# Einstein's Theories of Relativity

Shifting World Views,
Separating the Classical from
the Modern

# Classical Physics

- Boltzmann, 1899: “Many may have thought at the time of Lessing, Schiller and Goethe, that by constant further development of the ideal modes of poetry practiced by these masters dramatic literature would be provided for in perpetuity, whereas today one seeks quite different methods of dramatic poetry and the proper one may well not have been found yet. Just so, the old school of painting is confronted with impressionism, secessionism, pleinairism, and classical music with music of the future. Is not this last already out-of-date in turn? We therefore will cease to be amazed that theoretical physics is no exception to this general law of development.”

# Classical Physics (con’t)

- Boltzmann, 1899: The aim of classical physics is to seek “the law of action of a force acting at a distance between any two atoms and then integrating the equations that followed from all these interactions under appropriate initial conditions” to describe the general state of affairs. [Laplace’s program.]
- This was threatened by Maxwell and Hertz’s electromagnetic theory, the positivists (Mach), the energetics (Helm, Ostwald).
- Boltzmann defined himself as a classical theorist.

# Classical Physics (con' t)

Boltzmann, 1899: “I regard as my life’s task to help to ensure, by as clear and logically ordered an elaboration as I can give of the results of old, classical theory, that the great portion of valuable and permanently usable material that in my view is contained in it need not be rediscovered one day.”

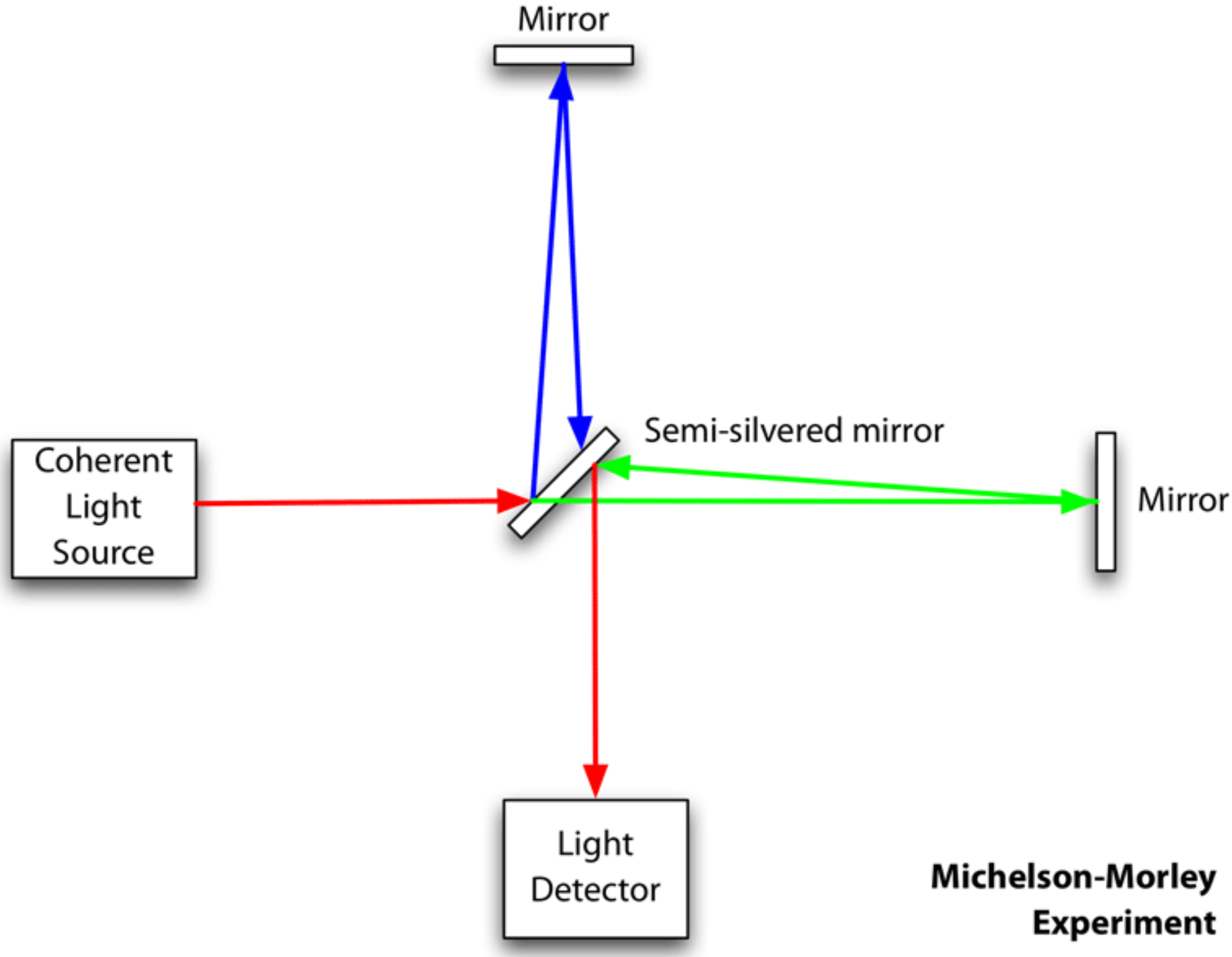
- Boltzmann’s talk was a turn-of-the-century address. It was meant to capture the spirit of rapidly changing world views and scientific styles.

