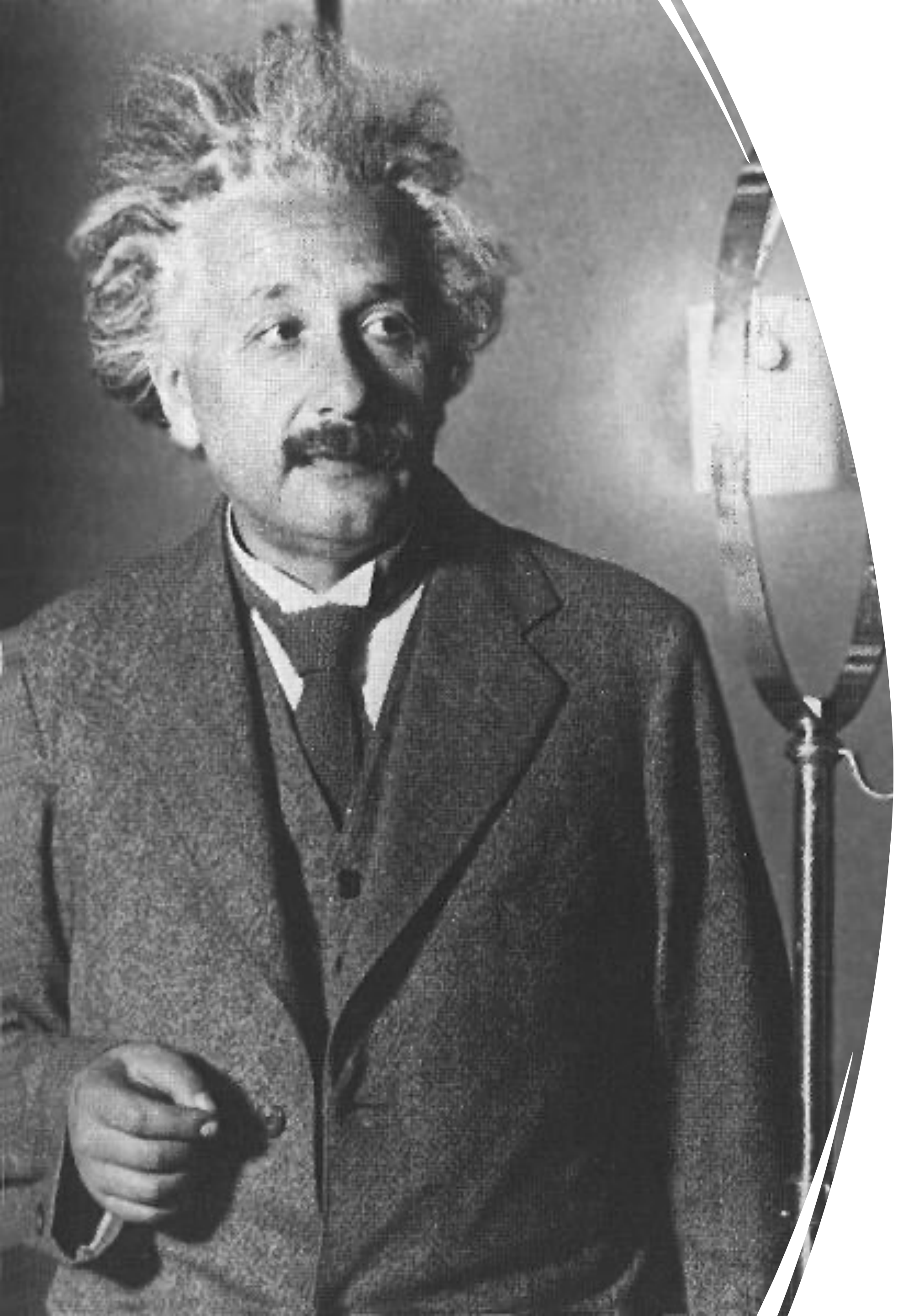


# Lecture 6 Special Relativity

GEB 3301 Space, Time, and Einstein for Everyone

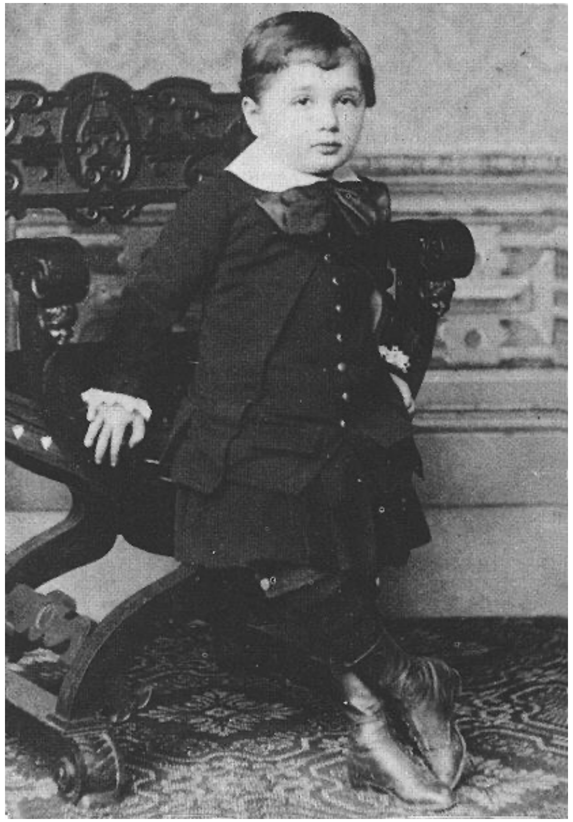
Lara Xiaoqian Hu

# Review of last last

- What do you guys remember about Kant?

# Albert Einstein

- Birth: March 14, 1879, in Ulm, Germany
- Childhood: Germany and Italy
- Education: Studied physics and mathematics at the Federal Polytechnic Academy in Zurich, Switzerland
- Citizenship: Became a Swiss citizen
- Ph.D. Award: Received Ph.D. from the University of Zurich in 1905
- "Annus Mirabilis" (Miracle Year): Published five influential theoretical papers in 1905
- Impact: Profoundly influenced the development of modern physics



# Albert Einstein

- Career aspiration: Wanted to teach math and science at a university
- Struggled with tests: Not a strong test-taker
- Difficulty obtaining university job: Test performance impacted employment prospects
- Rumored math test failure: Uncertainty due to grading methods of the time
- Photo: Einstein at age 16 during high school years

# Albert Einstein - 1905

- June 1905: Einstein, a patent examiner, submitted a paper to "Annalen der Physik"
- Title: Contains his special theory of relativity
- Objective: Address certain problems in electrodynamics
- Proposed idea: Alteration of our understanding of space and time behavior
- Significance: Groundbreaking theory with far-reaching implications

# Albert Einstein - 1905

- The theory Einstein described is now known as the "special theory of relativity." It is a "theory of relativity" because it is based on the **relativity of inertial motion**. The qualification "special" was not originally part of the theory.
- Over the coming decade, Einstein sought to develop his theory of 1905 in a way that would extend the treatment of relative motion to accelerated motion and would, at the same time, incorporate gravitation.
- The theory of 1905 came to be called the "special" theory to distinguish it from the later extension, "the general theory of relativity."

# Einstein in 1905

- In 1905, however, when Einstein first introduced it, it was a strange and even shocking theory. Then Einstein did not have the luxury of a simple text book on special relativity from which he could learn the theory. Somehow he had to see that such a theory was needed. And then he had to devise the theory and know it was not crazy speculation.
- How did he do it?
- He worked with resources and methods available to everyone. We shall see how he took the same pieces everyone had and assembled a masterpiece where everyone else faltered.

# Einstein in 1905

- To foreshadow what is to come, we will find that there was no good experimental foundation for special relativity prior to Einstein's time. That is, we needed reliable results on things that move very fast, close to the speed of light, before relativity theory could have solid experimental foundation. That foundation came with the electromagnetic theory of Maxwell and others in the nineteenth century. It gave the first reliable account of how some very rapidly moving things behave, including, most notably, light itself. Before Einstein's time, relativity theory could not properly emerge.

