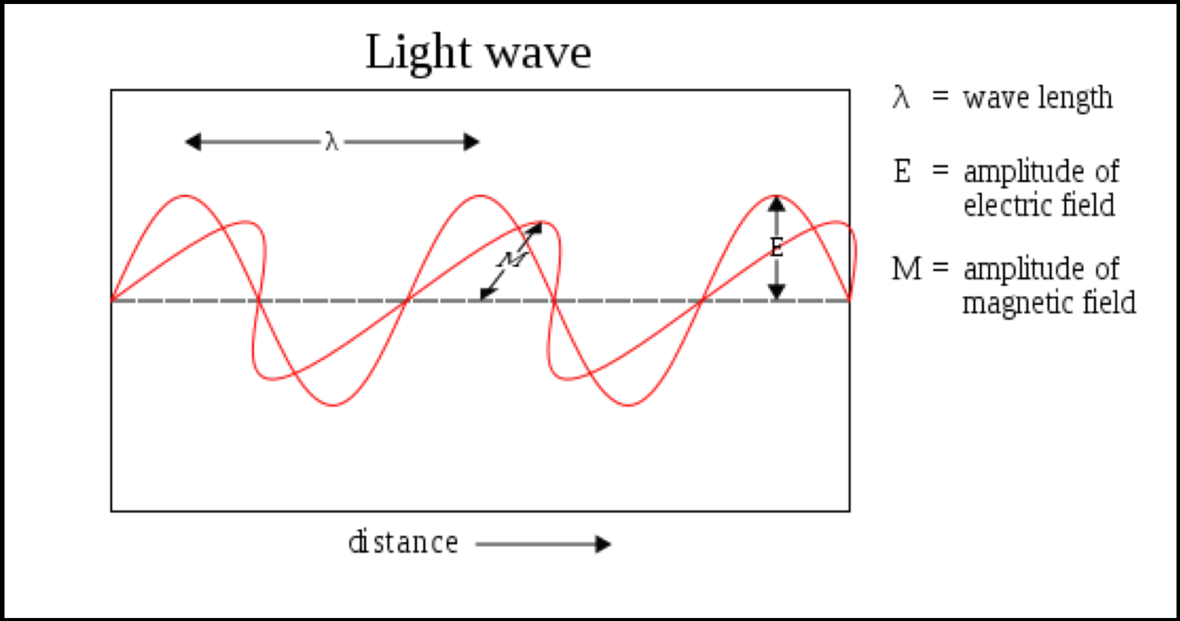
Wm. Thomson: "Stick your hand in a bowl of jelly, and see how it wiggles and vibrates as you move your hand around."

# Maxwell's Waves




Maxwell calculated how quickly disturbances would propagate in this material ether... and found that waves would travel at the speed of light.

# Maxwell's Waves




"The velocity of transverse undulations in our hypothetical medium agrees so exactly with the velocity of light calculated from optical experiments that we can scarcely avoid the inference that light consists of the transverse undulations of the same medium which is the cause of electric and magnetic phenomena." (1864)

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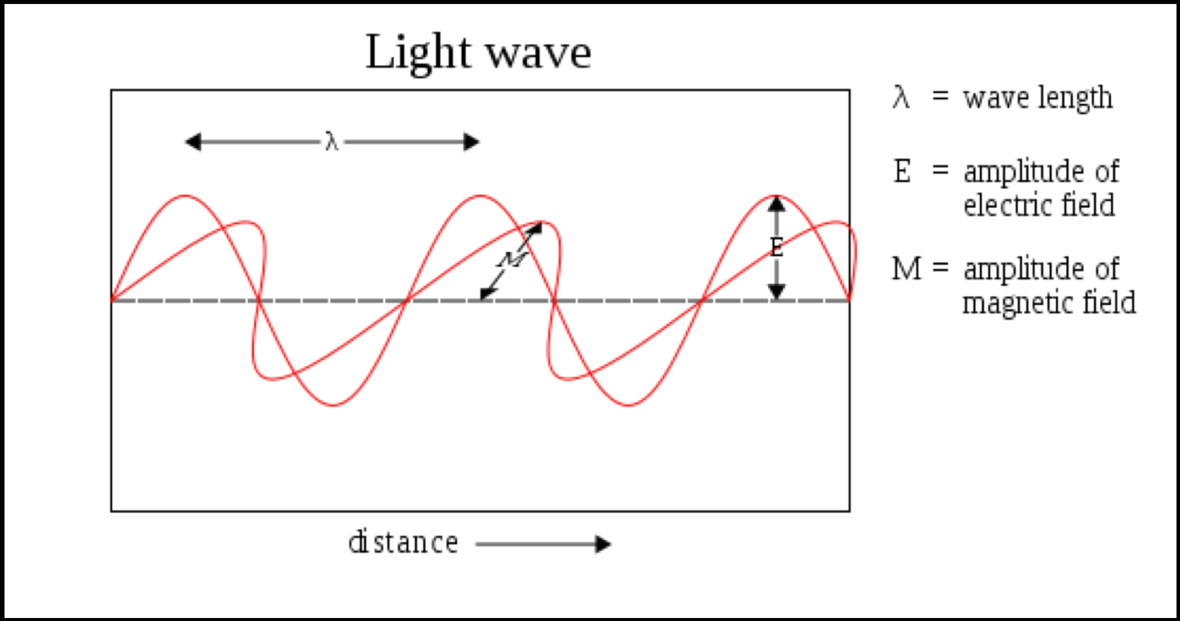


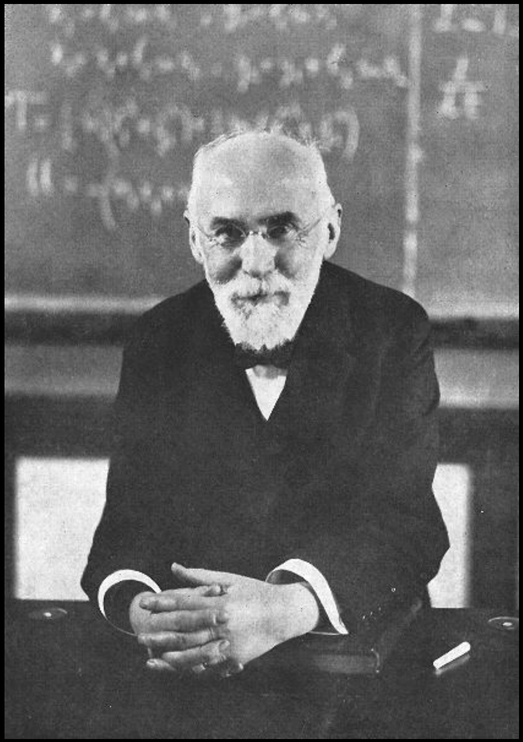

Luminiferous Ether

# Lorentz: Sources in Motion

Lorentz, 1890s: What if the source or receiver of light is *moving* with respect to the ether?

Galileo-Newton:

$$x' = x + vt$$
$$t' = t$$



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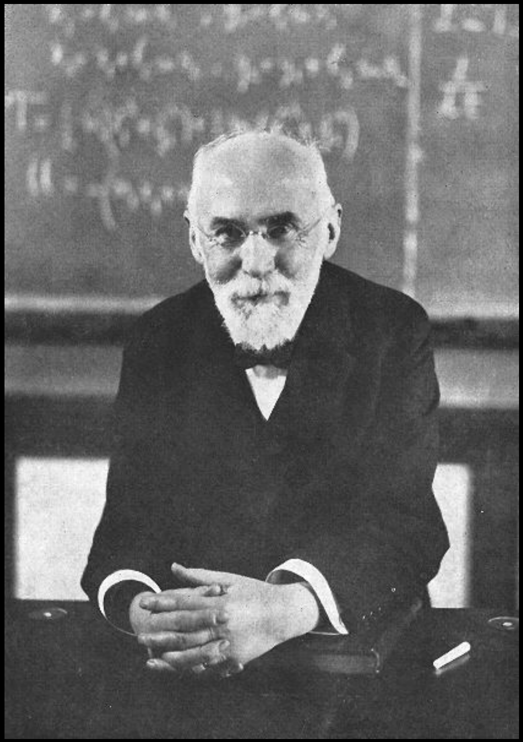

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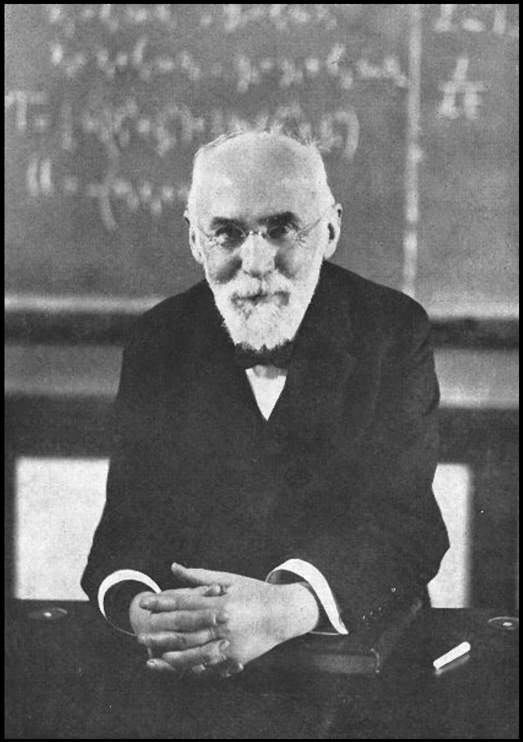

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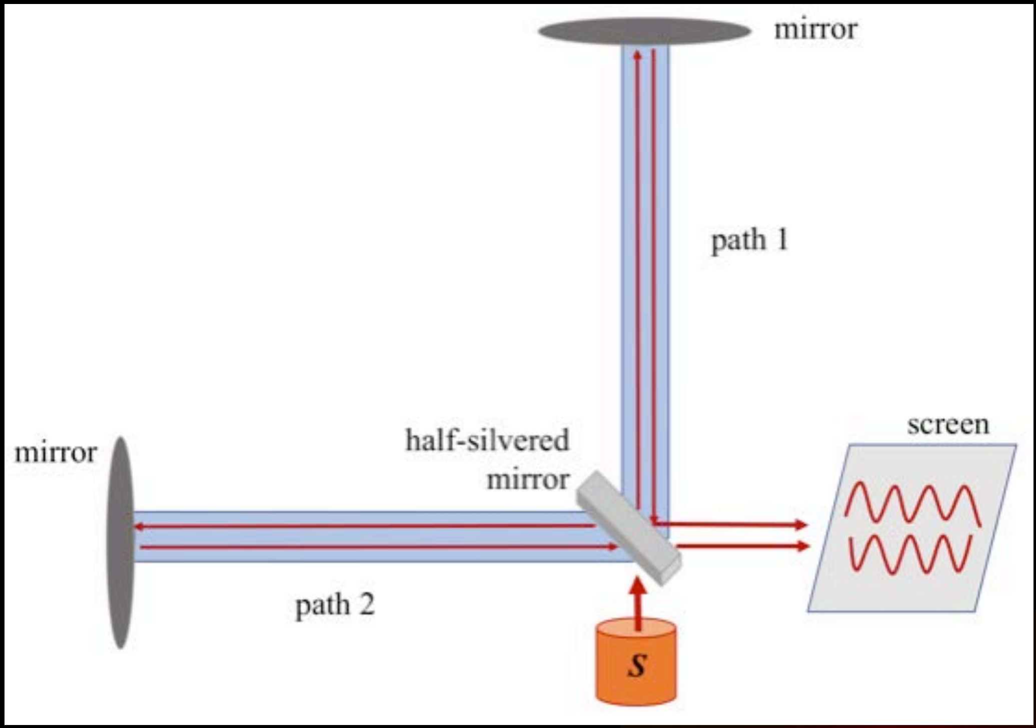
Lorentz introduced "local time," a purely fictitious time variable: $t' = f(x,t,v)$. The mathematical trick restored the form of Maxwell's wave equation. *Lorentz transformation*

# Interferometer

Albert Michelson (1852 – 1931) tried to *measure* the Earth's motion through the ether: look for "ether wind" effects on light.

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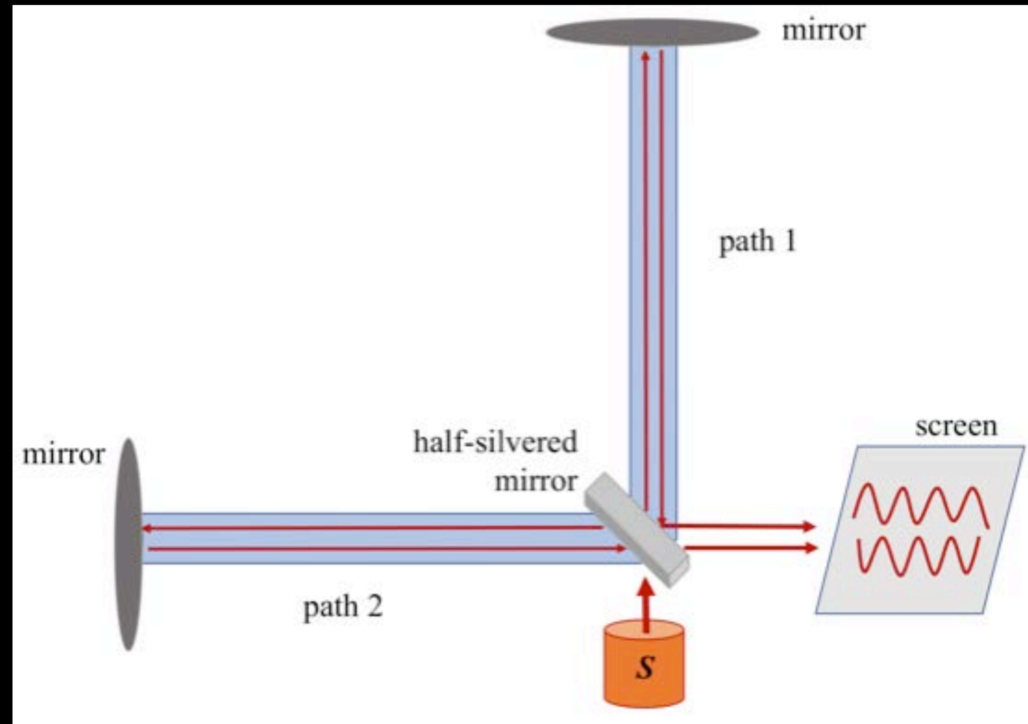