# Two Clouds

- In 1900 at a Friday Evening lecture at the Royal Institution, W. Thompson, now Lord Kelvin, discussed "two clouds" that hung over $19^{th}$ century physics.
- One was a technical assumption of the Maxwell-Boltzmann theory of heat radiation, which would be involved in the development of quantum dynamics.
- The other was the failure of Michelson and Morley to detect ether drift.

# The Michelson-Morley Experiment

- In 1887, at the Case School for Applied Science in Cleveland, OH, Michelson and Morley carried out a series of precise measurements of the speed of two beams of light traveling at right angles to one another.
- If the light were moving in a medium, there should have been detectible time differences in the two directions.
- There was not. Michelson and Morley believed that their equipment wasn't sensitive enough.

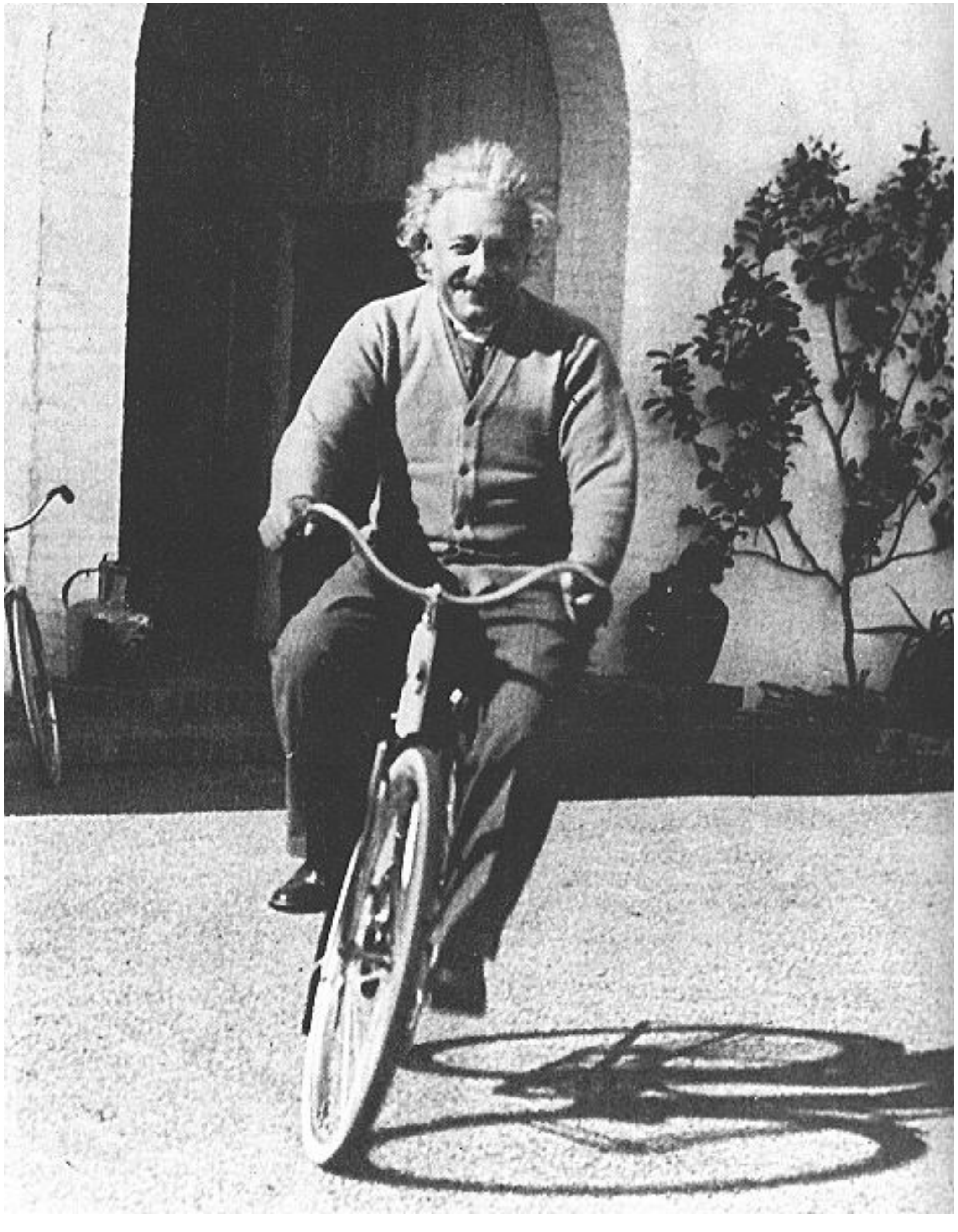

Mirror
Semi-silvered mirror
Coherent Light Source
Mirror
Light Detector
Michelson-Morley Experiment