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,
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and since there is no motion of the medium, equations (B), Art. 598, become

$$P = -\frac{dF}{dt}, \qquad Q = -\frac{dG}{dt}, \qquad R = -\frac{dH}{dt}. \tag{17}$$

Hence

$$u = -\frac{K}{4\pi}\frac{d^2F}{dt^2}, \qquad v = -\frac{K}{4\pi}\frac{d^2G}{dt^2}, \qquad w = -\frac{K}{4\pi}\frac{d^2F}{dt^2}. \tag{18}$$

Comparing these values with those given in equation (14), we find

$$\left.\begin{aligned} \frac{d^2F}{dz^2} &= K\mu\frac{d^2F}{dt^2}, \\ \frac{d^2G}{dz^2} &= K\mu\frac{d^2G}{dt^2}, \\ 0 &= K\mu\frac{d^2H}{dt^2}. \end{aligned}\right\} \tag{19}$$

The first and second of these equations are the equations of propagation of a plane wave, and their solution is of the well-known form

$$\left.\begin{aligned} F &= f_1(z-Vt)+f_2(z+Vt), \\ G &= f_3(z-Vt)+f_4(z+Vt). \end{aligned}\right\} \tag{20}$$

The solution of the third equation is

$$K\mu H = A + Bt, \tag{21}$$

where $A$ and $B$ are functions of $z$. $H$ is therefore either constant or varies directly with the time. In neither case can it take part in the propagation of waves.

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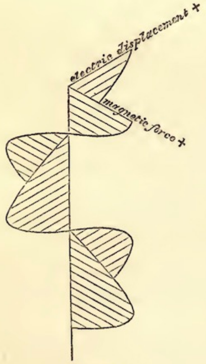



Fig. 66.

If we suppose $G = 0$, the disturbance will correspond to a plane-polarized ray of light.

The magnetic force is in this case parallel to the axis of $y$ and equal to $\frac{1}{\mu}\frac{dF}{dz}$, and the electromotive force is parallel to the axis of $x$ and equal to $-\frac{dF}{dt}$. The magnetic force is therefore in a plane perpendicular to that which contains the electric force.

The values of the magnetic force and of the electromotive force at a given instant at different points of the ray are represented in Fig. 66,

# Einstein in 1905

- Once electromagnetic theory had been developed, there was a sense that relativity theory already lived within the theory. H. A. Lorentz already discovered the basic equations Einstein would use later within special relativity. It had become **inevitable** (or is it?) that relativity theory or something like it would emerge. It was really only a question of who would have the ingenuity and flexibility of mind to find the theory first. That person proved to be Einstein.
- Let us first figure out Einstein’s special theory (and his two postulates).

# Inertial and Accelerated Motion

- There is a preferred motion in space known as inertial motion. Any body left to itself in space will default to an inertial motion, which is just motion at uniform speed in a straight line.
- The existence of such motions as the natural default is a fundamental fact about space and time. We need to discover which of all possible motions in space comprise the inertial motions. We do that by observing things in motion when they are free of deflecting forces; or by correcting the motions we observed for the deflecting effects of these motions.

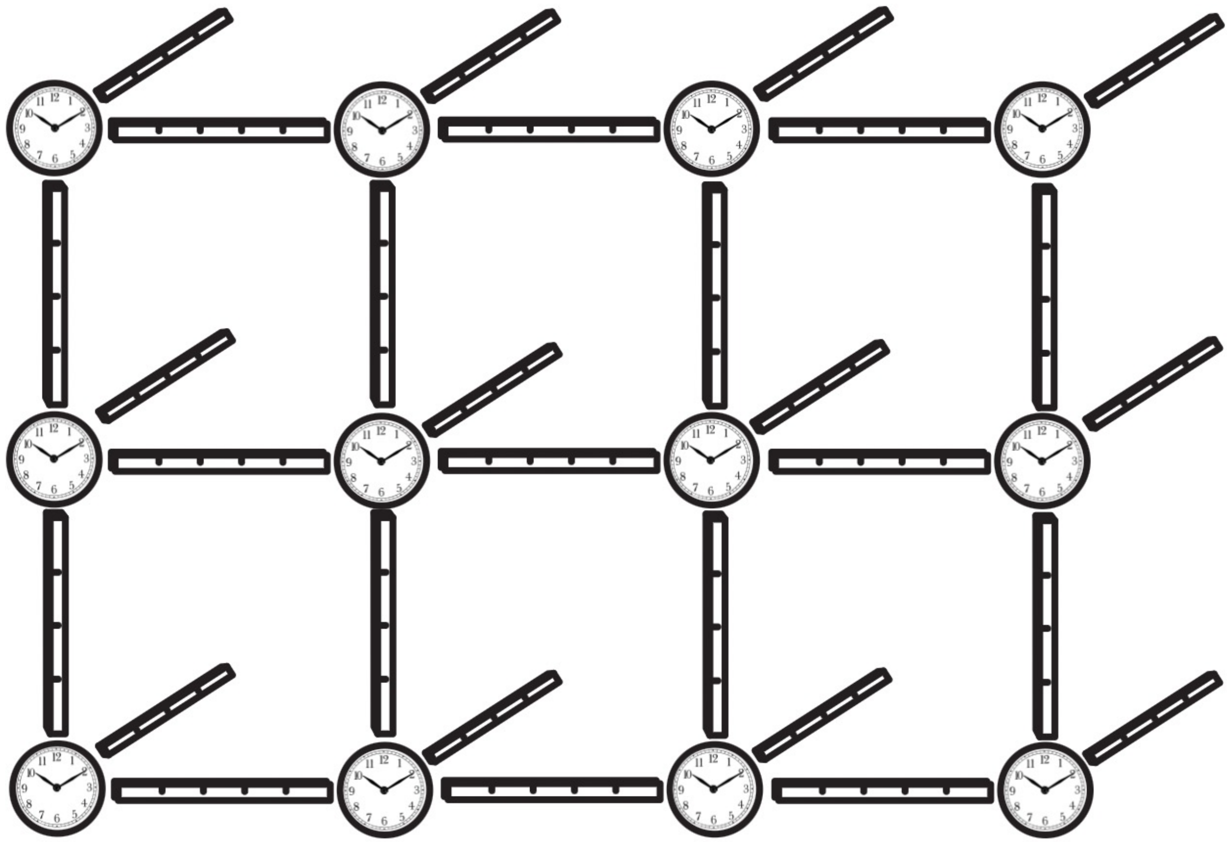
# Inertial and Accelerated Motion

- Any other motion is accelerated. This includes motion at uniform speed in a circle. While the speed stays the same, the direction does not. So the motion is accelerated.
- Sometimes we will talk of an "inertial observer." It is just an observer who moves inertially.
- Such an observer might set up an elaborate system of measuring rods and other physical devices to fix the positions of events; and an elaborate system of clocks to fix their timing. Such a system is an inertial frame of reference.

# Inertial and Accelerated Motion

One way that we might build an inertial frame, We fill space with an array of clocks and use them to determine the time of an event coincident with the clock.

Example: We connect the clocks with measuring rods so that we can locate any point in the frame merely by giving directions in the form of three numbers. "(4,3,7)" means, say, go right 4 rods from the starting point, up 3 and then back 7.