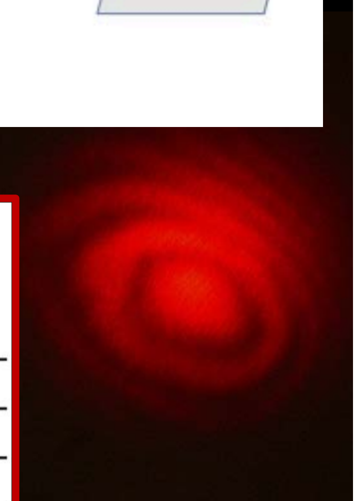

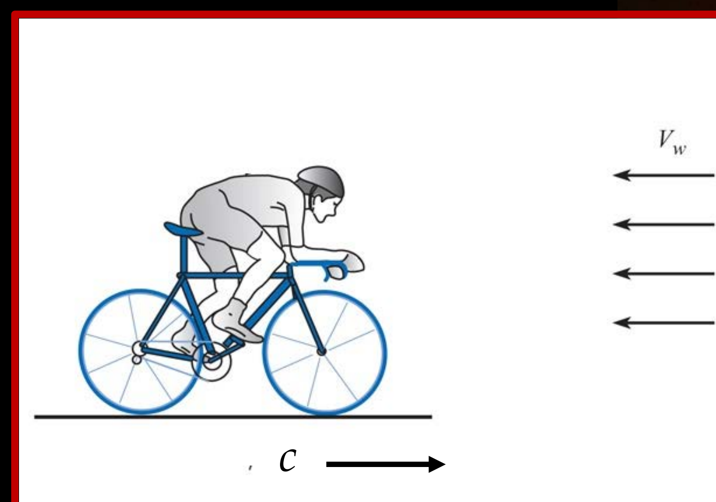

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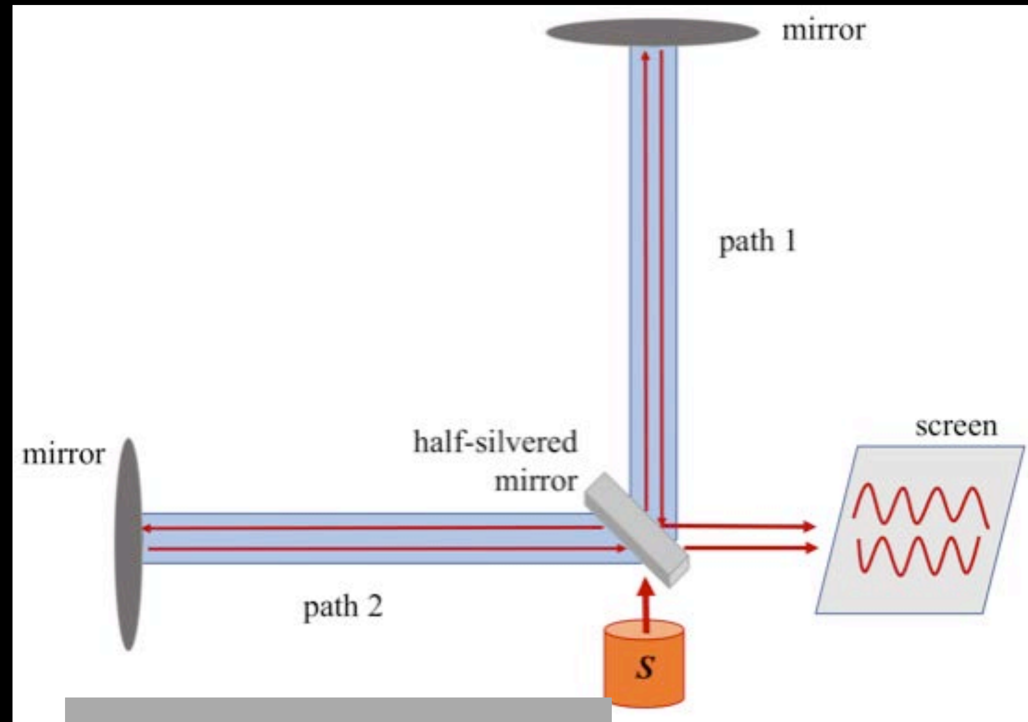
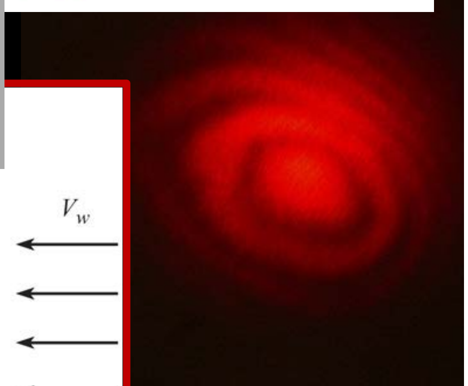
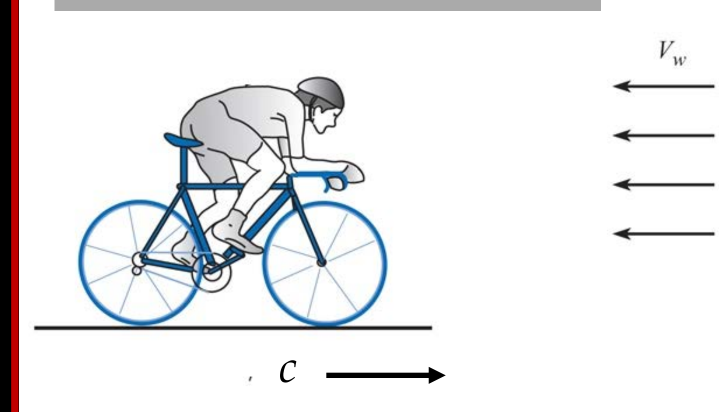


"Second order": sensitive to $(v/c)^2$



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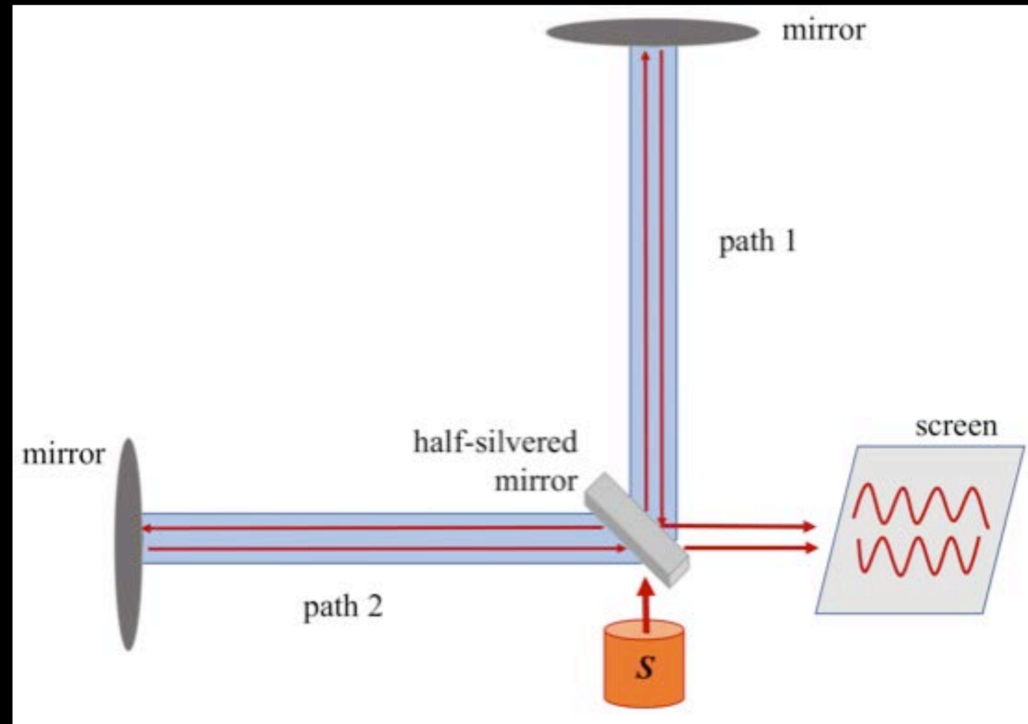
With his colleague Edward Morley, Michelson searched for *years* to find evidence of the Earth's motion through the ether.

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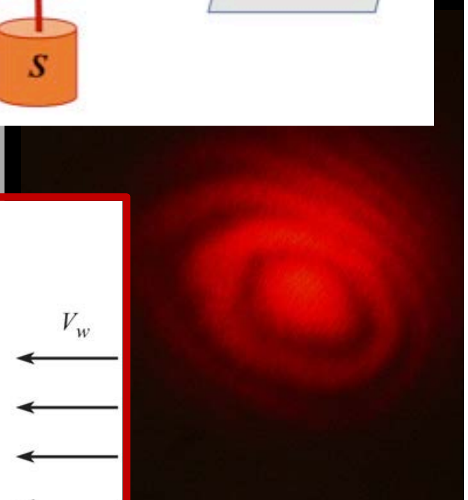

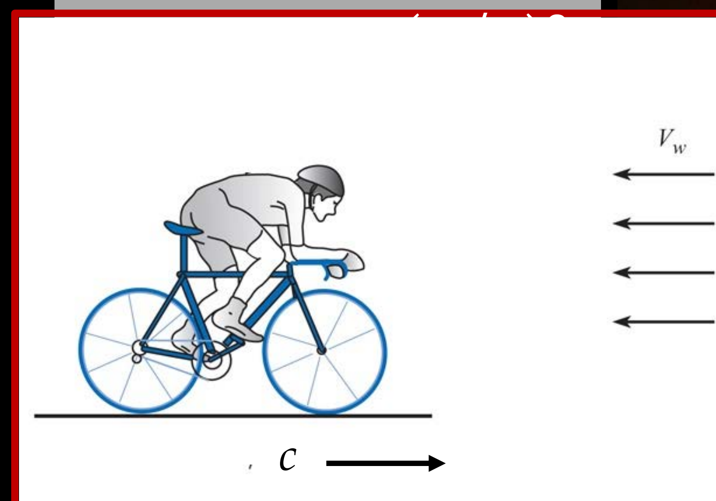

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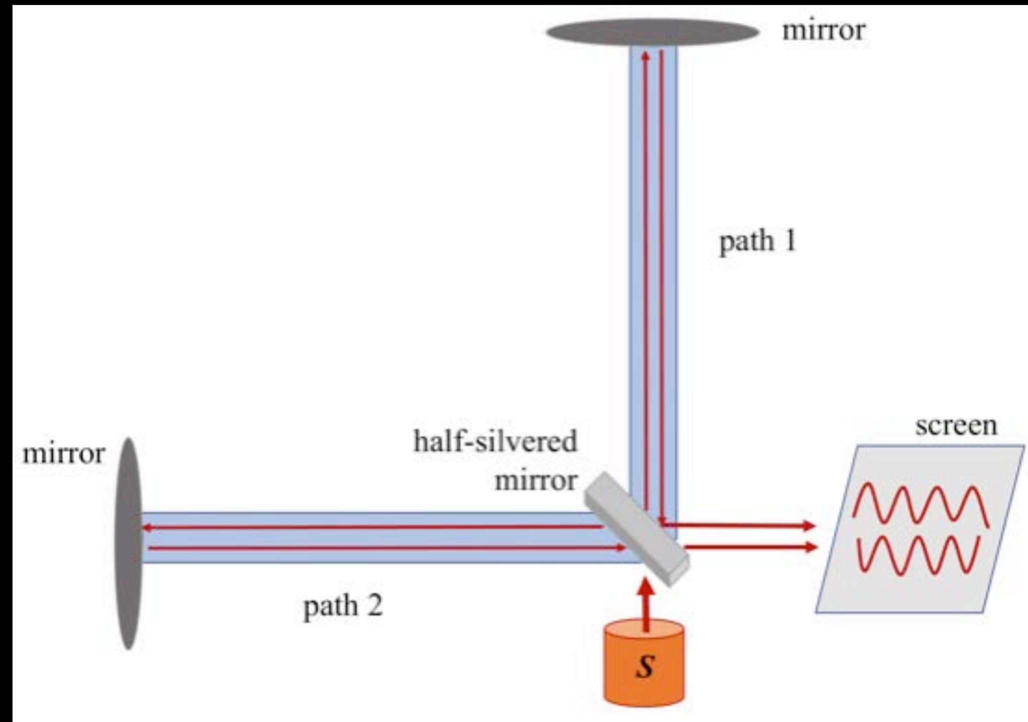
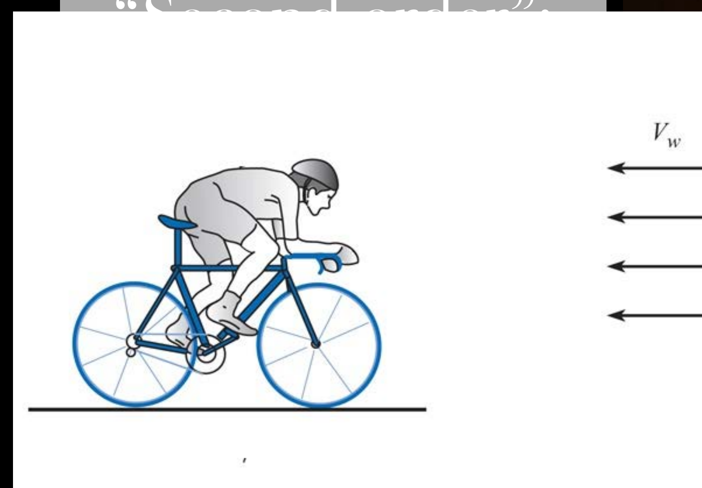
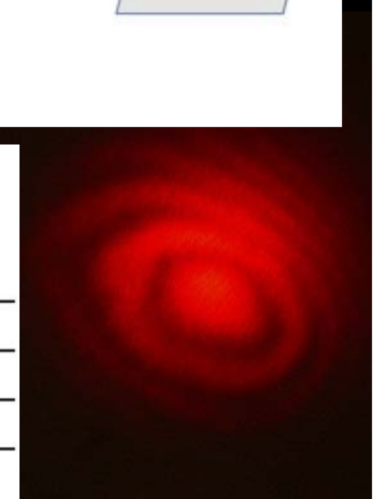


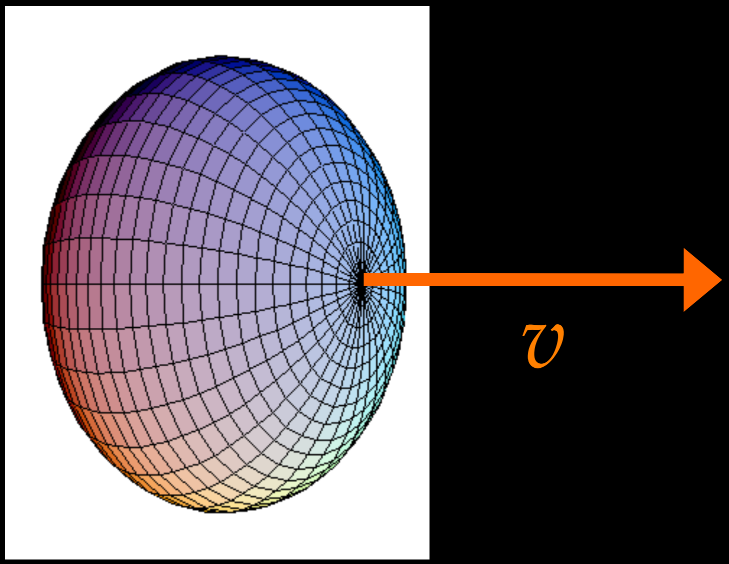





1887: Despite years of careful measurement, they found *no evidence* of the Earth's motion through the ether.

# Lorentz Contraction

Lorentz was concerned about Michelson’s (null) result. He thus had a *physical* as well as a *mathematical* reason to change $x'$ and $t'$.



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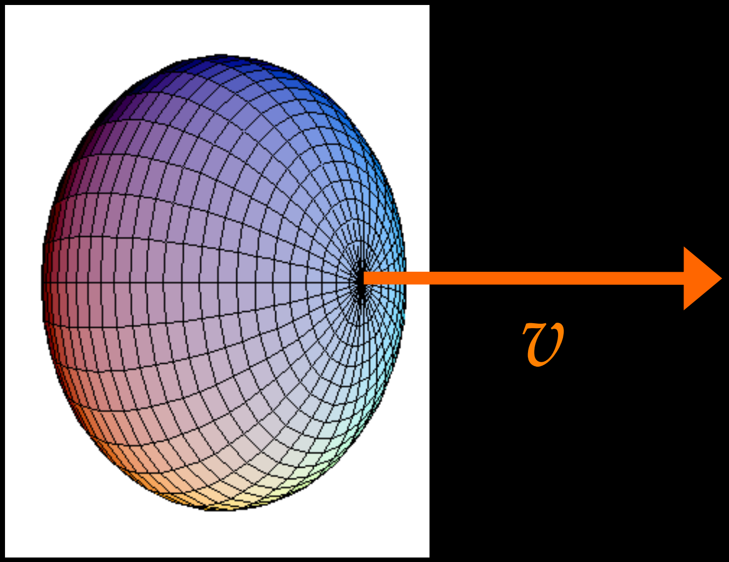


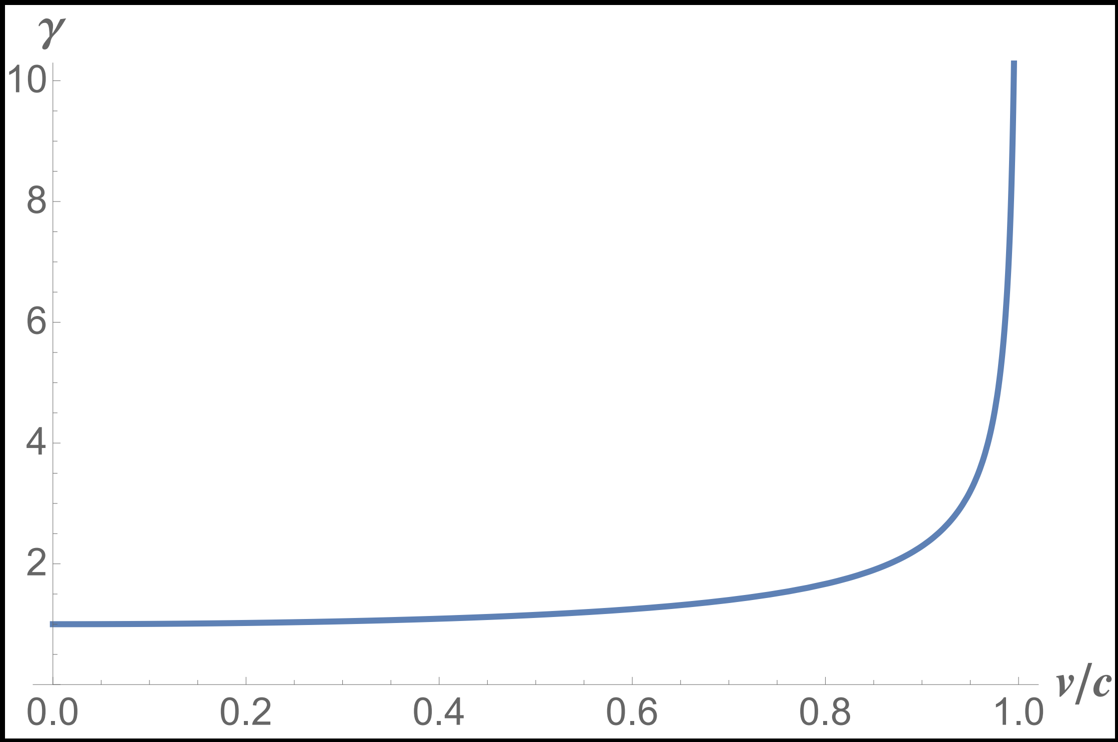


$$L' = L/\gamma$$

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

# 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.

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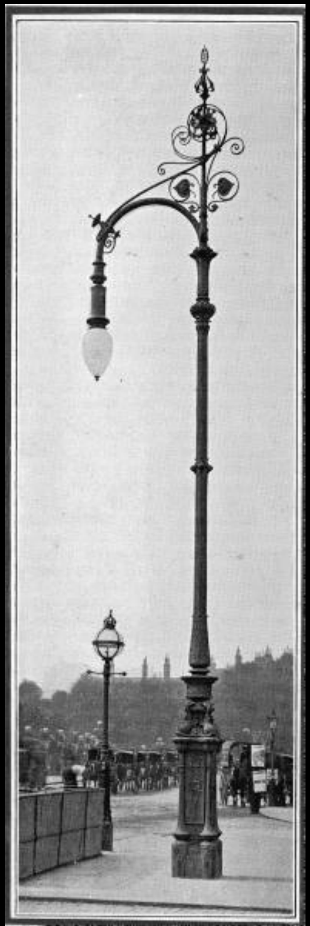