# Inertial and Accelerated Motion

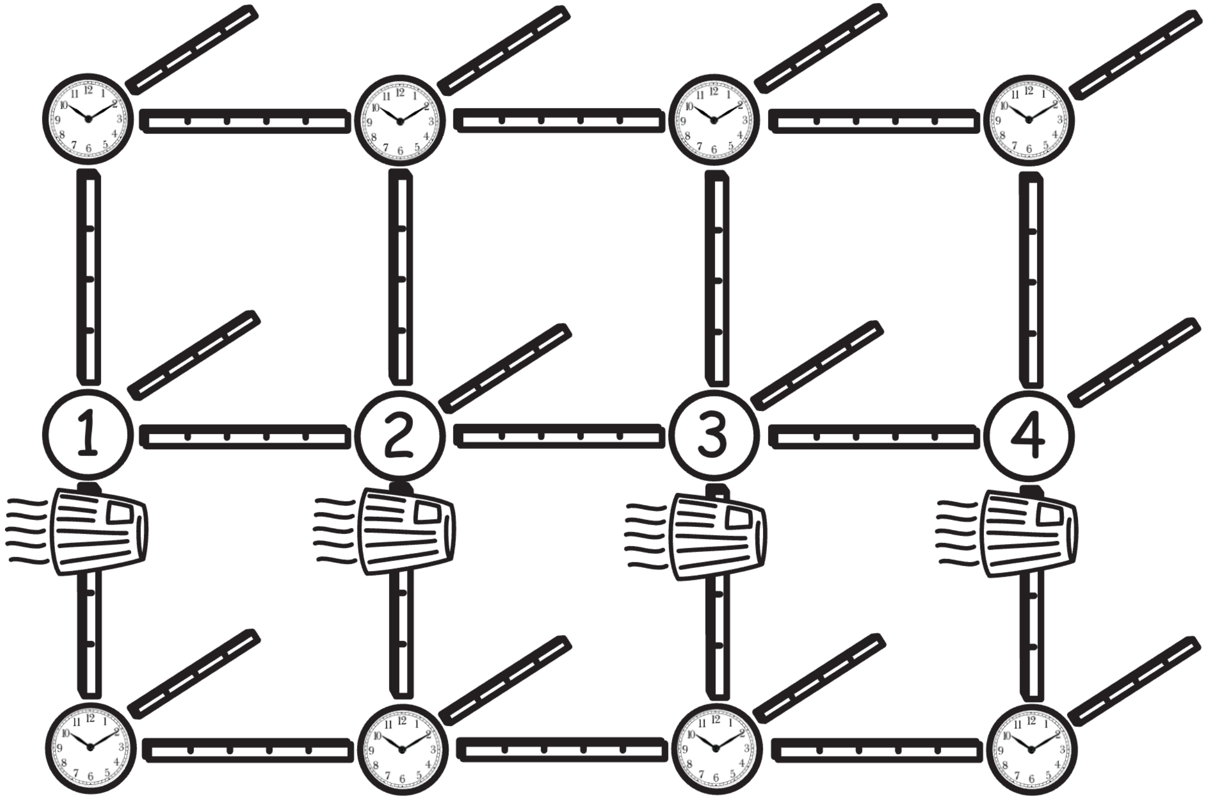
- What is important is that the frame consists of physical devices--typically measuring rods and clocks--that are at rest relative to the inertial observer. This is important since we shall see soon that the lengths and times read by such devices are affected by their motion, according to special relativity.

# Inertial and Accelerated Motion

If some spaceship moves uniformly in a straight line in the frame, that means that it covers equal distances in the frame in equal time, while moving in one direction.

The "equal distances" are distances as measured by the rods of the frame. The “equal times” are times as measured by the frame's clocks.

The spaceship passes from clock to clock in equal times, as indicated by the clocks recording "1," "2,", "3," etc. when it passes them. The distances between the clocks are the same: one rod length.



# Absolute motion vs. relation motion (again)

- Relative motion arises when one body moves with respect to another. For example, our spaceship might move relatively to a nearby planet.
- Absolute motion (recall Newton): “Absolute motion is the translation of a body from one absolute place into another; and relative motion, the translation from one relative place into another.”

# Absolute motion vs. relation motion (again)

- Einstein's theory does discard the absolutes of Newton's physics by introducing the idea of the relativity of all inertial motion. That means that we cannot distinguish any special motions among all the inertial motions, such as a preferred rest state.
- We cannot say that this one is fast, that one is slow and another is at rest. We must always add a qualification. We must say that this is one is fast with respect to that; that one is slow with respect to another; or at rest with respect to another again.

# Absolute motion vs. relation motion (again)

- In Einstein’s special theory of relativity, the relativity of motion is implemented only for inertial motions. It does not extend to accelerated motions. They are motions that change their speed or direction or both.
- We can still say that something accelerates without adding a further qualification "with respect to...". Thus, acceleration is an “absolute” for Einstein's special theory.

# Absolute motion vs. relation motion (again)

- Acceleration is discoverable by an experiment within a closed body. If the body is accelerating, that will be revealed by effects within the body. For example, an airplane flies inertially until it hits an air pocket. Then the plane lurches--accelerates--and things inside are thrown about. Everyone inside has no doubt of the acceleration.
- However, beware of oversimplified slogans: like "It's all relative." or "All motion is relative." That is not what we learn from Einstein's special theory. It eradicates absolute motion. We learn that something can only be at rest if it is at rest with respect to something else. So, the better slogan would be "All rest is relative."

# Two postulates

- Einstein found it most convenient to base his theory of relativity on two postulates; once they were assumed it became an exercise in logic to develop the whole theory.

- The two postulates are:
  I. The Principle of Relativity and
  II. The Light Postulate.

# The Principle of Relativity

- The first principle, the principle of relativity, says something about all the laws of physics. To state the principle, we must first express those laws in a particular way, that is, in terms of the quantities defined within an inertial frame of reference.
- Take Newton's first law of motion, for example. (It is a law that also holds in special relativity.) It says in Newton's original wording:
- “Every body continues in its <u>state of rest</u>, or in <u>uniform motion</u> in a right [straight] line, unless it is compelled to change that state by forces impressed upon it.”

# The Principle of Relativity

- The terms used in this formulation of Newton's first law require that we refer to some inertial frame of reference.
- "State of rest" means that the body remains at the same position in the inertial frame over time.
- "Uniform motion" means that the body covers the same distance in the same time, where distance is measured by the frame's measuring rods and time is measured by the frame's clock.

# The Principle of Relativity

- The principle of relativity asserts: **The laws of physics are the same in all inertial frames of reference.**
- That just means this: if we express some law of physics using the quantities of one inertial frame of reference, the resulting statement of the law will be exactly the same in any other inertial frame of reference.

# The Principle of Relativity

- We can use the example of Newton's first law of motion to illustrate the principle. Assume that we have three different inertial frames of reference, corresponding to the three observers shown below, then the statement of the law is the same in each frame.

In this inertial frame of reference, Newton's first law of motion reads:

*Every body continues in its state of rest, or in uniform motion in a right [straight] line, unless it is compelled to change that state by forces impressed upon it.*

Example 1

# The Principle of Relativity

In this inertial frame of reference, Newton's first law of motion reads:

*Every body continues in its state of rest, or in uniform motion in a right [straight] line, unless it is compelled to change that state by forces impressed upon it.*

Example 2

# The Principle of Relativity

In this inertial frame of reference, Newton's first law of motion reads:

*Every body continues in its state of rest, or in uniform motion in a right [straight] line, unless it is compelled to change that state by forces impressed upon it.*

Example 3

# The Principle of Relativity

- That the law has exactly the same form in each inertial frame of reference precludes absolute motions.
- Consider a pre-Newtonian view of motion. According to it, all motions would automatically slow down until they arrived at a unique state of rest. This law cannot be formulated in the same way in all inertial frames of reference. We would need one form of the law if the frame at issue is the true rest frame. We would need a different form in all the other frames of reference.

# The Principle of Relativity

- Assume that the middle motion is the unique state of rest "A". Then the pre-Newtonian law is expressed differently in the other two frames and in a way that requires specific mention of the unique state of rest "A".

In this frame of reference, the pre-Newtonian law reads:

*Every body alters its motion until it moves like "A".*

Example 1

# The Principle of Relativity

The unique state of rest "A".

In this frame of reference, the pre-Newtonian law reads:

*Every moving body slows to rest.*

Example 2

# The Principle of Relativity

In this frame of reference, the pre-Newtonian law reads:

*Every body alters its motion until it moves like "A".*

Example 3

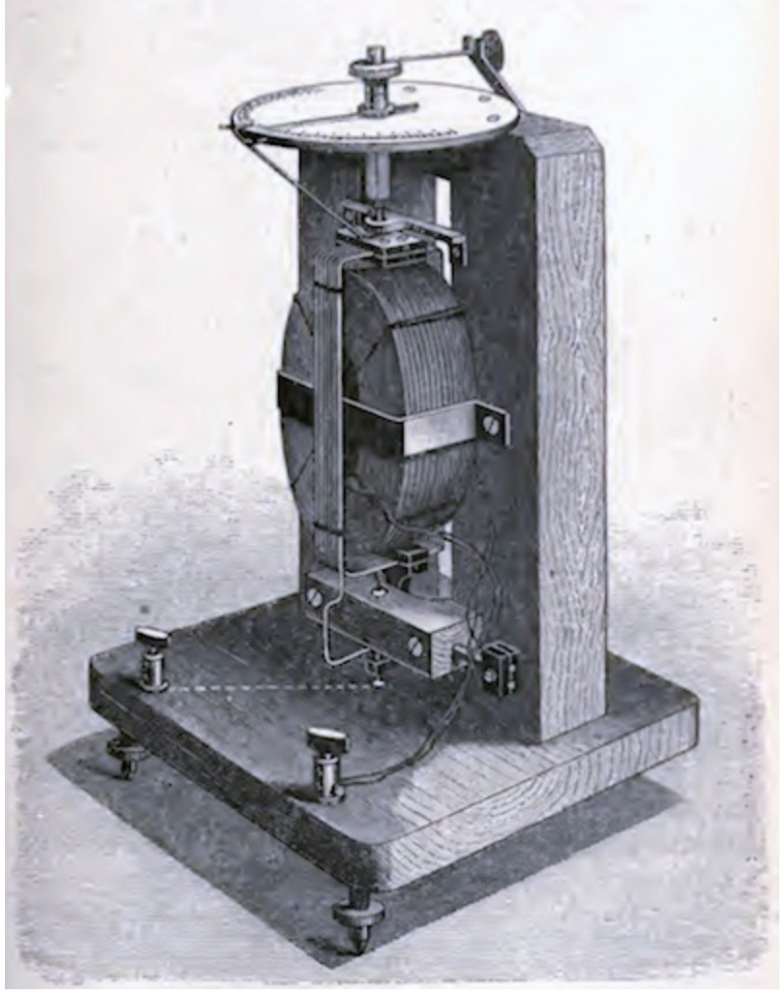
# The Principle of Relativity

- That is, we **infer** from the principle of relativity:
- **Absolute motion cannot appear in any law of physics.** (Note: we infer this from the principle of relativity. So this conclusion might not say as much as the principle does. It might be logically weaker. That is, this conclusion is not the principle itself.)
- There are more important conclusions that we will draw from the principle of relativity. One of the most useful pertains to experiments. To make the connection, we need to see that laws of nature are really compact **summaries of a huge range of possibilities**.

# The Principle of Relativity

- For example, Ohm's law $(V = IR)$ just tells us that the voltage across a resistor is proportional to the current flowing. That proportionality is really a summary statement of a huge number of facts, each of which applies to a specific case.

# The Principle of Relativity



Siemens electro-dynamometer for measuring strong currents.
p.58 in J. E. H. Gordon, School Electricity. London: Sampson Low, Marston, Searle, & Rivington, 1886.

It says:

For a 1 Ohm resistor:

When the voltage is 1V, the current is 1A.
When the voltage is 2V, the current is 2A.
When the voltage is 3V, the current is 3A.
When the voltage is 4V, the current is 4A.
...

For a 2 Ohm resistor:

When the voltage is 2V, the current is 1A.
When the voltage is 4V, the current is 2A.
When the voltage is 6V, the current is 3A.
When the voltage is 8V, the current is 4A.
...

And so on indefinitely for many more cases.

# The Principle of Relativity

- Each one of these possibilities describes **a little experiment** and tells us what the result must be. For example, one of them tells us that, if we procure a 1 Ohm resistor and apply a voltage of 2V ("Volts") to it, 2A ("Amps") of current will flow.
- Imagine now that we carry out this experiment in <u>one inertial frame of reference</u>. Assume that the experiment succeeds, returning the above result of 2A of current. We now know that this possibility is one of the possibilities listed by the applicable law of physics.

# The Principle of Relativity

- Since the laws are the **same in each inertial frame** of reference, it follows that the lists of possibilities in each inertial frame of reference are the same. Hence if the experiment proceeds as described in one inertial frame of reference it must also proceed in the same way in any other inertial frame of reference.
- Conclusion: **All experiments run the same in all inertial frames of reference**.

# The Principle of Relativity

- All experiments run the same in all inertial frames of reference. That means that anything that happens in one inertial frame can also happen in any other. It follows that **there can be no sign** that the inertial frame you are in is intrinsically special, that is, in itself different from the others.
- What an experiment can do it to determine **whether the inertial frame is moving with respect to** something else. That does not show there is anything intrinsically special about the inertial frame.

# The Principle of Relativity

- Thus no experiment can pick out just one inertial frame of reference as distinguished. Since absolute rest and absolute motion, if detectible, would require just such a distinguished rest frame, we can conclude:
- **No experiment can reveal the absolute motion of the observer.**
- This is a consequence of the principle of relativity. Another way to see it is to recall that the principle of relativity leads us to conclude that absolute motion cannot figure in any law of physics. But if it is not in the laws and the laws determine what can be, then absolute motion cannot be. So no experiment could detect it.

# The Principle of Relativity

- The principle of relativity of Einstein's special theory is restricted to **inertial motion**. The relativity it asserts **does not extend to accelerated motion**. If something accelerates, then it does so absolutely in Einstein's theory. There is no need to say that it "accelerates with respect to..."
- A traditional indicator of acceleration is inertial forces. If you are in an airplane that flies uniformly in a straight line, you have no sense of motion. If the airplane hits turbulence and accelerates, you sense immediately the acceleration. Inertial forces throw things around in the cabin. Those effects reveal the absolute acceleration of the airplane.

# The Principle of Relativity

- Here is the principle of relativity and the three important consequences collected in one place:
- **Principle of Relativity: The laws of physics are the same in all inertial frames of reference.**
- It follows that:
- Absolute motion cannot appear in any law of physics.
- All experiments run the same in all inertial frames of reference.
- No experiment can reveal the absolute motion of the observer.

# The Light Postulate

- The light postulate is much narrower in scope. It makes no reference to all the laws of physics, as does the principle of relativity. Rather it refers to the propagation of light. If we have light propagating in any inertial frame, we **measure its speed using the rods and clocks** of that frame.
- We will find:
- **The speed of light is the same in all inertial frames of reference.**
- hat speed is 186,000 miles per second or 300,000 kilometers per second. Because this speed crops up so often in relativity theory, it is represented by the letter "c".

# The Light Postulate

- The speed referred to here is the speed of **light in a vacuum**. Light passing through any dense medium, such as glass or water, is appreciably slowed by the medium. Light in water travels at 75% its speed in a vacuum. There is even a very slight effect in air. But it is very slight: a slowing of 0.03%.
- That Einstein should believe the principle of relativity should not come as such a surprise. We are moving rapidly on planet earth through space. But our motion is nearly invisible to us, as the principle of relativity requires.

# The Light Postulate

- Why nearly invisible?
- It is because the motion at any point on the earth's surface is not quite inertial. In the course of a full day, the direction of motion of the point will turn through a full 360 degrees. This very slow turning produces effects that can be measured, by, for example, the Foucault pendulum experiment that is so popular in science museums.
- Why Einstein should believe the light postulate is a little harder to see.

# The Light Postulate

- The principal reason for Einstein's acceptance of the light postulate was his lengthy study of electrodynamics, the theory of electric and magnetic fields. The theory was the most advanced physics of the time.
- Some 50 years before, Maxwell had shown that light was merely a ripple propagating in an electromagnetic field. Maxwell's theory predicted that the speed of the ripple was a quite definite number: c.

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Hence

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Comparing these values with those given in equation (14), we find

$$\left.\begin{aligned} \frac{d^2F}{dz^2} &= K\mu\frac{d^2F}{dt^2}, \\ \frac{d^2G}{dz^2} &= K\mu\frac{d^2G}{dt^2}, \\ 0 &= K\mu\frac{d^2H}{dt^2}. \end{aligned}\right\} \tag{19}$$

The first and second of these equations are the equations of propagation of a plane wave, and their solution is of the well-known form

$$\left.\begin{aligned} F &= f_1(z-Vt)+f_2(z+Vt), \\ G &= f_3(z-Vt)+f_4(z+Vt). \end{aligned}\right\} \tag{20}$$

The solution of the third equation is

$$K\mu H = A + Bt, \tag{21}$$

where $A$ and $B$ are functions of $z$. $H$ is therefore either constant or varies directly with the time. In neither case can it take part in the propagation of waves.