Electric street lighting, ca. 1900

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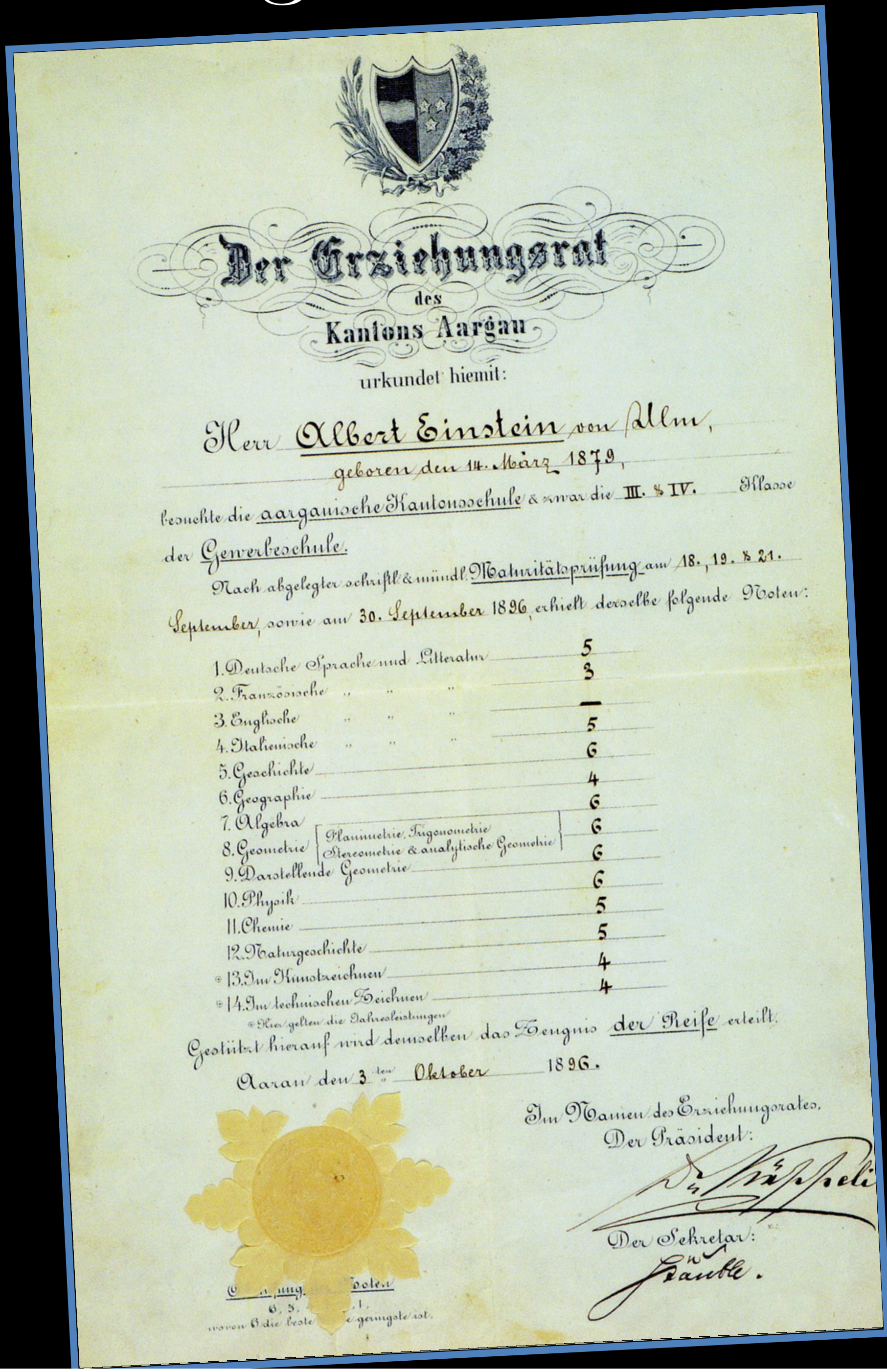
# Young Albert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Nach abgelegter schriftl. & mündl. Maturitätsprüfung am 18., 19. & 21.
September, sowie am 30. September 1896, erhielt derselbe folgende Noten:

| | |
|---|---|
| 1. Deutsche Sprache und Litteratur | 5 |
| 2. Französische " " | 3 |
| 3. Englische " " | — |
| 4. Italienische " " | 5 |
| 5. Geschichte | 6 |
| 6. Geographie | 4 |
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| 11. Chemie | 5 |
| 12. Naturgeschichte | 5 |
| * 13. Im Kunstzeichnen | 4 |
| * 14. Im technischen Zeichnen | 4 |

* Hier gelten die Jahresleistungen.

Gestützt hierauf wird demselben das Zeugnis der Reife erteilt.

Aarau, den 3ten Oktober 1896.

Im Namen des Erziehungsrates,
Der Präsident:

Der Sekretär:

[illegible] Noten
6, 5, [illegible] 1,
wovon 6 die beste [illegible] geringste ist.


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

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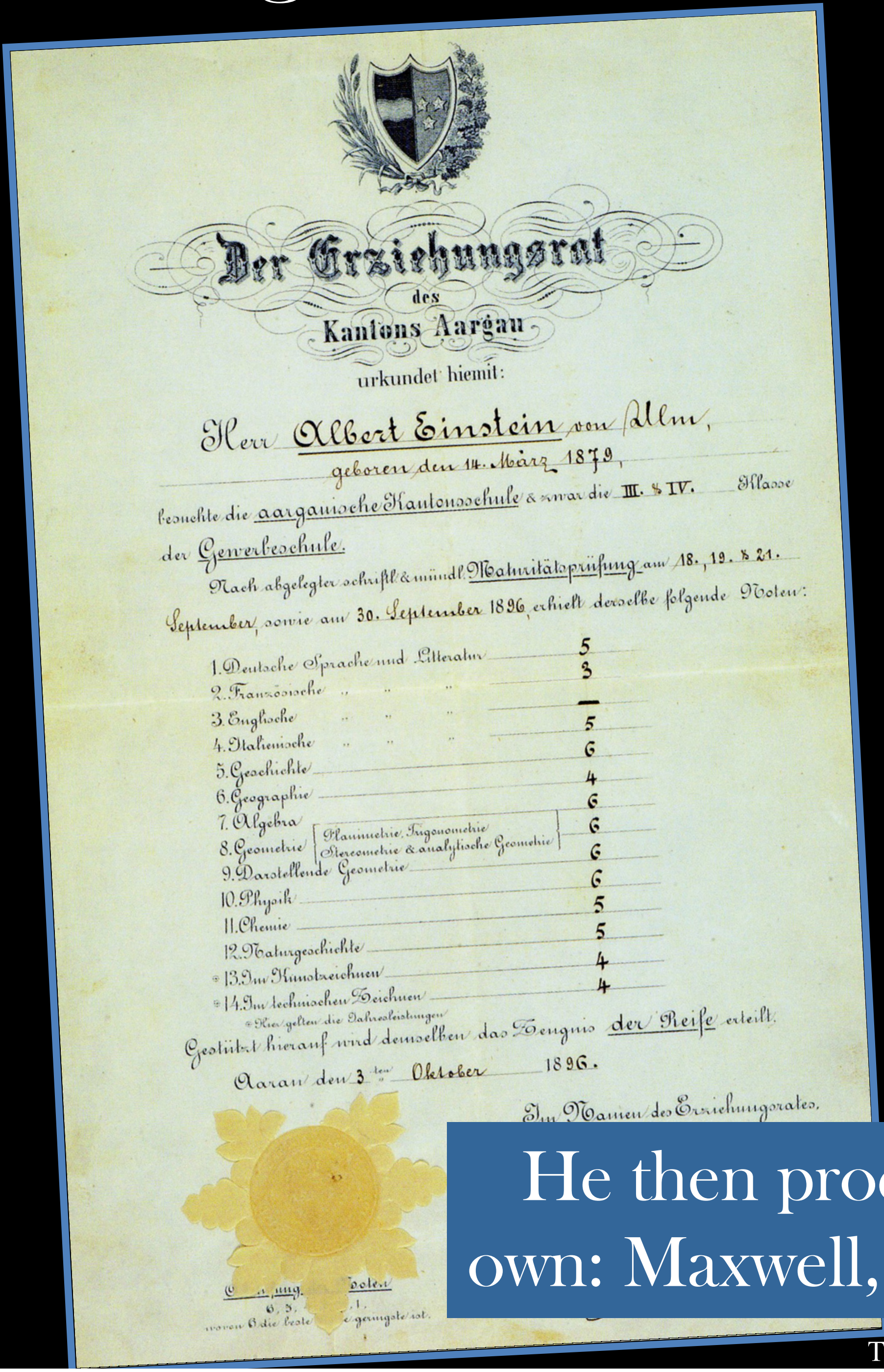

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He then proceeded to cut classes to read on his own: Maxwell, Boltzmann, etc.

# 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

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

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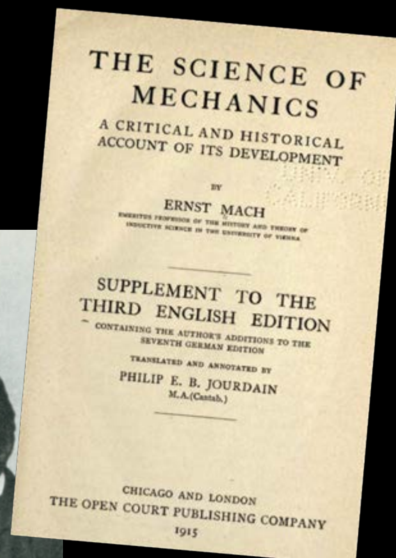
THE SCIENCE OF MECHANICS

A CRITICAL AND HISTORICAL ACCOUNT OF ITS DEVELOPMENT

BY

ERNST MACH

EMERITUS PROFESSOR OF THE HISTORY AND THEORY OF INDUCTIVE SCIENCE IN THE UNIVERSITY OF VIENNA

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

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Einstein at the Patent Office, 1905



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



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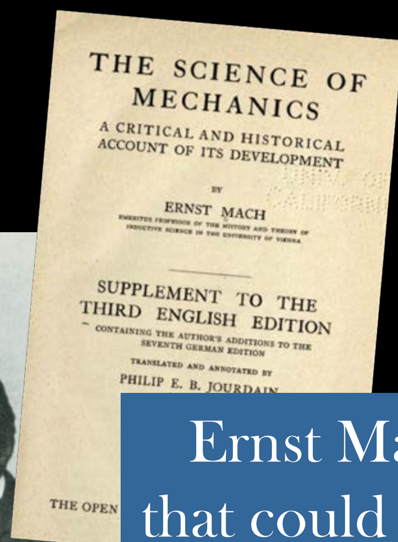
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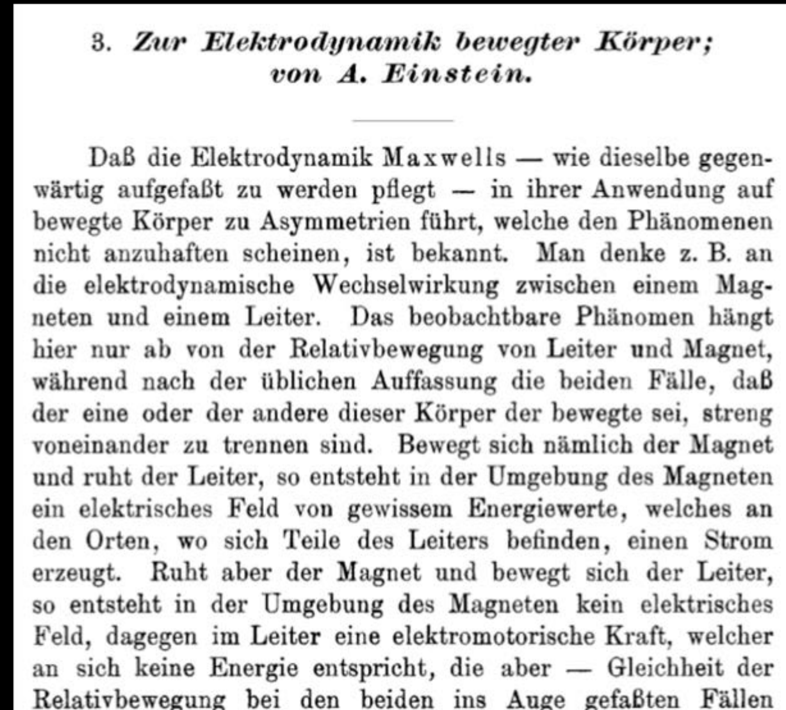
"Olympia Academy": Solovine, Habicht, Einstein, ca. 1905



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.

# Not a Bad Year…

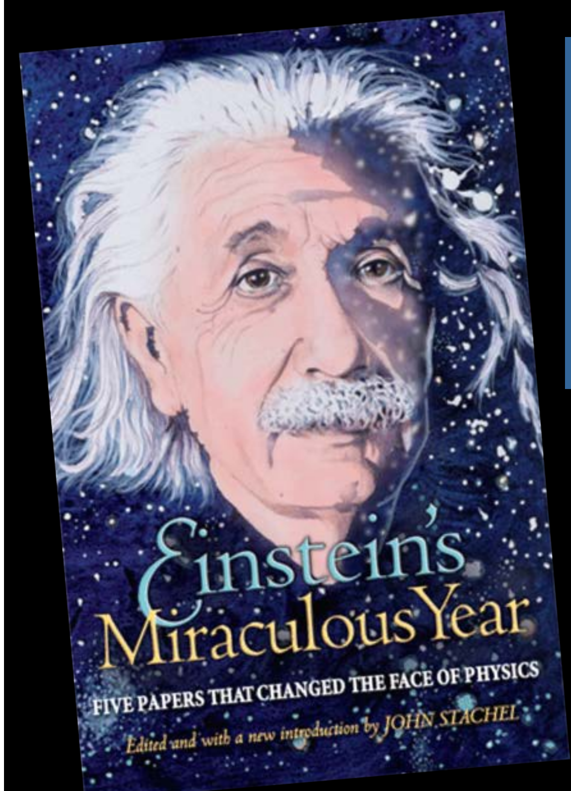
While working at the patent office, Einstein submitted several papers to the *Annalen der Physik*.