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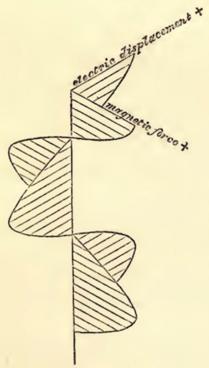



Fig. 66.

If we suppose $G = 0$, the disturbance will correspond to a plane-polarized ray of light.

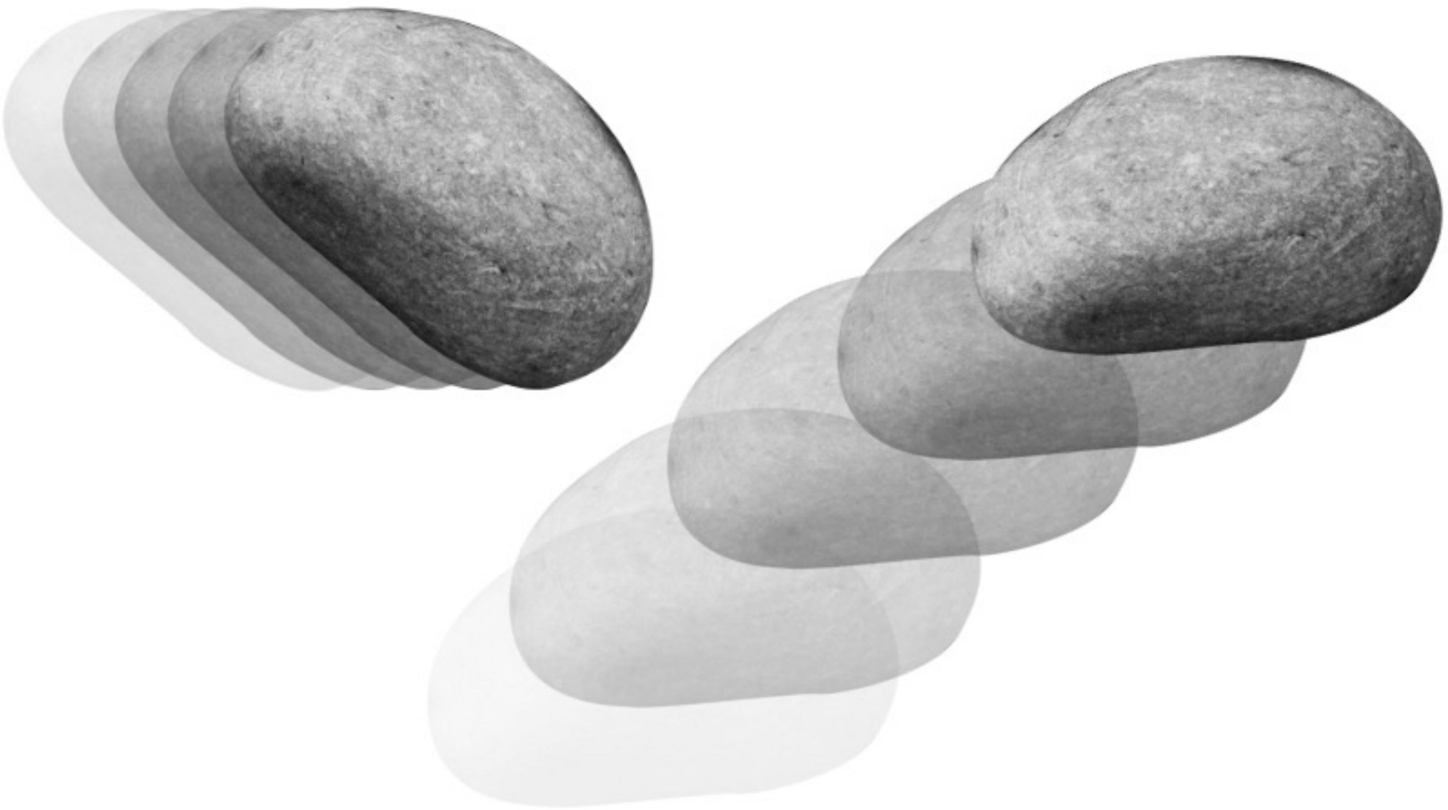
The magnetic force is in this case parallel to the axis of $y$ and equal to $\frac{1}{\mu}\frac{dF}{dz}$, and the electromotive force is parallel to the axis of $x$ and equal to $-\frac{dF}{dt}$. The magnetic force is therefore in a plane perpendicular to that which contains the electric force.

The values of the magnetic force and of the electromotive force at a given instant at different points of the ray are represented in Fig. 66,

# The Light Postulate

- The speed of a light signal was quite **unlike the speed of a pebble**, say. The pebble could move at any speed, depending on how hard it was thrown. It was different with light in Maxwell's theory. No matter how the light signal was made and projected, its speed always came out the same. For Maxwell, that speed was always the same in just one frame of reference, the rest frame of his electromagnetic ether.

# The Light Postulate



# The Light Postulate

- The principle of relativity assured Einstein that the laws of nature were the same for all inertial observers. That light always propagated at the same speed was a law within Maxwell's theory. If it held in one inertial frame of reference, it must hold in all. So, if **the principle of relativity was applied to Maxwell's** law about light, the light postulate resulted immediately.

# Astronomical Origins of the Principle of Relativity

- The principle of relativity tells us that we cannot detect our uniform motion. Whether uniform motion was detectible or not became a pressing issue in the sixteenth and seventeenth century.
- Up to then, the widely accepted idea was that the earth was at rest at the center of the cosmos. The sun, moon and planets orbit around it.

# Astronomical Origins of the Principle of Relativity

- Nicolaus Copernicus had other ideas. Using powerful astronomical arguments collected in his 1543 *On the Revolutions of the Heavenly Spheres*, he urged that the **earth is not motionless**. Rather, it is the sun, not the earth, that is at the center of the motions of the cosmos. In this heliocentric (sun-centered) cosmology, the earth is just another planet orbiting the sun.
- In addition, the daily rising and setting of the sun, moon and stars arises not from their motion, but from the daily rotation of the earth on its axis.

# Astronomical Origins of the Principle of Relativity

- If Copernicus' idea was to survive, physics would have to be renewed so that the motion of the earth under out feet would be undetectable by physical means.
- In later language, we needed a new physics that conformed with the principle of relativity. While Copernicus had made some small efforts in this direction, the challenge was taken up most fully by Galileo Galilei. His most mature defense of the Copernicus system came in his 1632 *Dialogue Concerning the Two Chief World Systems.* The two systems are the Ptolemaic and the Copernican.

# Astronomical Origins of the Principle of Relativity

- Galileo's work pointed to what the new physics would be like. The work of developing that new physics was completed by Isaac Newton in his magisterial *Mathematical Principles of Natural Philosophy* of 1687. Conformity with the principle of relativity was built into Newton's physics from the outset.
- To see how, consider a naive physics that arises from casual observation of ordinary things in the world. The default "natural" state of bodies is to be at rest.
- Newton's Principia changed this default conception at the outset.

# Astronomical Origins of the Principle of Relativity

- The natural state of bodies, according to his first law of motion, is uniform motion in a straight line. If left to themselves, bodies would, to use the later expression, persist in inertial motion. Deviations from inertial motion are due to impressed forces.
- According to Newton's second law of motion, these forces do not cause motion, but *changes* of motion. In a more recent formulation, we associate forces with accelerations.

# Astronomical Origins of the Principle of Relativity

- These two principles made it possible for Newton's physics to conform with the principle of relativity in the most important aspect: processes we can measure and check run in the same way in all uniformly moving systems. Nothing in them will allow us to pick out the motion of one as preferred. We may be on a rapidly moving earth, but casual observations and experiments will not reveal it.

# Astronomical Origins of the Principle of Relativity

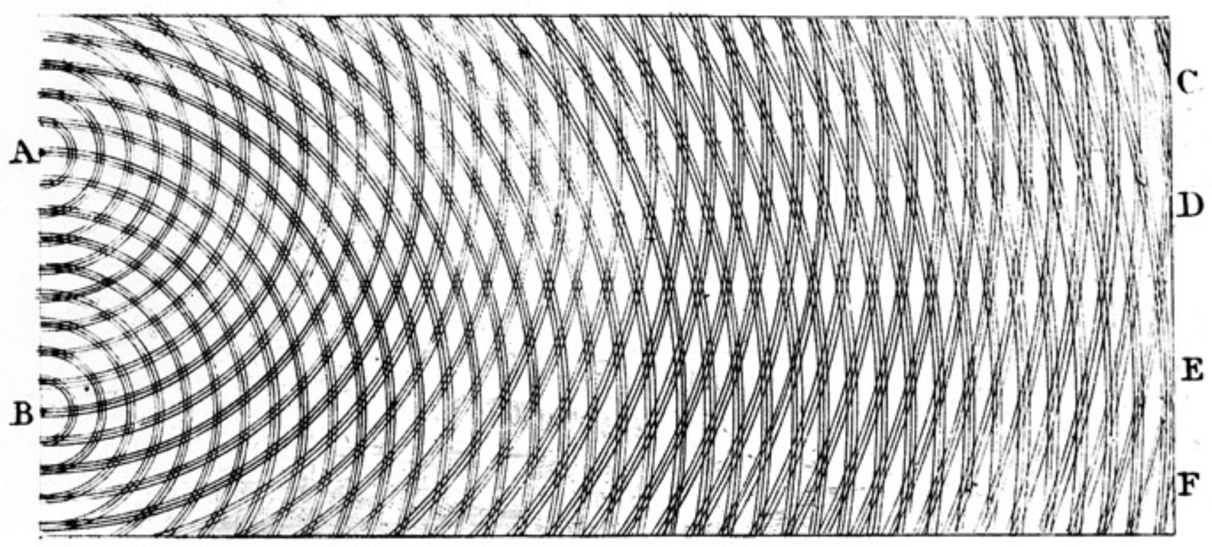
- Newton did not write explicitly of the principle of relativity. This focus on it as a principle is a late 19th century and early 20th century innovation. Rather, he built his physics, as we saw in previous classes, on the notion of absolute rest.
- The principle relativity was respected in the weaker sense that no experiment we could do on the earth would reveal our motion with respect to this absolute state of motion.

# Light

- What altered this happy arrangement in the nineteenth century were advances in the theory of light.
- Newton has supposed that light consisted of rapidly moving corpuscles; they obeyed the principle of relativity as much as anything else in his universe. Following the work of Fresnel and others early in the nineteenth century, this account was replaced by one of light as a propagating wave.

# Light

- One of the most important indications that light was a wavelike process was the discovery of interference effects, shown below in Thomas Young's famous two slit experiment. Two light sources produce the characteristic interference patterns familiar to anyone who has thrown two pebbles into a calm pond.



# Light

- If light was a wave, it was assumed that the wave must be carried by some medium, just as sound waves are carried by air and water waves are carried by water. How else could the peak and the trough of two waves annihilate one another to produce the interference patterns if the wave was not a displacement in some medium?
- That medium was known as the **luminiferous (=light bearing) ether**. The moving earth was now supposed to be moving through a medium that must stream past the earth, much as water streams past a boat moving through the ocean.

# Ether Current Experiments Fail

- This ether now made plausible that our planet's absolute motion might be detectable by experiments on the earth. All we had to do was to seek to **see the current of ether** flowing past. It proved quite easy to devise experiments to do this. Recall that the ether carries light waves, much as air carries sound waves or water, water waves. So if the ether is flowing past us, that flow ought to be revealed in measurements on light.

# Ether Current Experiments Fail

- A series of experiments were devised in the 19th century to detect this ether current. They were experiments on light. Typically they involved the passing of light through a combination of prisms, lenses and the like, creating inference fringes and then looking for an effect in these fringes. The striking result of all these experiments was that the flow of ether had no effect on optical experiments. In that sense, all the experiments failed.

# Ether Current Experiments Fail

- Curiously, it was as though the earth just happened to be at perfect rest in the ether. In retrospect, this is a puzzling outcome. At the time, however, there was nothing like the sense of crisis you might expect. Rather it had become a simple regularity of experiment that the ether drift was invisible to us.
- In some ways the attitude was not so different from what we now take to be a reasonable attitude to atoms. We know that they are there. Yet at the same time we know that they are so small that no (19th century) instrument will allow us to see them individually.

# Ether Current Experiments Fail

- The experiments could be catalogued according to the size of the effect they hoped to detect and, as a result, the sensitivity of the instruments needed. The largest effects were "first order" effects. They needed the least sensitive instruments and were easiest to conduct. Many of these **first order experiments** were undertaken and all failed to demonstrate an ether current.

# Ether Current Experiments Fail

- First order effects are proportional in size to the speed of the ether, as a fraction of the speed of light. Second order effects are proportional to the square of this fractional quantity. Since this fraction is very small, its square is smaller still. That means that second order effects are very much harder to detect than first order effects.

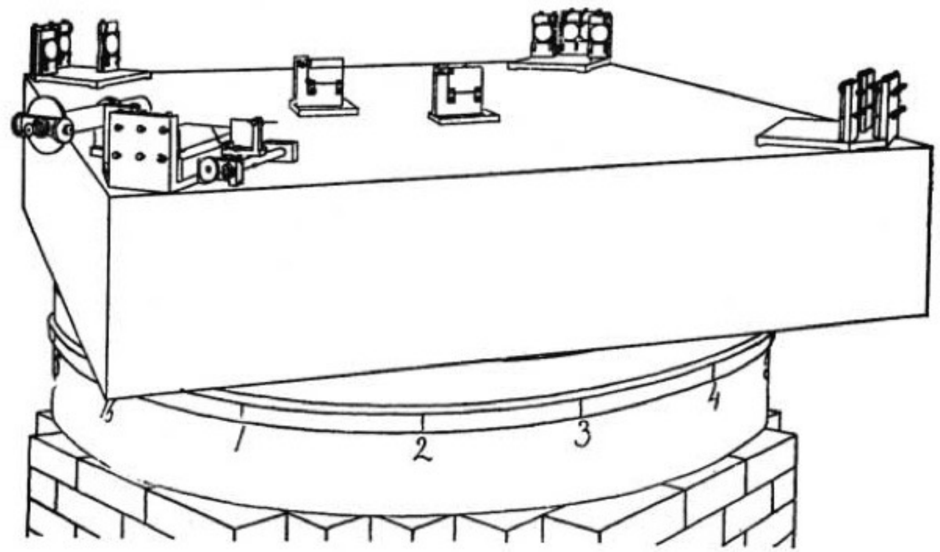
# Ether Current Experiments Fail

- Why look at first, then second, then third order effects, and so on? What makes the sequence natural is consider the effect as a function of the fractional speed of the ether wind. After a constant, the first term in the series expansion is the first order effect, the second term is the second order effect, and so on; so that considering these orders exhausts all the possibilities.

# Michelson Morley Experiment

- There was only one successfully executed in the 19th century, the celebrated experiment of Albert A. Michelson and Edward W. Morley of 1887 that completed Michelson's earlier efforts at such an experiment.
- Indeed the experiment was so difficult that Michelson won the Nobel prize principally for his highly sensitive optical interferometer used in the experiment.

3.




THE

# AMERICAN JOURNAL OF SCIENCE.

[THIRD SERIES.]