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






March 1905: light quanta

May 1905: Brownian motion

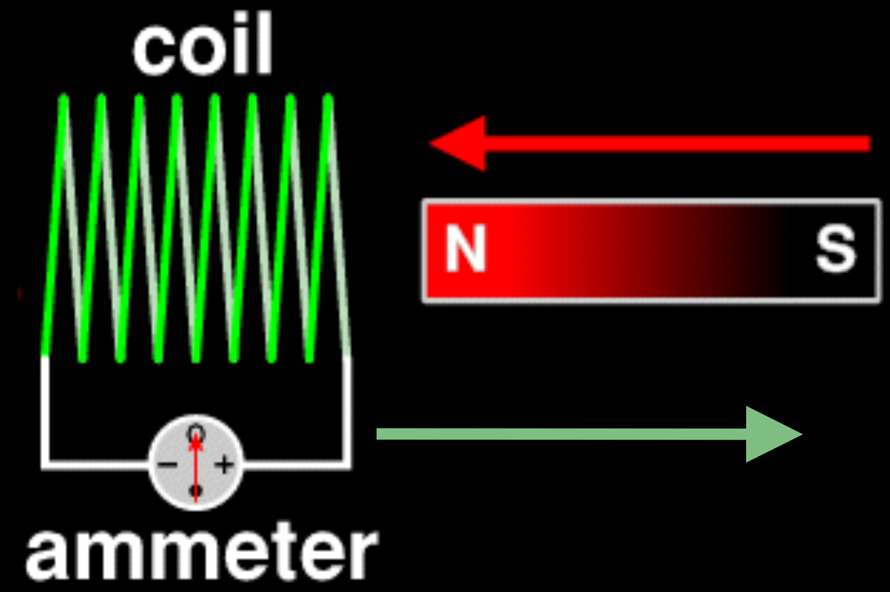
**June 1905: special relativity**

September 1905: $E = mc^2$

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

# "An Asymmetry in the Explanation"

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



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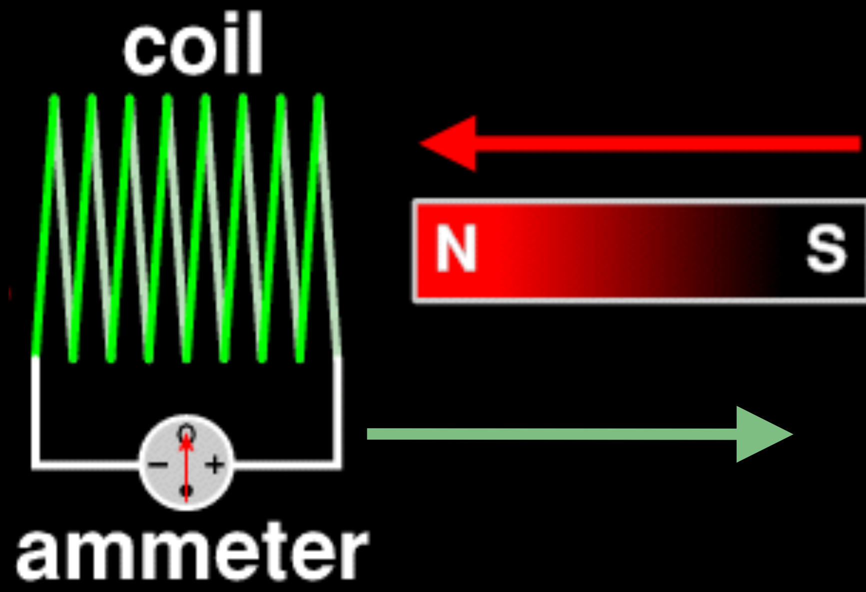
When the magnet and coil were in relative motion, an electric current was produced.

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



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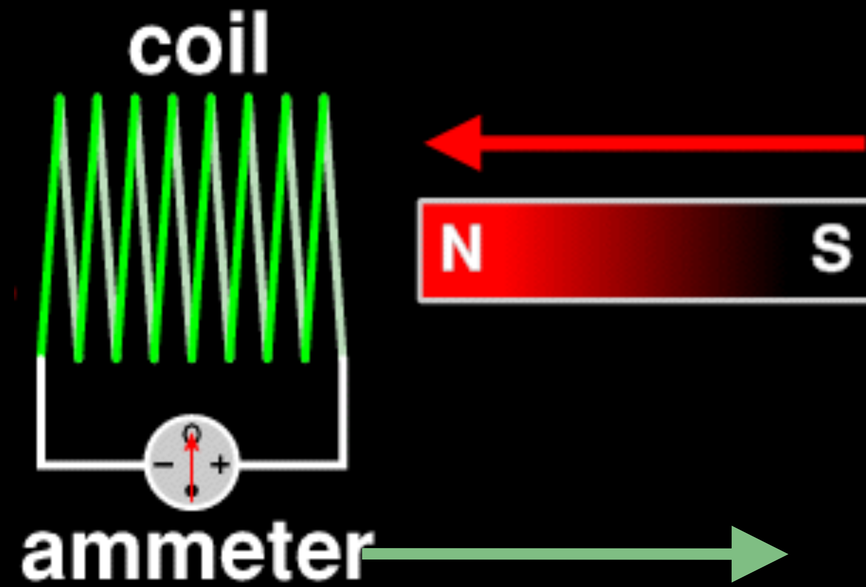




*Case 1*: Moving magnet, stationary coil:

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.

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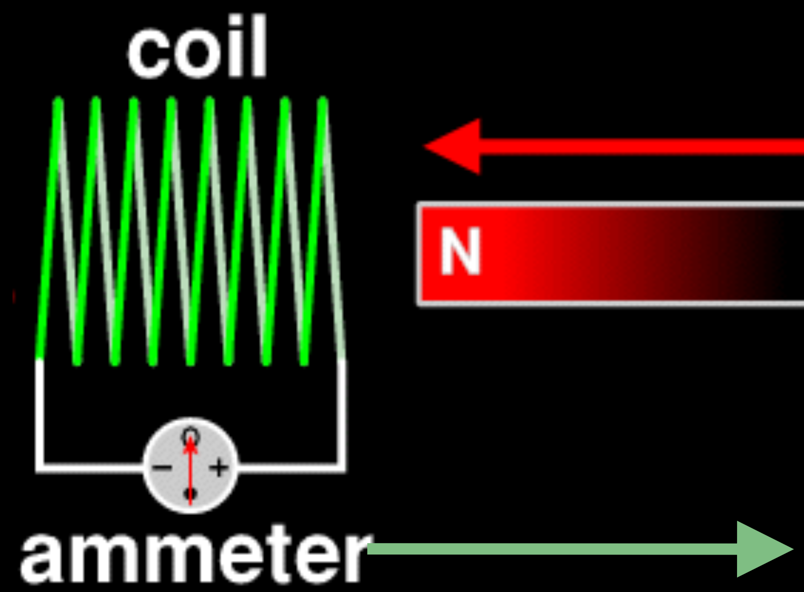




*Case 2*: Stationary magnet, moving coil:

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

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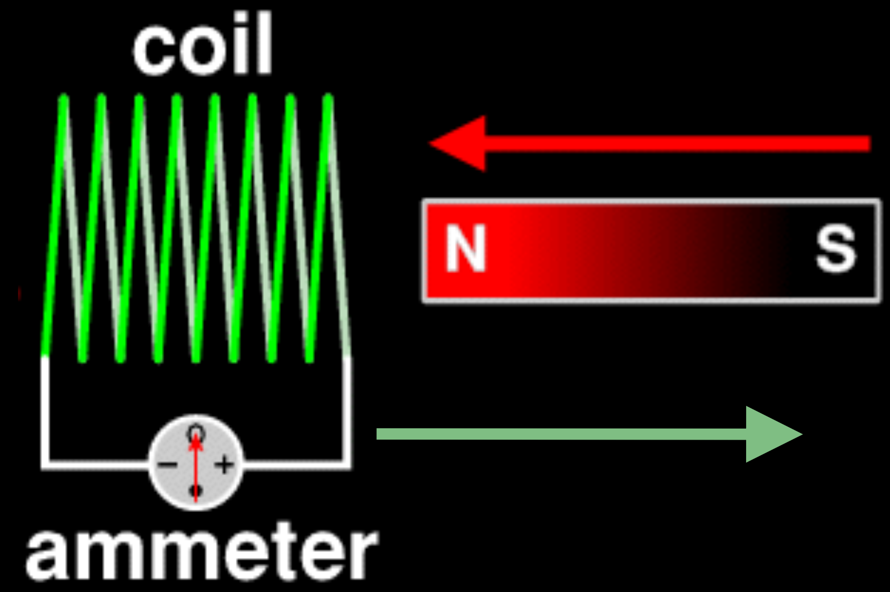




Einstein insisted that physicists had been too clever by half: there was only *one phenomenon*, so there should only be *one explanation.*

# Two Postulates

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



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.

# Two Postulates

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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.

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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

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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."

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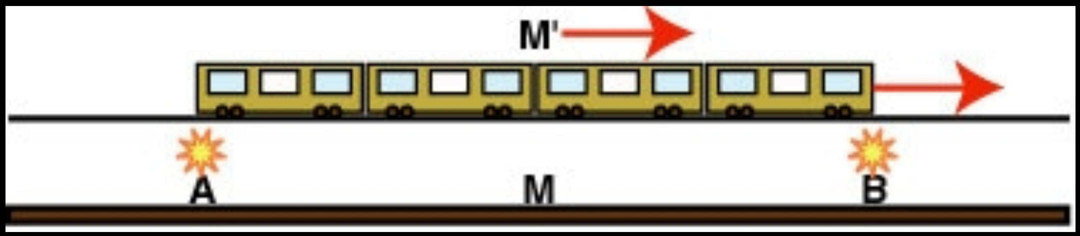
# Relativity of Simultaneity

If there is no absolute time, how can we compare times measured in different places? By sending *light signals*, since $c$ = constant.



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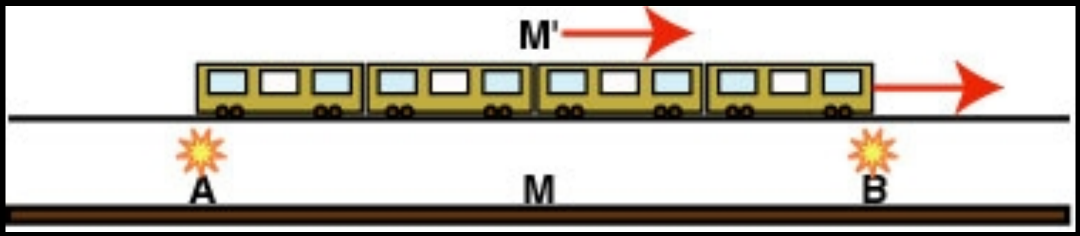


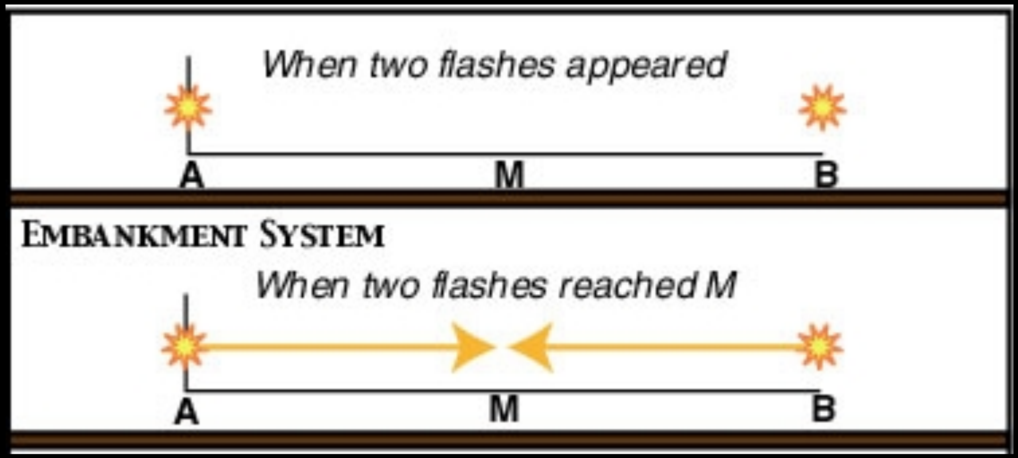


The observer on the train platform at $M$ was an equal distance from locations $A$ and $B$, and she received light waves from $A$ and $B$ at the same time. Thus, she concludes, the flashes were emitted *simultaneously* from $A$ and $B$.

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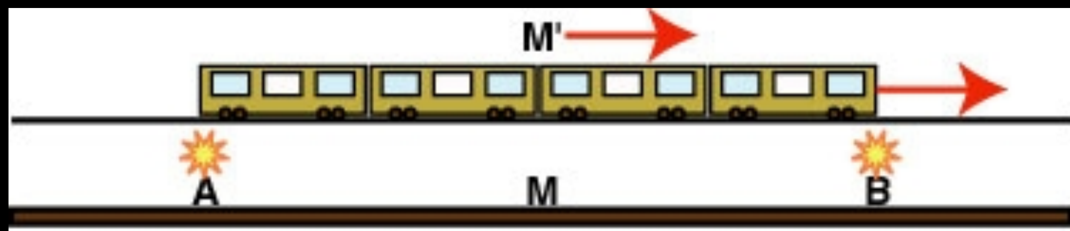


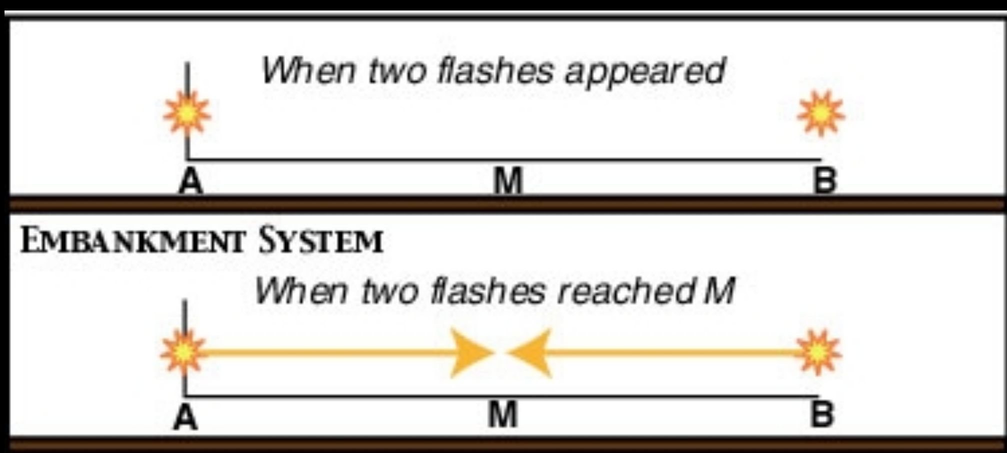


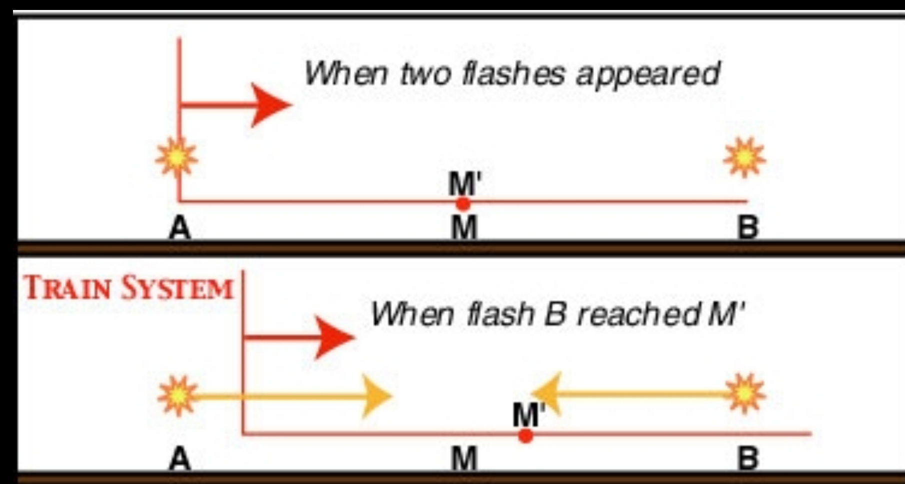


The observer on the train at *M′* was an equal distance from locations *A* and *B*, but she received the light wave from *B before* she received the light wave from *A*. Thus, she concludes, the flashes were *not* emitted simultaneously from *A* and *B*.

# Relativity of Simultaneity

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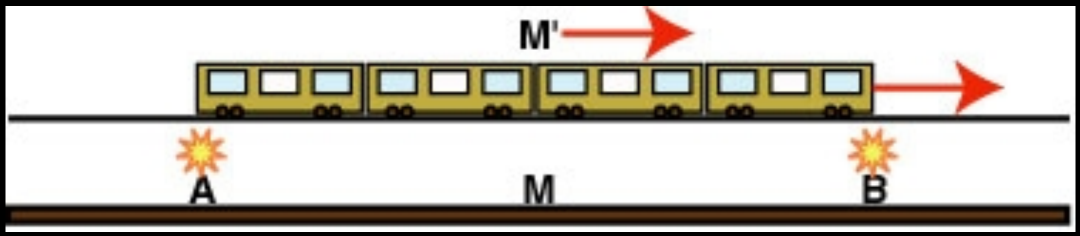


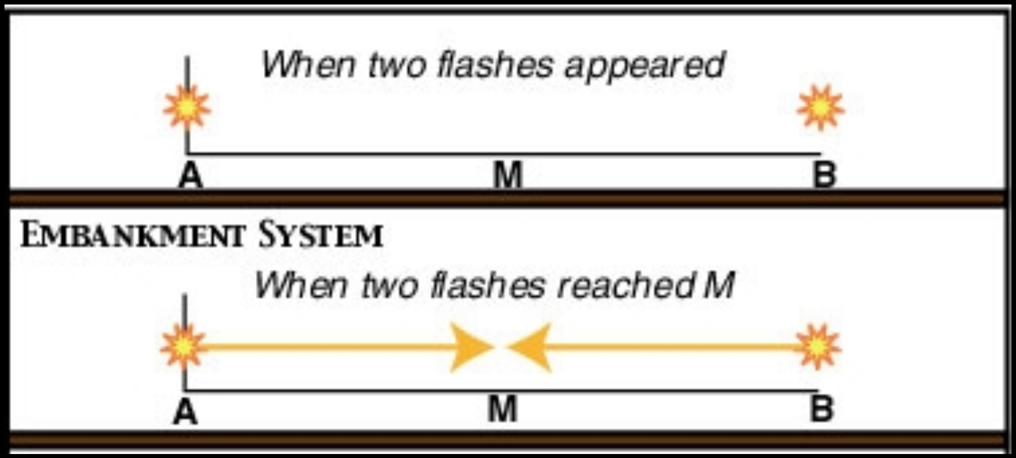


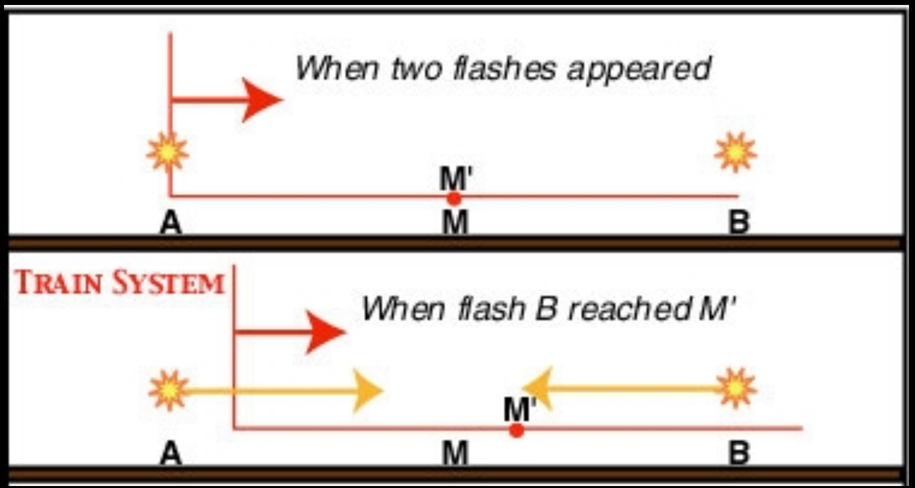


Who was correct? *Both!* Recall postulate 1: The laws of physics are valid in *any* frame of reference moving at a constant speed (*inertial* frames of reference).

# Relativity of Simultaneity

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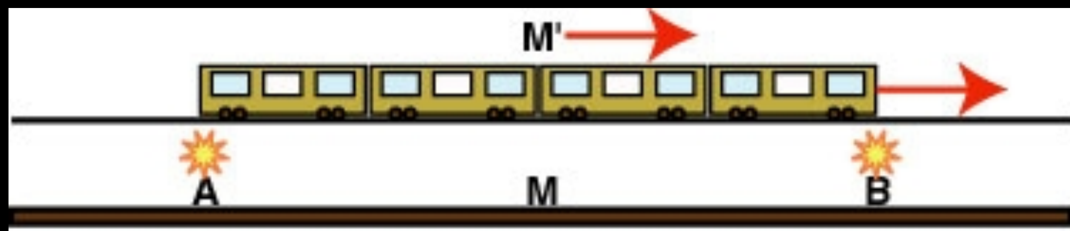
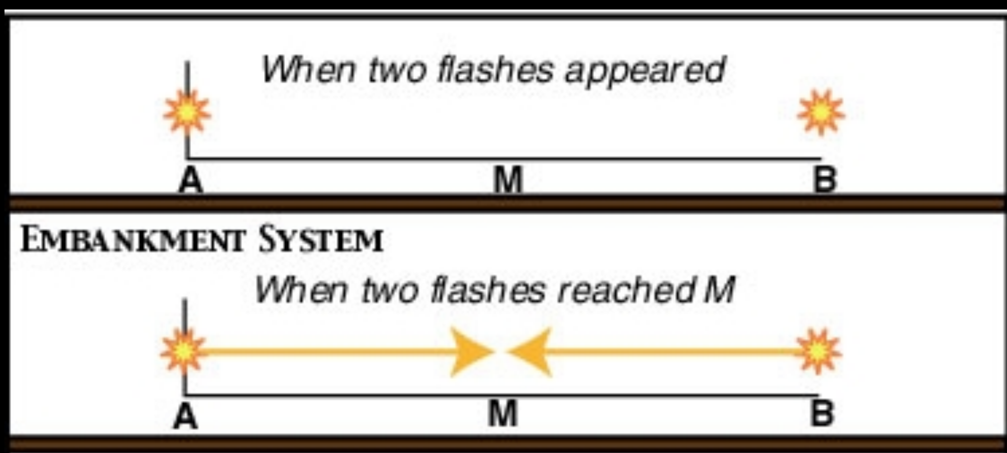
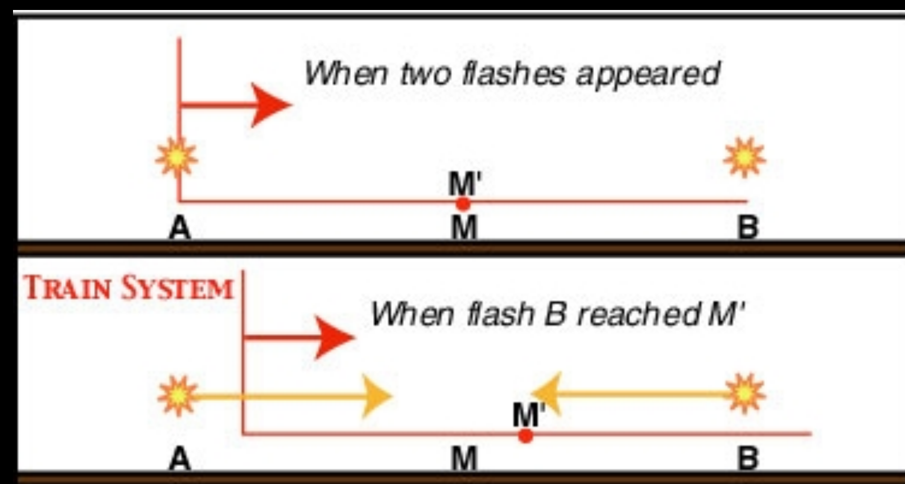
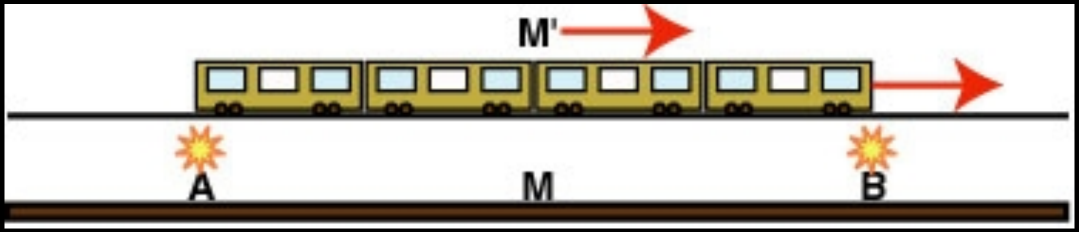


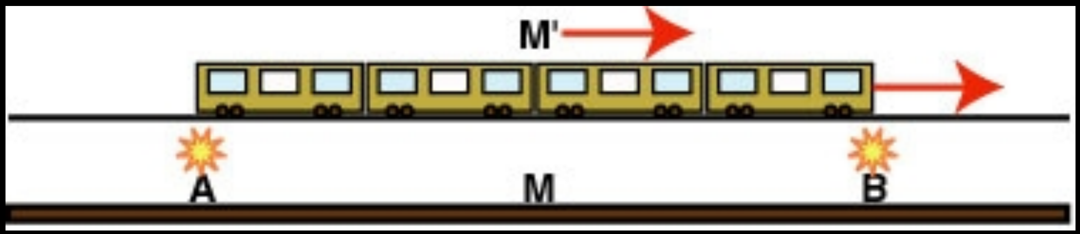

Thus we see that we can attribute no *absolute* meaning to the concept of simultaneity, but that two events which, examined from a coordinate system, are simultaneous, can no longer be interpreted as simultaneous events when examined from a system which is in motion relatively to that system.

# Length Contraction




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.

# Length Contraction





train at rest

$L$

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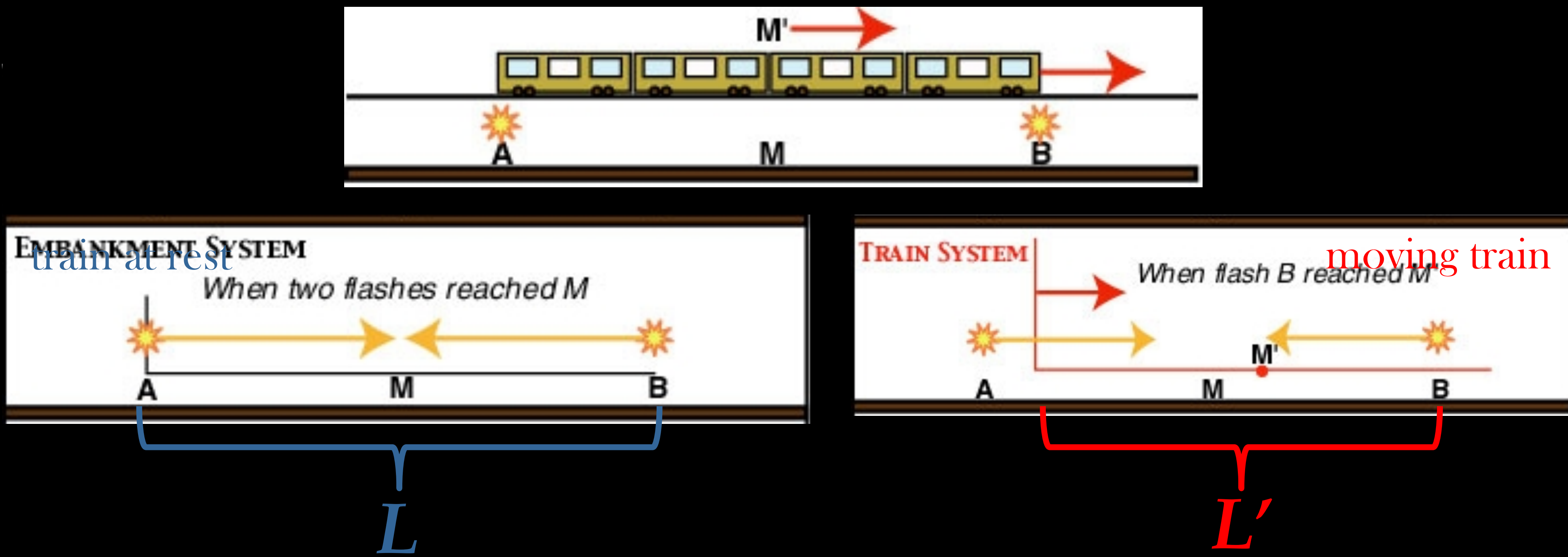


How do we measure the *length* of an object? *At the same time*, measure the locations of the front and the back of the object, and take the difference.

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

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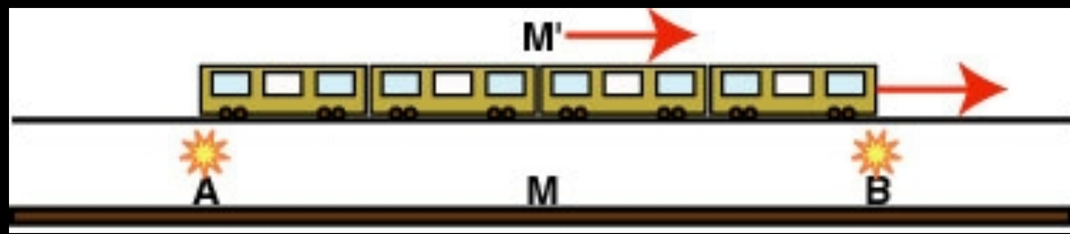


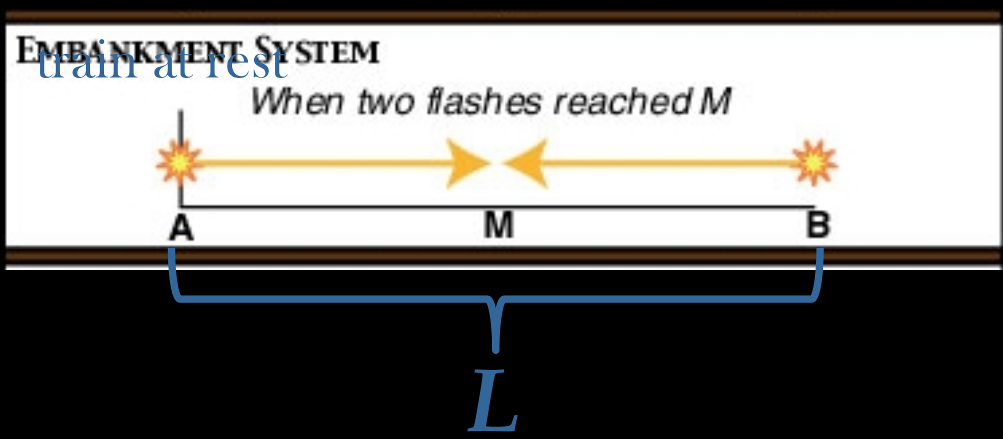


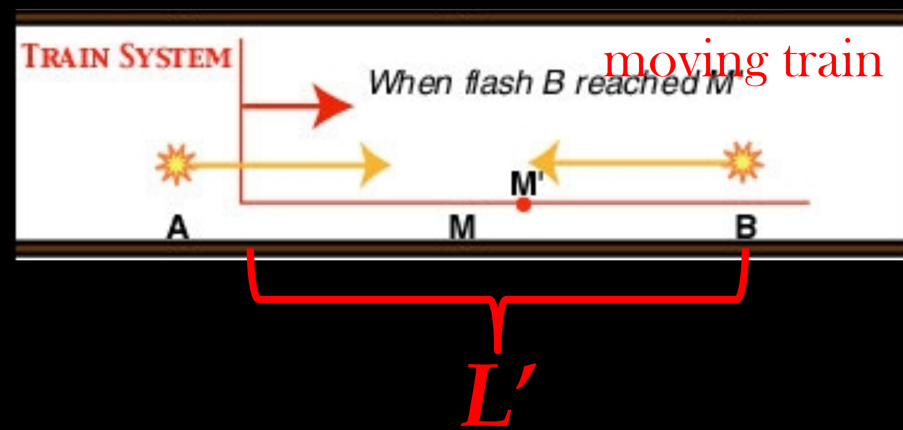


The passenger on the train says that the person on the platform *first* measured the location of the front, then *waited* while the train moved, and only *later* measured the location of the back – so of course their measurement was *too short.*

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.