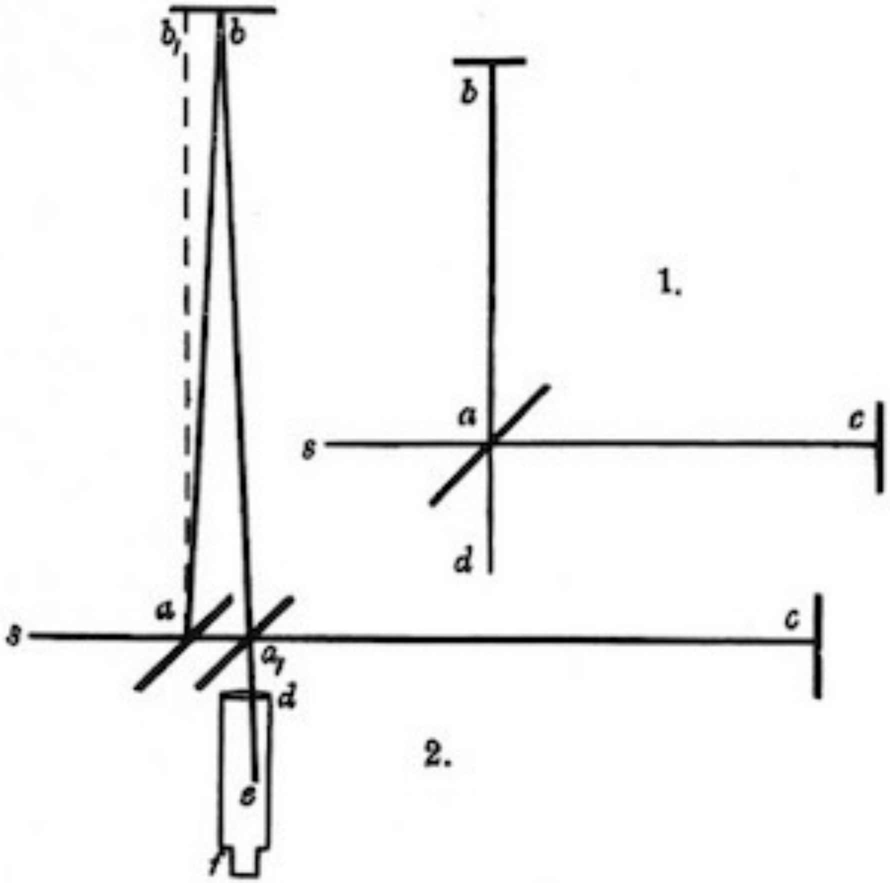
ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

THE discovery of the aberration of light was soon followed by an explanation according to the emission theory. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. The difficulties in this apparently sufficient explanation were overlooked until after an explanation on the undulatory theory of light was proposed. This new explanation was at first almost as simple as the former. But it failed to account for the fact proved by experiment that the aberration was unchanged when observations were made with a telescope filled with water. For if the tangent of the angle of aberration is the ratio of the velocity of the earth to the velocity of light, then, since the latter velocity in water is three-fourths its velocity in a vacuum, the aberration observed with a water telescope should be four-thirds of its true value.†

* This research was carried out with the aid of the Bache Fund.

† It may be noticed that most writers admit the sufficiency of the explanation according to the emission theory of light; while in fact the difficulty is even greater than according to the undulatory theory. For on the emission theory the velocity of light must be greater in the water telescope, and therefore the angle of aberration should be less; hence, in order to reduce it to its true value, we must make the absurd hypothesis that the motion of the water in the telescope carries the ray of light in the opposite direction!

Let *sa*, fig. 1, be a ray of light which is partly reflected in *ab*, and partly transmitted in *ac*, being returned by the mirrors *b* and *c*, along *ba* and *ca*. *ba* is partly transmitted along *ad*,



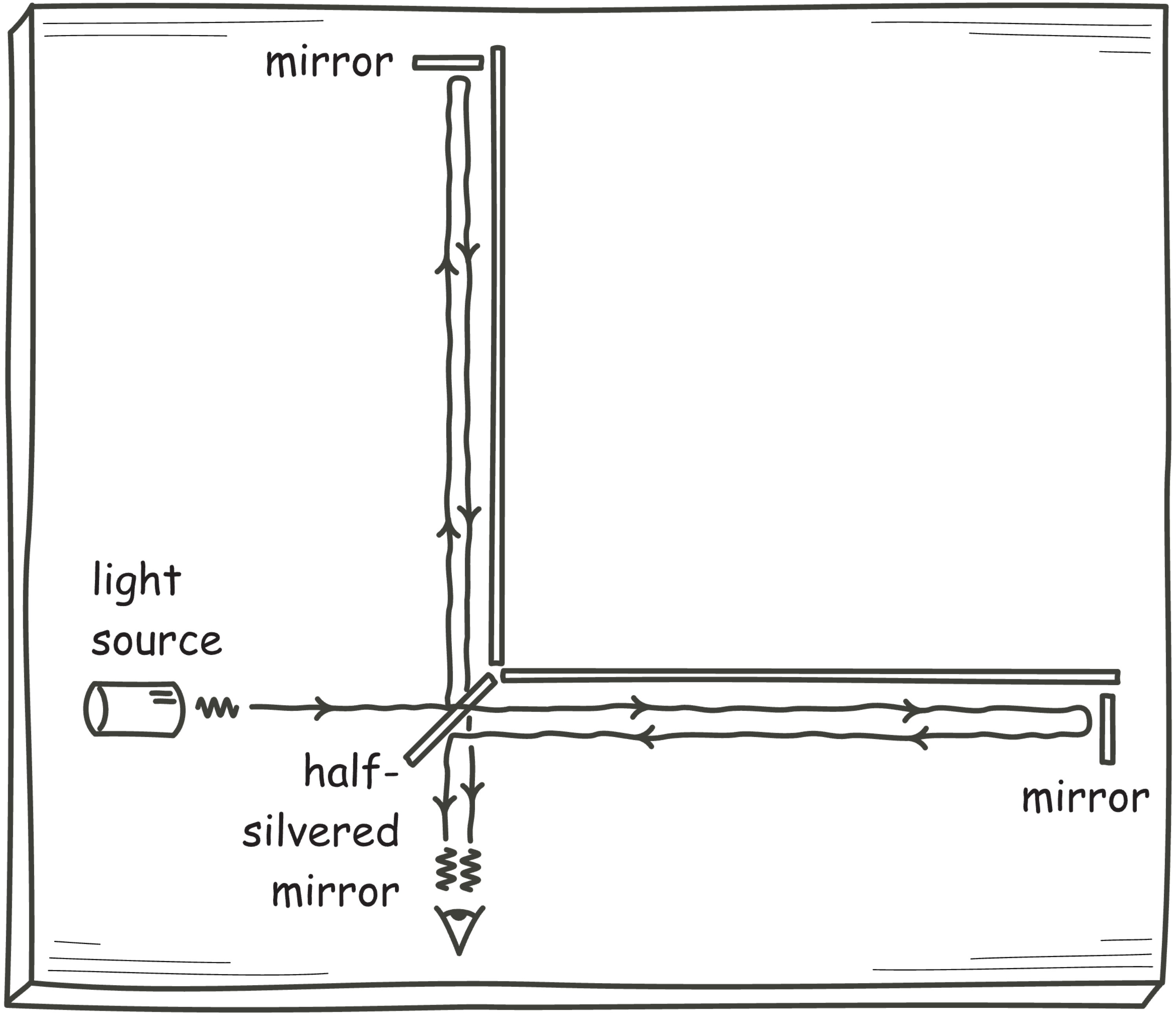

and *ca* is partly reflected along *ad*. If then the paths *ab* and *ac* are equal, the two rays interfere along *ad*. Suppose now, the ether being at rest, that the whole apparatus moves in the direction *sc*, with the velocity of the earth in its orbit, the direc-

# Michelson Morley Experiment

- The basic idea of the experiment is that **light moves differently** on a moving earth according to whether it propagates transverse to the direction of the earth's motion or parallel to the direction of the earth's motion.
- In the first case the ether current flows across the propagating light, slowing it a little. In the second case, it provides a kind of head wind that slows the light more or a tail wind that speeds it up.
- Here is a schematic picture of the way the experiment sought to look for these differences.

# Michelson Morley Experiment

- A light source sends a beam of light to a half silvered mirror that splits the beam in two.
- One half continues in the same direction; the other is sent off at 90 degrees. They both strike mirrors at equal distances which reflect them back to a place where they can be viewed.
- That the mirrors are placed at equal distances from the half-silvered mirror is represented by the two rods of equal length in the figure that connect them.


mirror
light
source
half-
silvered
mirror
mirror

# Michelson Morley Experiment

- You can grasp the way the experiment works most simply if you imagine not a beam of light, but merely a **pulse of light**, as shown in the figure.
- Since the distances to the two mirrors are the same, the two pulses will require the same time to traverse the distance out and back and they will be detected at the same time.