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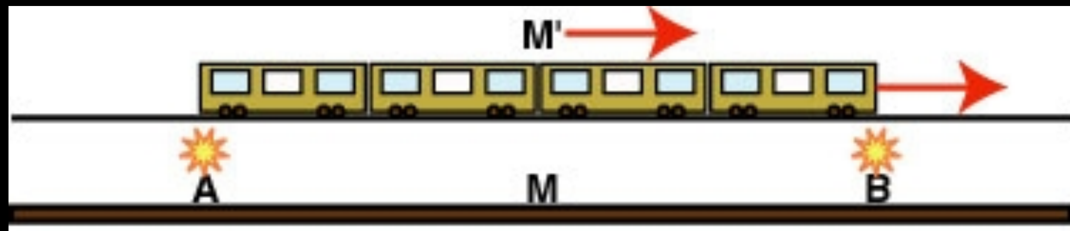
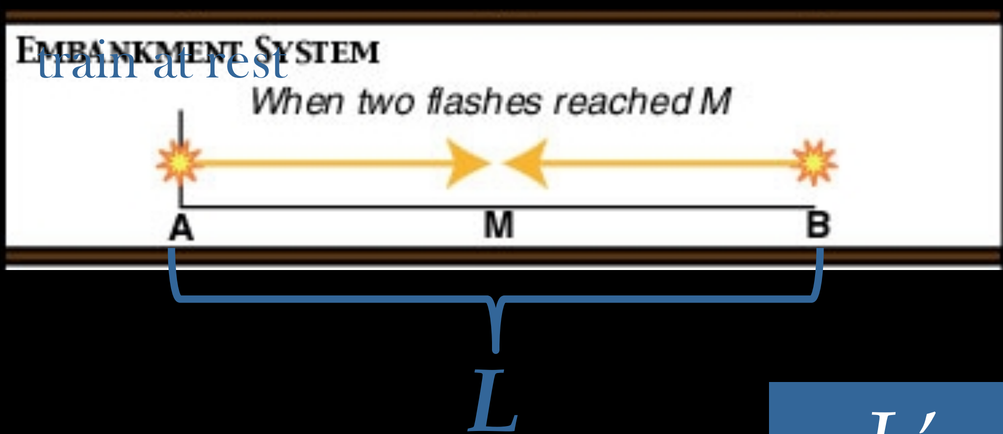
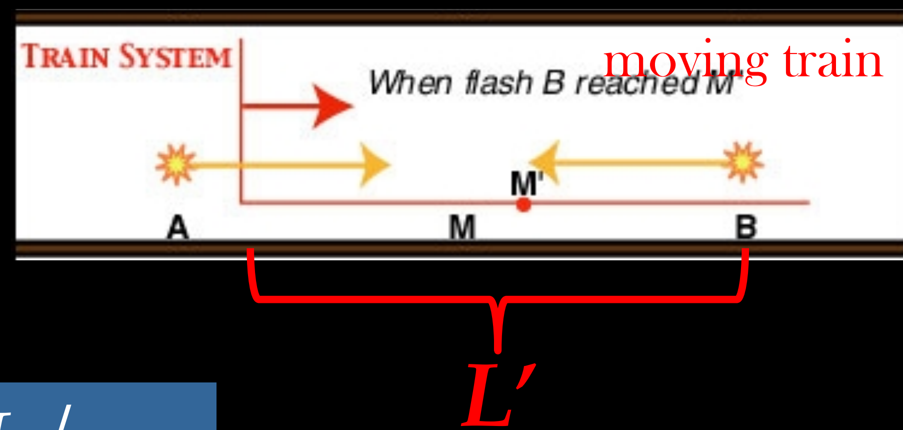
# Length Contraction

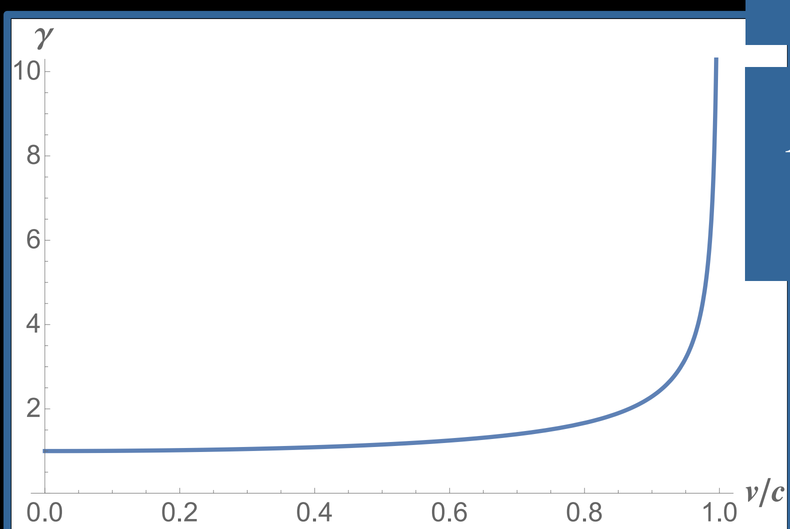


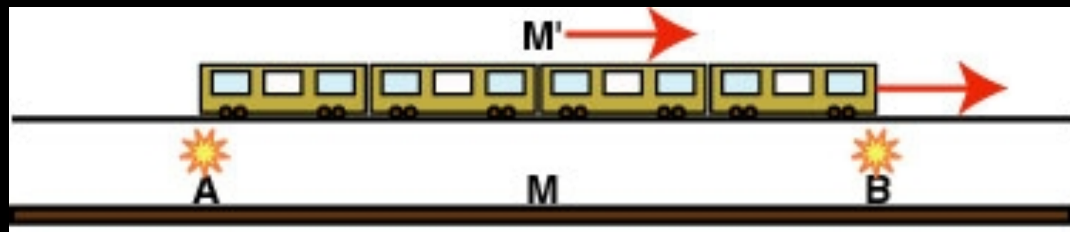

$$L' = L/\gamma$$

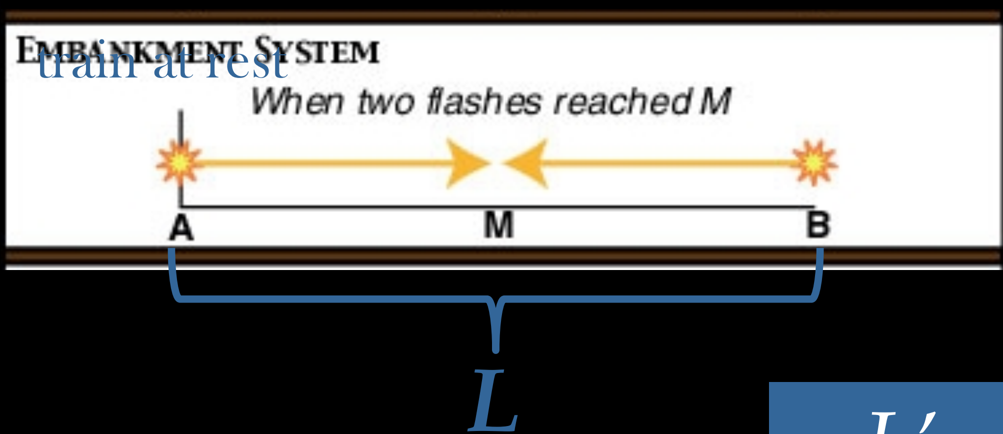
A moving object *shrinks* along its direction of motion.

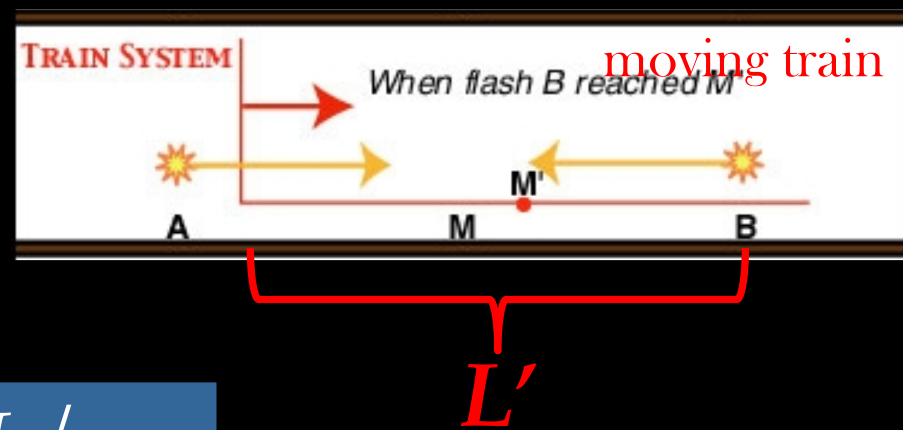



$$\gamma = \frac{1}{\sqrt{1 - (v/c)^2}}$$

# Length Contraction

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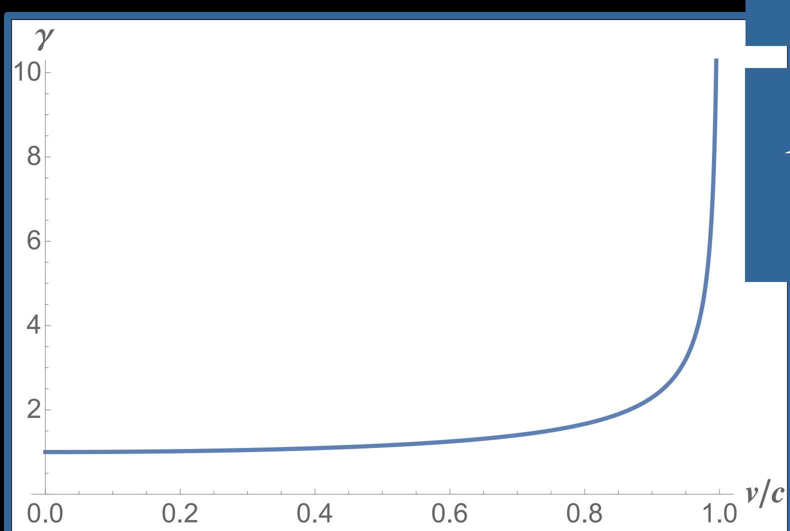
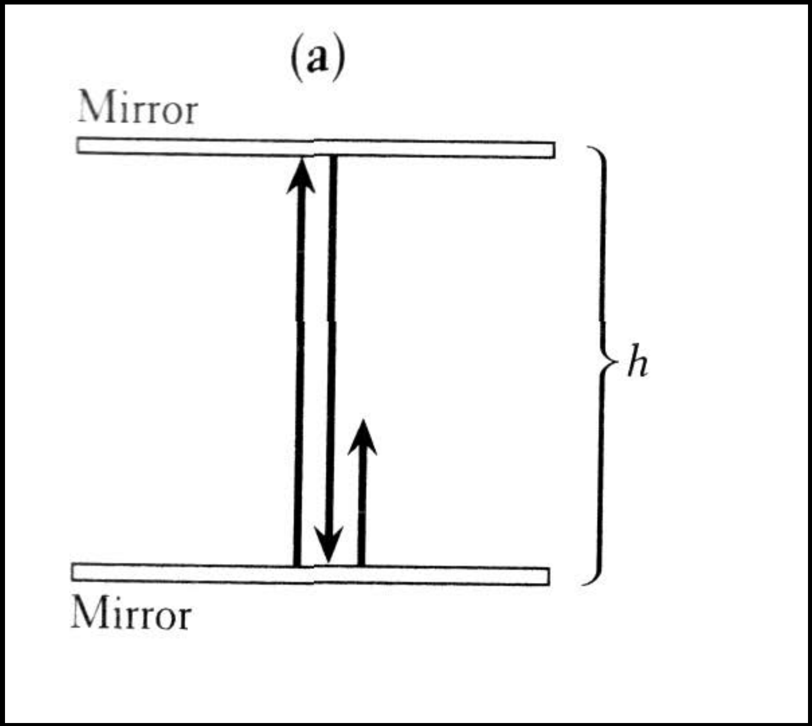



To Einstein, length contraction had *nothing to do with forces exerted by an ether (dynamics)*; it was simply a consequence of *kinematics*.

# Time Dilation



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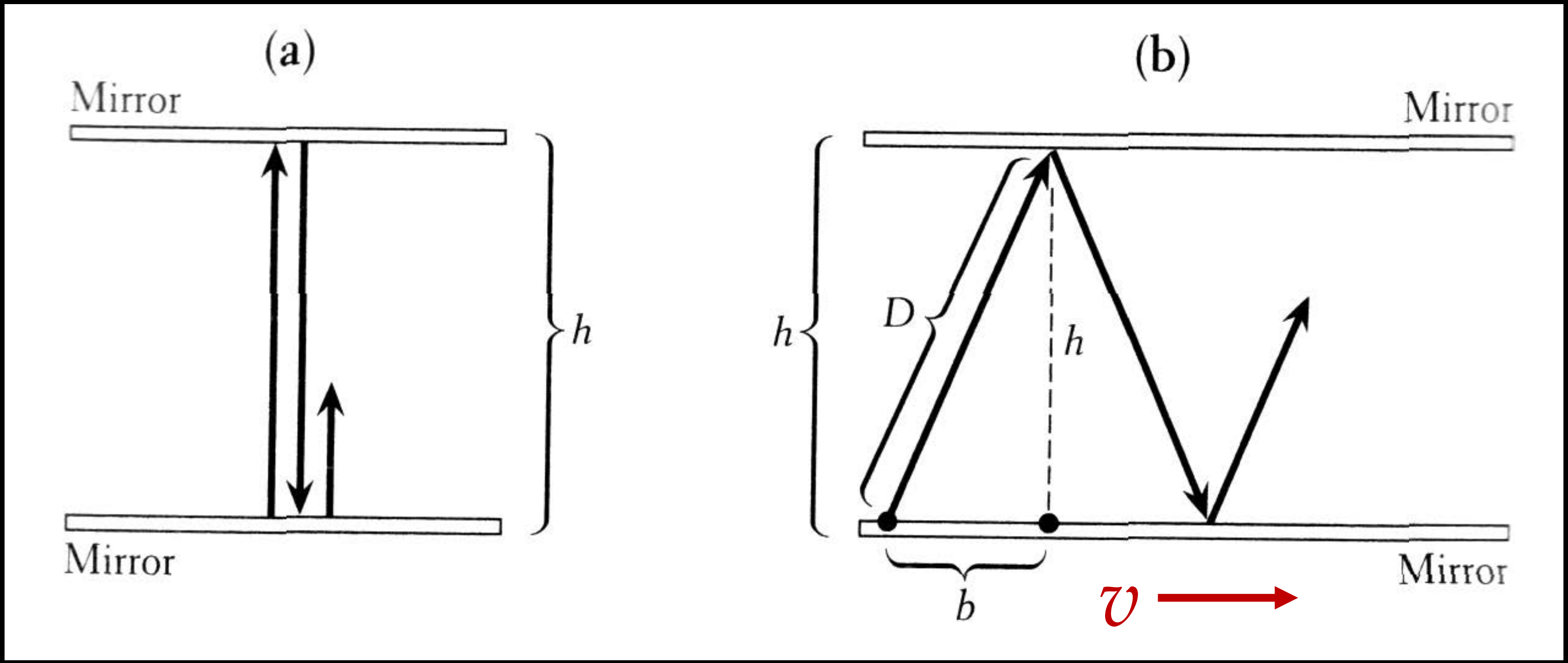

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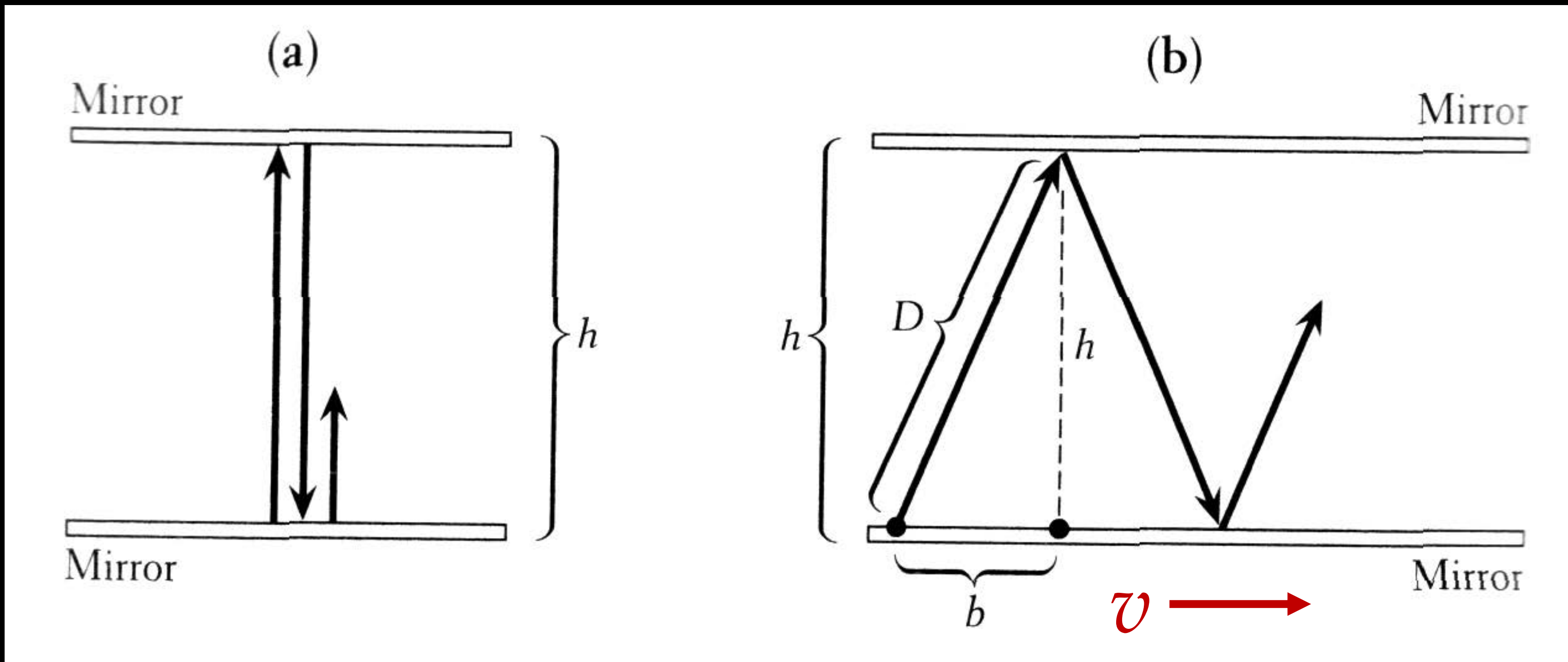


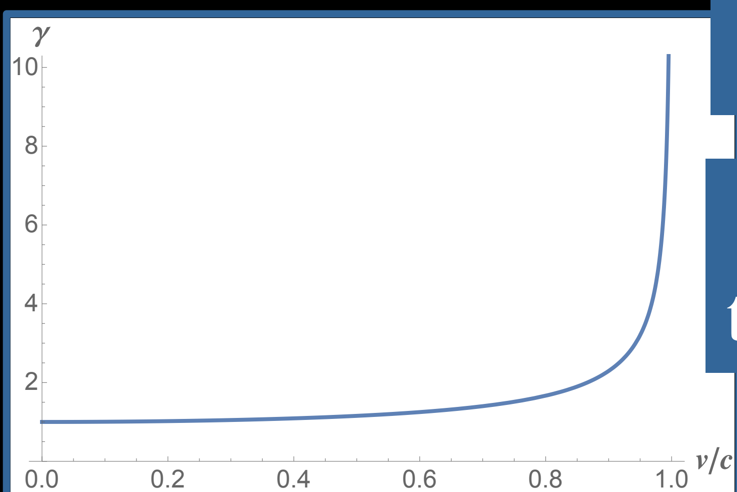


$$\Delta t' = \gamma \, \Delta t$$

A moving clock ticks *slowly*.

$$\gamma = \frac{1}{\sqrt{1 - (v/c)^2}}$$

# Spacetime

To Minkowski, $(x, t)$ and $(x', t')$ were merely *projections* of events onto arbitrary axes. Yet a combination of those coordinates was *invariant.*

$$s^2 = c^2 (\Delta t)^2 - (\Delta x)^2 = c^2 (\Delta t')^2 - (\Delta x')^2$$

Hermann Minkowski (1864 – 1909)

Courtesy of Smithsonian Institution on Flickr.

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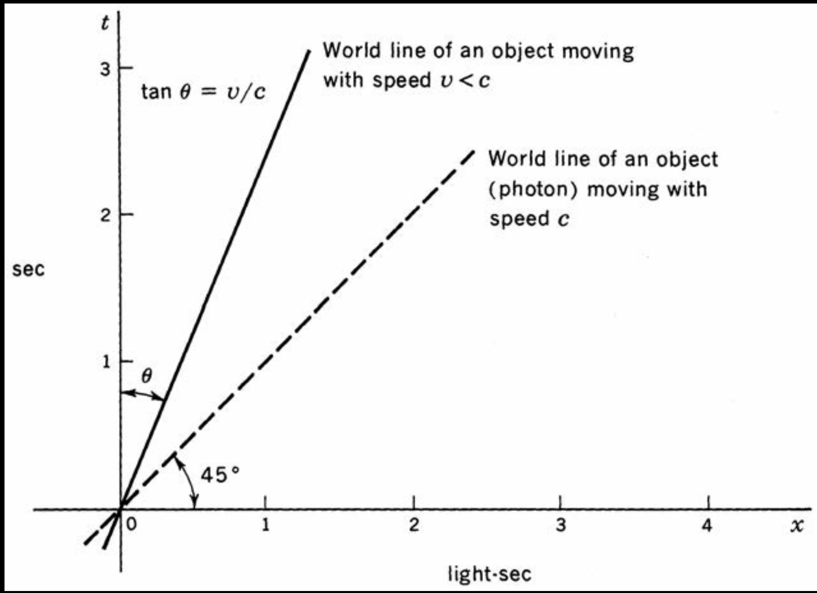
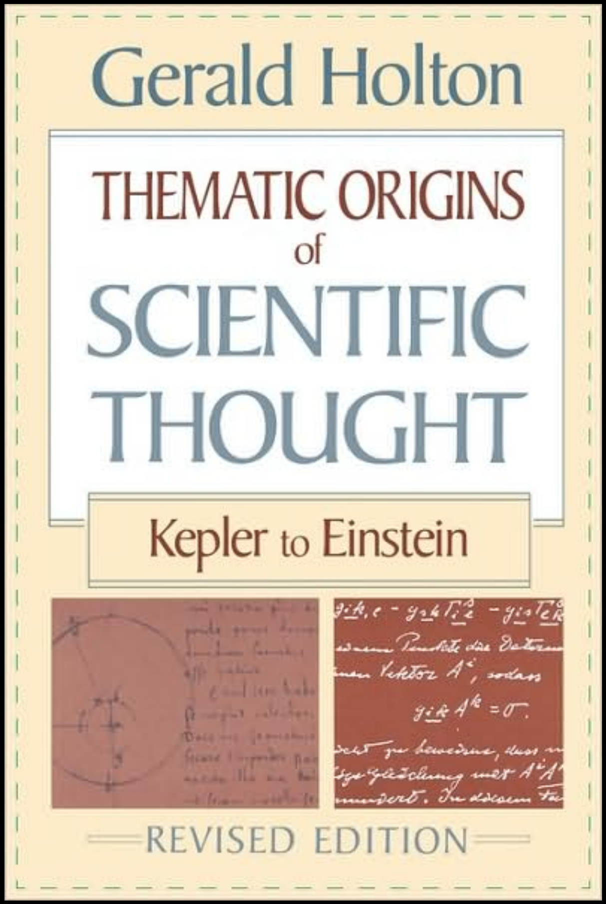



"Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve independence." (1908)

# Einstein and Experiment

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



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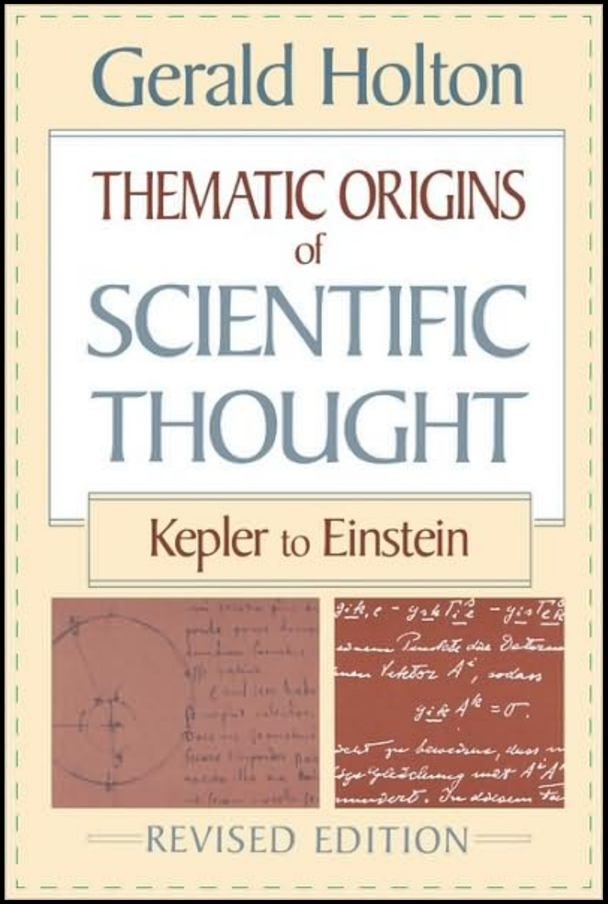
Yet it’s not clear whether Einstein even *knew* about the results at the time. Either way, they don’t seem to have played much role in his thinking.



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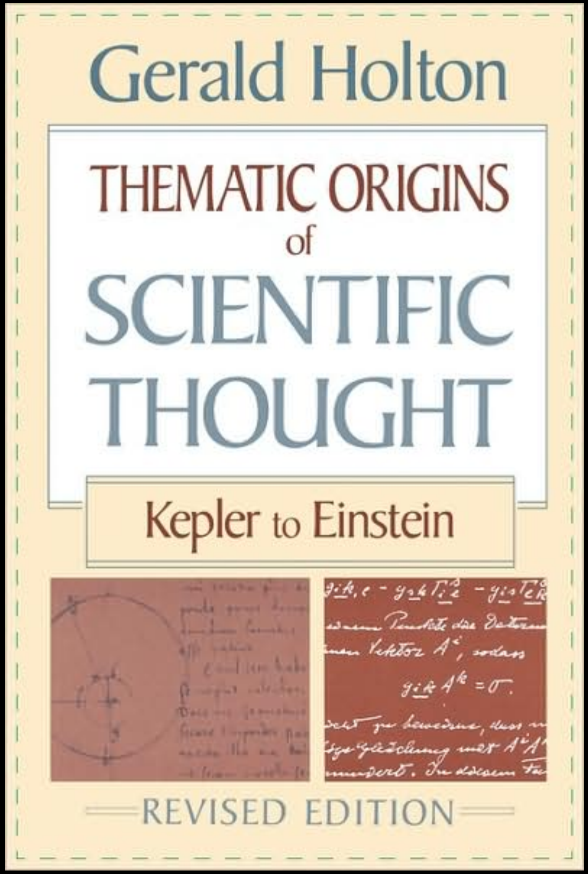




Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," lead to the conjecture that to the concept of absolute rest there correspond no properties of the phenomena, neither in mechanics, nor in electrodynamics, but rather that 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.

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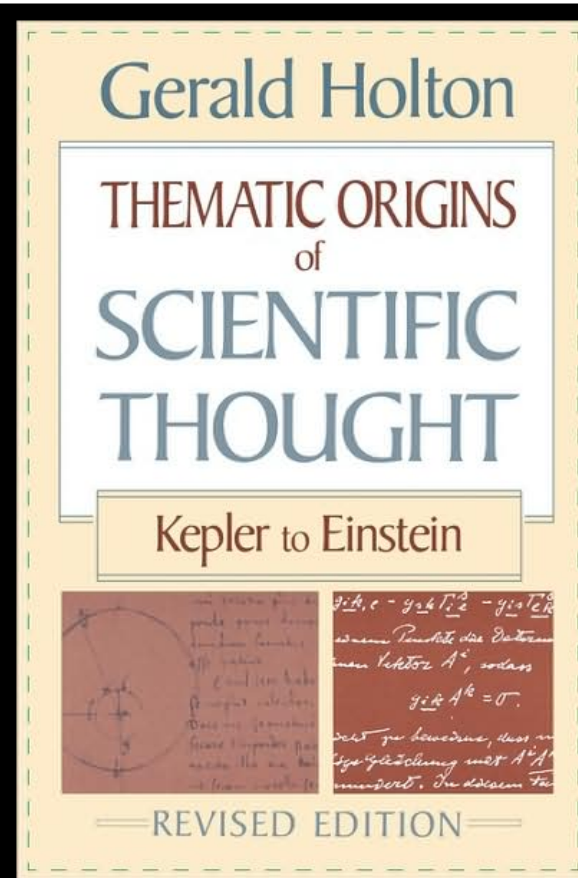




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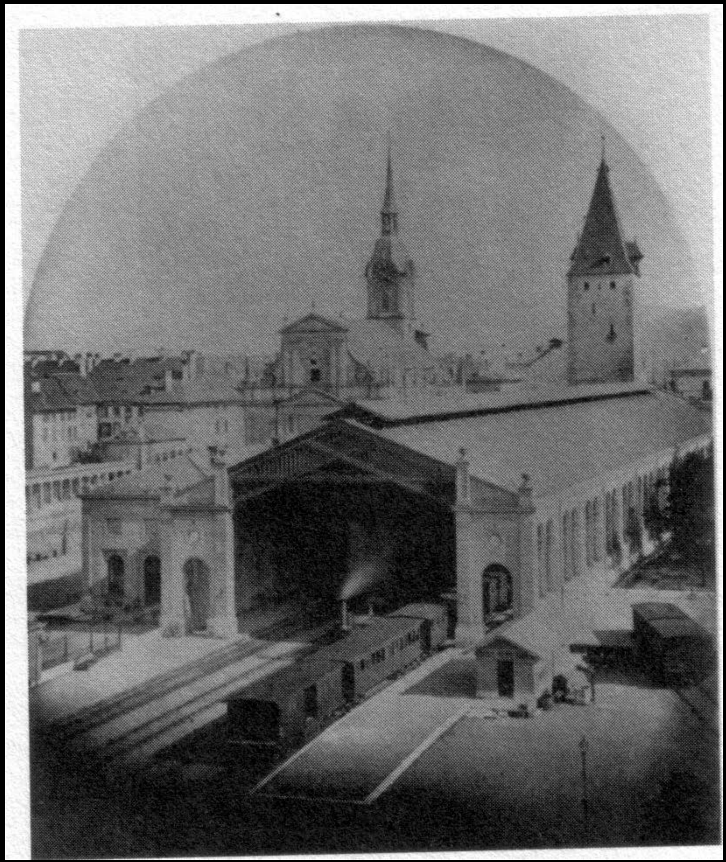
Does that mean that Einstein was uninterested in experiments?

# 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

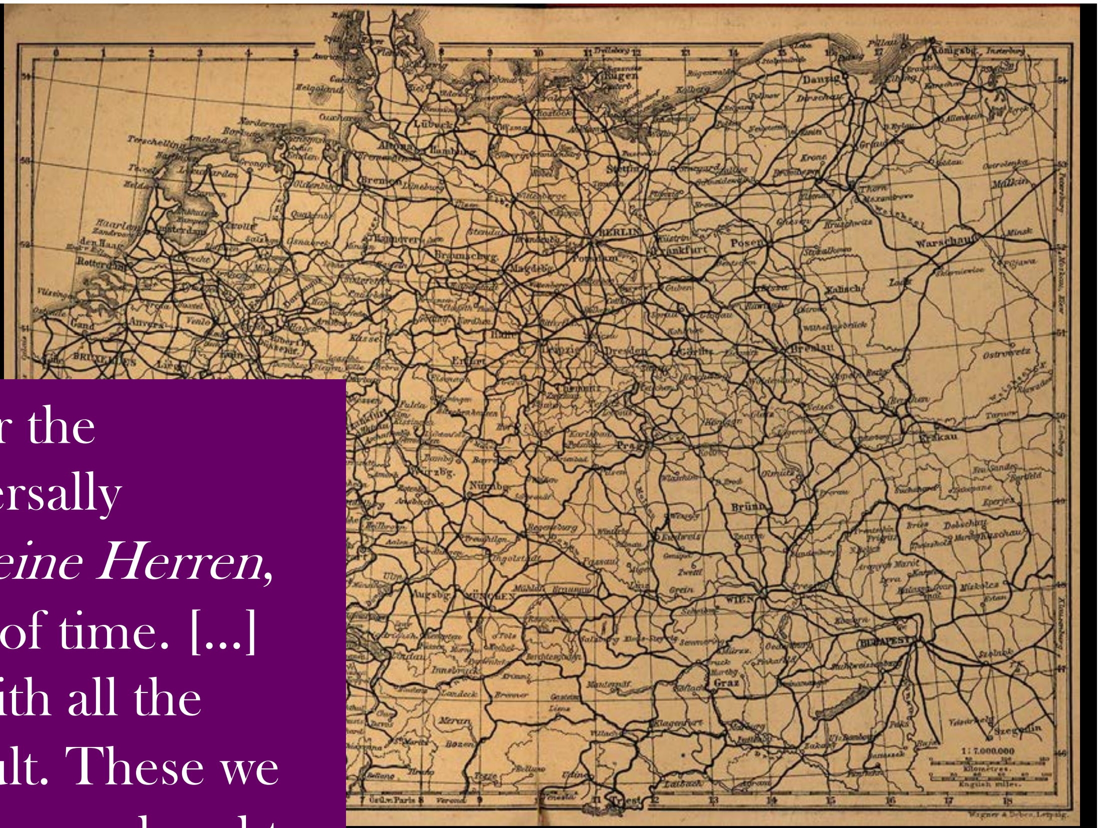


French train wreck, 1895



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

# Time Zones



German railway system, 1910



"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."

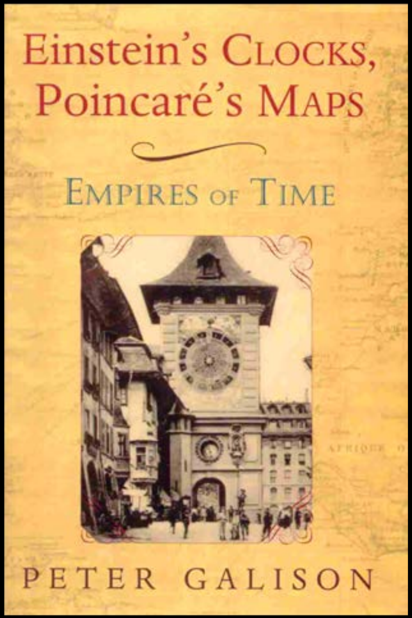
Count von Moltke, 1891

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

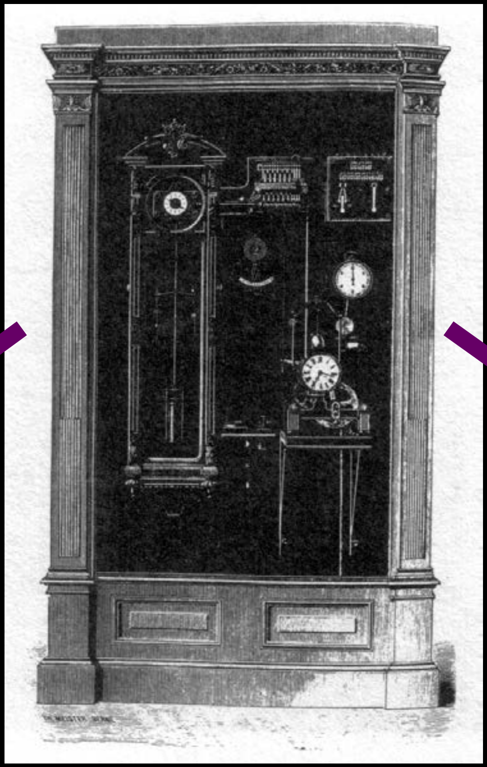
All during Einstein's childhood.