# Michelson Morley Experiment

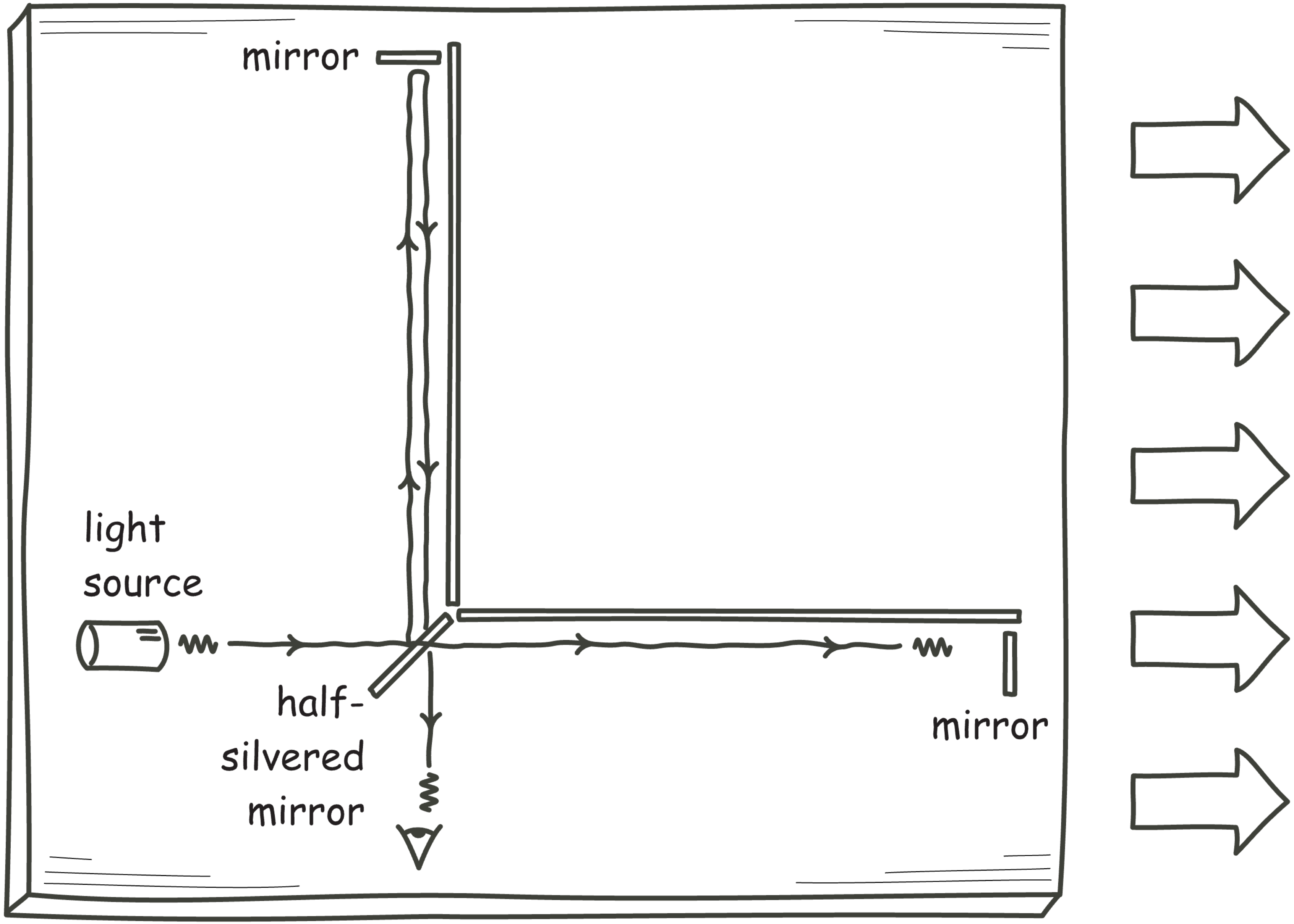
- In practice, pulses are not used. A steady light beam is used. However the basic analysis remains the same.
- Each individual peak and trough in the light beam behave like a single pulse. Any difference in propagation time will be manifested by the peaks and troughs of the waves misaligning when they are combined at the detecting screen. The combining of these two waves produces interference fringes at the detecting screen. Any change in the alignment of the peaks and troughs is revealed as a change in **the interference fringes**.

# Michelson Morley Experiment

- In use, the apparatus is turned very slowly so that the ether current passes over it from successively different directions.
- During this turning, the ether current affects the light traveling in the two directions differently and these changes are expected to be manifested as changes in the observed interference patterns.

# Michelson Morley Experiment

- Imagine, for example, that the horizontal direction in the figure below aligns with the direction of motion of the earth in the ether.
- Then, thinking classically, we expect the ether current to slow the travel time of a light pulse making the round trip in the direction transverse to the ether current. The net effect of the ether current on the pulse that makes the round trip parallel to the ether current is an even greater slowing.


mirror
light
source
half-
silvered
mirror
mirror

# Michelson Morley Experiment

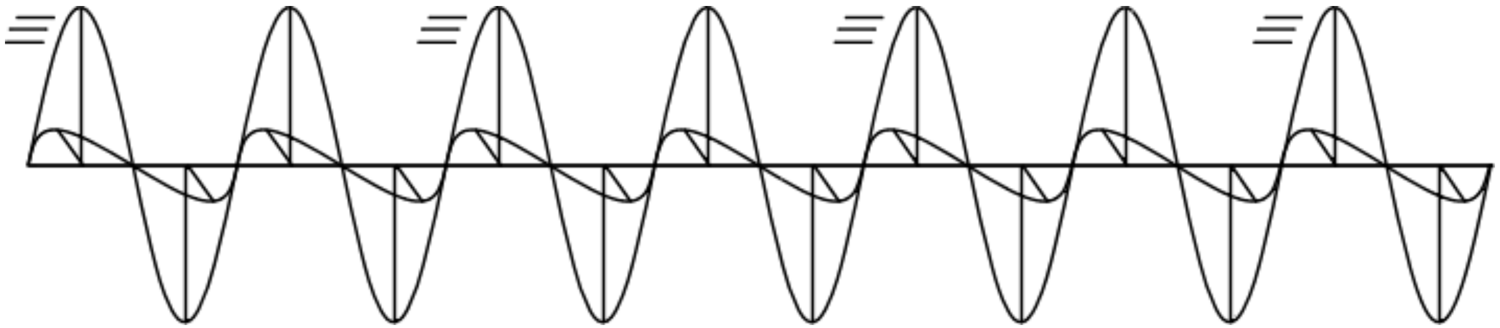
- For example, in an extreme case and unrealistic, if the apparatus moves at .866c, then the transit time for the transverse pulse is doubled; and it is quadrupled for the longitudinal pulse.
- So, as the figure shows, by the time the transverse pulse reaches to detector, the longitudinal pulse is still traversing the apparatus.
- **The result was negative**. Michelson and Morley found shifts in the interference fringes, but they were very much smaller that the size of the effect expected from the known orbital motion of the earth.

# Michelson Morley Experiment

- These difference in arrival times will change as the apparatus rotates and they will be manifested as changes in the observable interference fringes.
- The outcome of the 19th century tradition of experiments aimed at detecting the ether current was negative. The wave theory of light of the 19th century depended upon this ether. It was what carried the light wave, just as air carries sound waves. Yet no experiment could show the direction or magnitude of the ether current.

# Michelson Morley Experiment

- The puzzle was deepened and broadened by the end of the 19th century through the assimilation of optics into Maxwell's theory of electric and magnetic fields. In the 1860's, Maxwell showed that **a light wave is really a wave of electric and magnetic fields, an electromagnetic wave**. So now the luminiferous ether was also the ether that carried these fields.



# Attendance

https://www.wjx.cn/vm/h4hwle8.aspx#

# Michelson-Morley experiment – Tutorials on Thursday

- On Wednesday, please discuss the following:
- The Michelson-Morley experiment failed to reveal the motion of the earth through the ether. Discuss the experimental setup of Michelson Morley Experiment and its result. How do you explain this failure (hint: H. A. Lorentz has an explanation)?