# Coordinating Clocks at a Distance

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

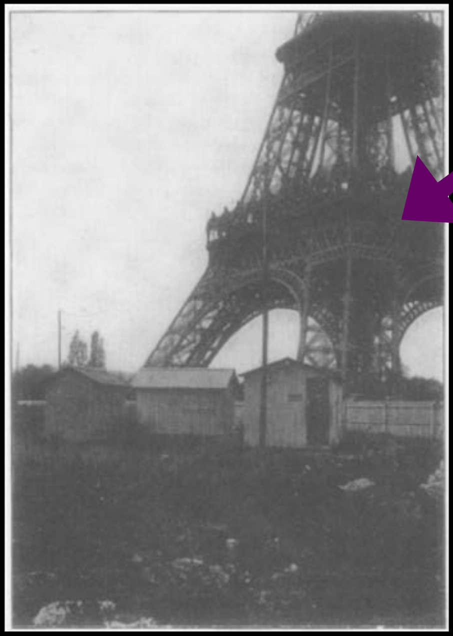




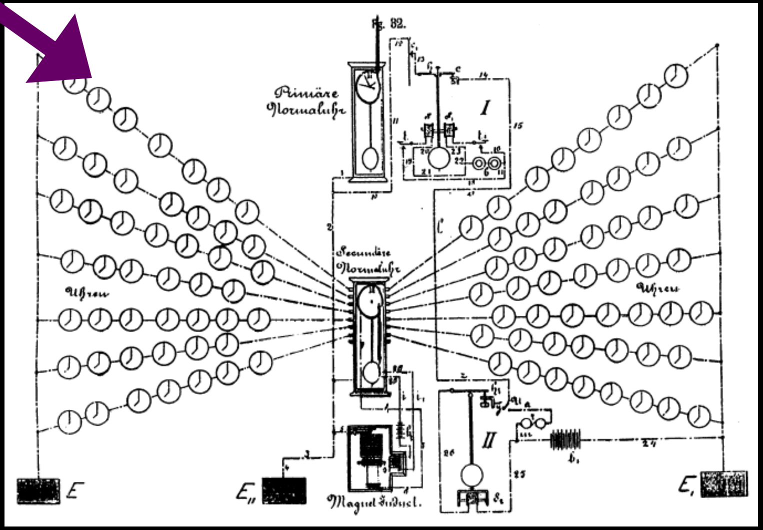
“Mother clock” in Neuchatel, Switzerland, ca. 1920





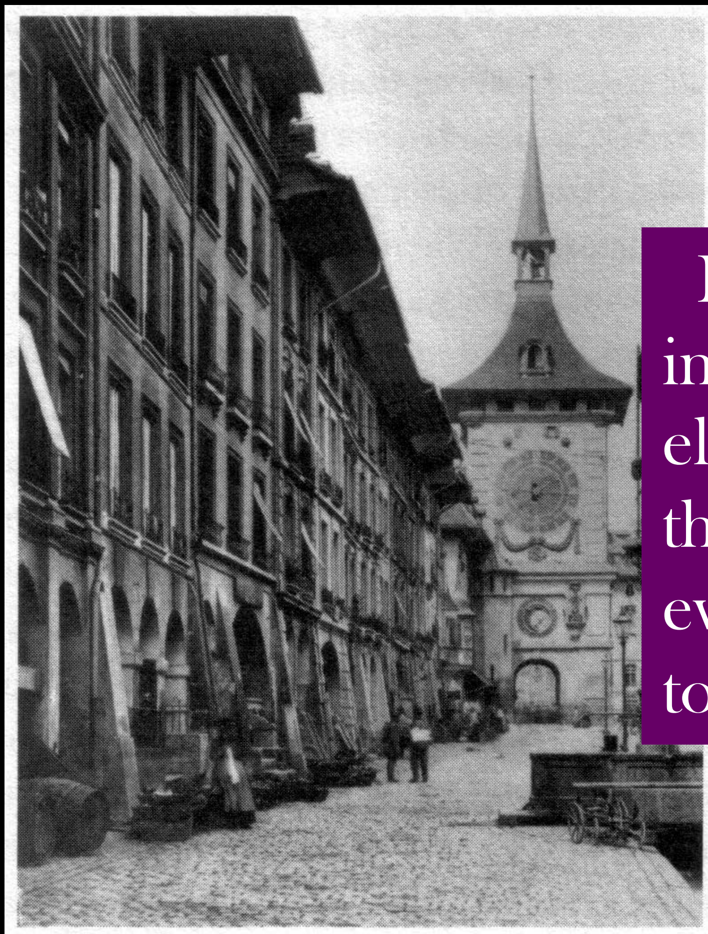
Eiffel Tower radio station, ca. 1910





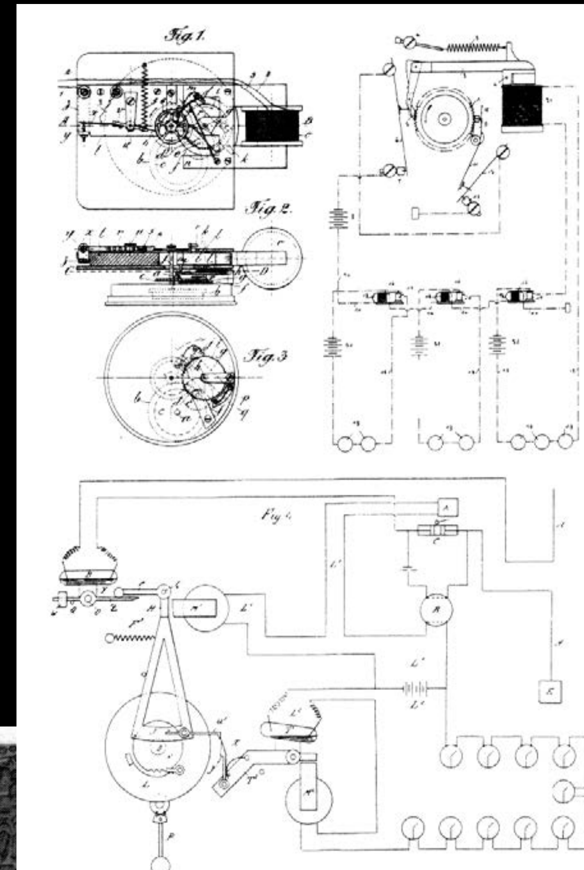

Time synchronization scheme, 1890

# Patents and Pathways

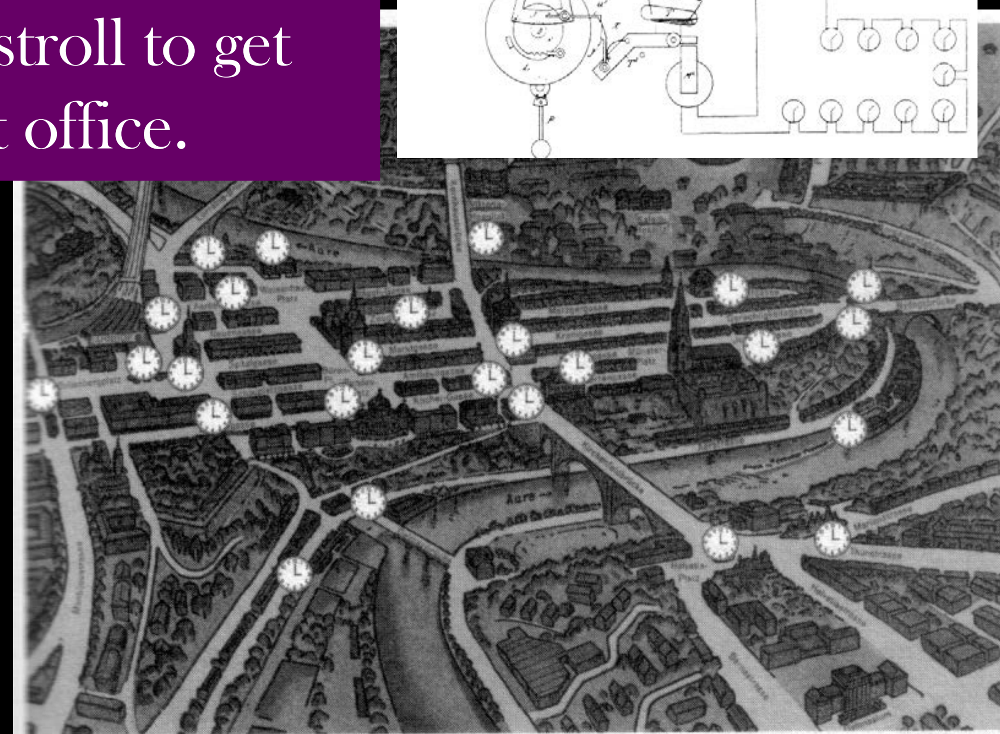


Coordinated clock on Einstein's block, 1905

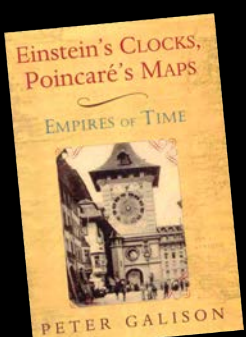
Patents on clock coordination components, 1903–1905




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



# 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

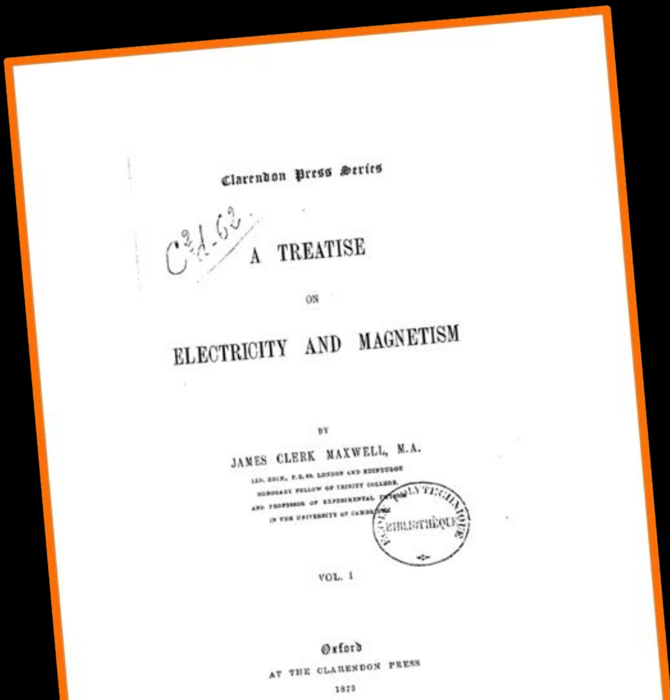


Lack of references: emphasize priority, downplay precedents;

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

*Looks like a patent application...*

# Ideas, Machines, and Spacetime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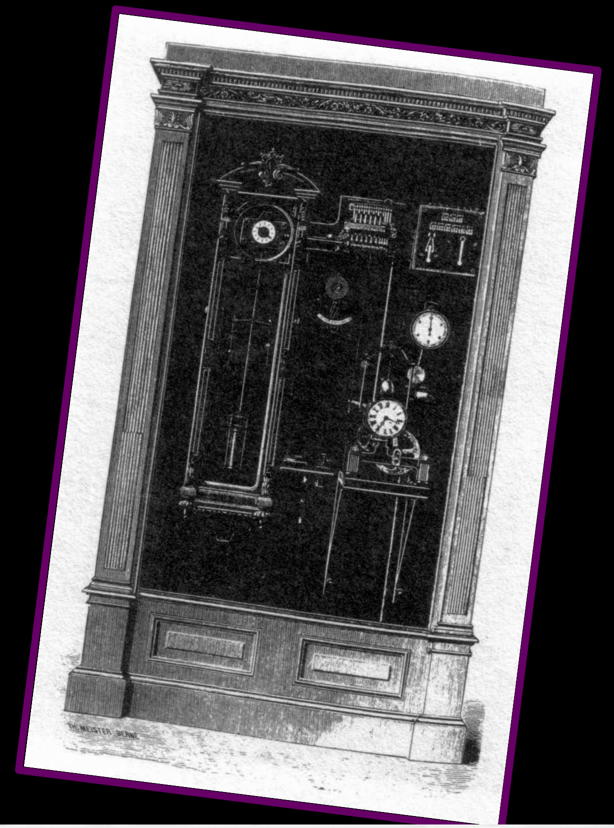

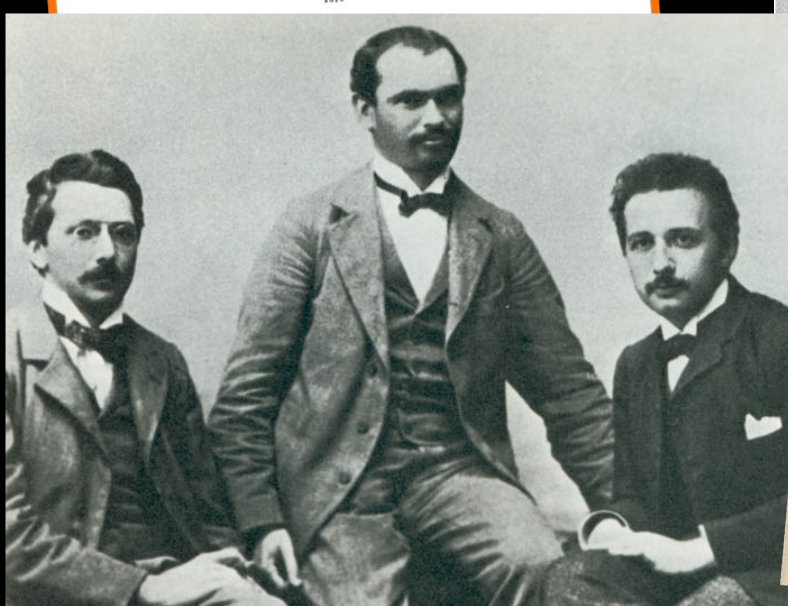

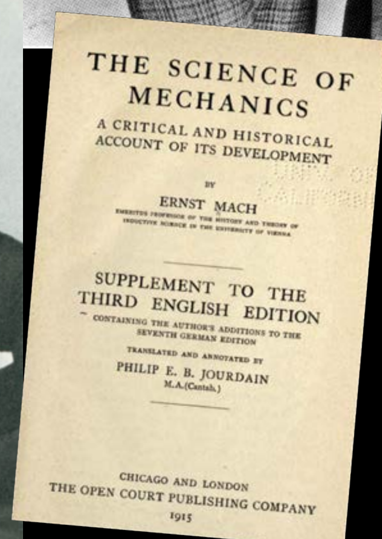
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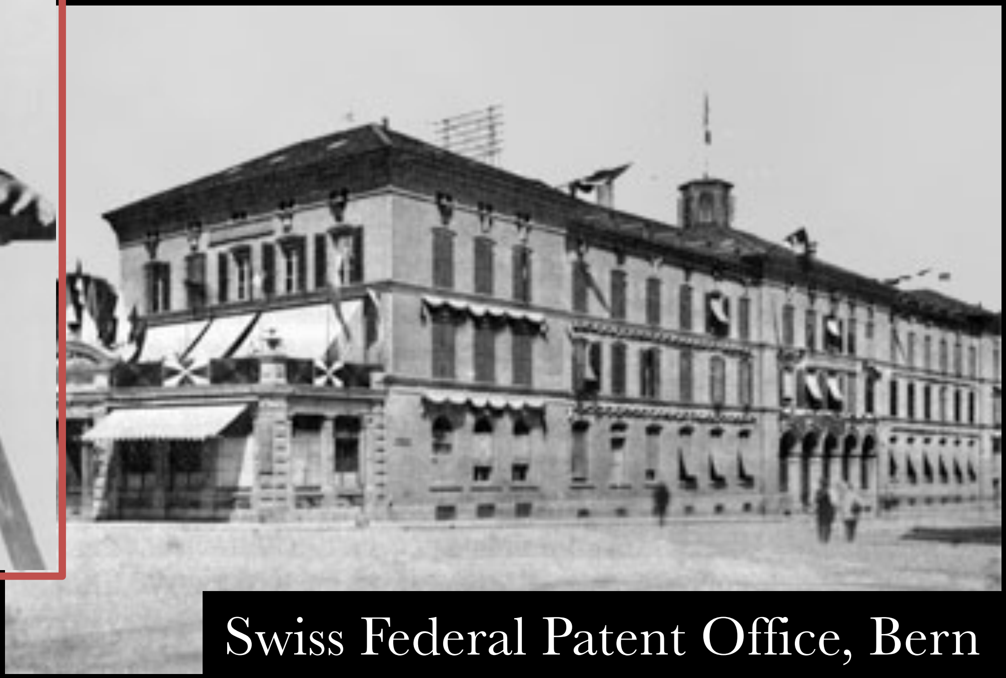

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# "Lorentz-Einstein theory"

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IAP 2021