# Non-classical Mechanics

- In 1902, Poincaré stated that there is no absolute space, no absolute time, and no direct intuition of simultaneity. Moreover that it might be possible to enunciate mechanical facts with reference to a non-Euclidean space.
- Poincaré, 1904: It should be possible to "construct a whole new mechanics, of which we only succeed in catching a glimpse, where inertia increasing with velocity, the velocity of light would become an impassible limit. The ordinary mechanics, more simple, would remain a first approximation, since it would be true for velocities not too great, so that we should still find the old dynamics under the new."

# Albert Einstein (879-1955)

- From a middle-class Jewish family. They moved around between Germany, Italy and Switzerland when he was young.
- Educated at Swiss Federal Institute of Technology and U of Zurich.
- Worked in the Swiss patent office.
- In 1905 published 5 papers, some of the most important in the 20th century. [Wonder year.]



# Einstein’s Life (con’t)

- Taught at a number of different Us.
- 1914, Professor at Berlin U, member of the Prussian academy.
- Refused to sign the 1914 manifesto “To the Civilized World.”
- 1915, published the general theory of relativity. Became an international celebrity when GR was experimentally confirmed.

# Einstein’s Life (con’t)

- In 1933, when the National Socialists (Nazis) were elected, he renounced his German citizenship and never returned.
- Professor at Princeton Institute for Advanced Study.
- Was instrumental in mobilizing the scientific community to work on the atomic bomb.
- Spent the post-war years working on a unified field theory and toward international peace.

# Einstein’s Work

- Developed the special and general theories of relativity.
- Was instrumental to the development of early quantum theory but never agreed with quantum dynamics.
- Spent his later years working in isolation on a unified field theory (a theory of everything). This was unsuccessful.
- Wrote books popularizing his theories and on more philosophical subjects.

# The Special Theory of Relativity “The Theory of Invariance”

- “On the Electrodynamics of Moving Bodies,” 1905.
- The point of the theory was to show that the equations of electromagnetism are the same in any frame of reference.
- Einstein wanted to call it the theory of invariance, or covariance.
- It was called ‘relativity theory’ by Plank in 1906.

# Principles of Relativity

(1) "The same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good." [The laws of electrodynamics are the same in any reference frame moving at constant linear velocity.]

(2) "Light is always propagated in empty space with a definite velocity, $c$, which is independent of the state of motion of the emitting body." [The velocity of light, $c$, is constant in every reference frame.]

# The Speed of Light

- The fundamental assumption of the theory of relativity is that the speed of light is constant to all observers, irregardless of their speed or the speed of the light source. *This makes the speed of light unlike the speed of any other moving object*.
- Hence, the velocity of everything else has to be determined on the basis of this constant, *c* approx. = 300,000 km/s.
- In order to do this, the observers use theoretical *rigid yardsticks* and *light clocks*.

# Measuring Time and Distance

- Einstein claims that it is *impossible* to have an intuitive understanding of the real nature of time and space.
- In order to know the distance between two objects, we have to use rigid measures to mark off the distance relative to some rigid body, some physical reference frame. There is no direct access to distances.
- In order to know the time between two events, we have have to record the time it takes for a beam of light to get from our eye to the event and back. Then we measure the distance and calculate the time. There is no direct access to time intervals.

# Inertial Frames

- In the special theory, we assume that observers are traveling in different reference frames, at different but constant velocities.
- Each observer can only directly measure the distances in her own frame. Each observer can only directly read the clocks immediately next to her.
- In order to determine the distances in the other frame, or in order to read the clocks that are far away from her, she has to send out a beam of light and make a calculation.

# Consequences of Special Relativity

- We imagine that there are two coordinate systems (x,y,z,t) moving relative to one another.
- We then generate a series of four equations to transform each point in one system to a point in the other system.
- That is, we try to ask what one system "looks like" from the perspective of the other system.

# Lorentz-Fitzgerald Equations

- With two frames $K(x,y,z,t)$ and $K'(x',y',z',t')$ moving relative to one another along the $x$ axis, we get strange results for the transformation from $x$ and $t$ to $x'$ and $t'$.
- We can derive the fact that distances are shortened by a factor of $\sqrt{(1-(v^2/c^2))}$, while time is lengthened by the same factor.
- This means that distances appear to be shorter and time appears to be running slowly in the other frame of reference.
- It also means that these results are negligible for low speeds.

# Time and Space

- The consequences of this simple assumption are very peculiar.
  - Each observer sees his own measuring devices as constant but they get out if sync with those of other observers moving at different speeds.
  - For speeds close to *c*, time appears to elongate (clocks run slower) while distances diminish (yardsticks get shorter). (Not to the observes moving at these speeds, but to others who are observing them.)
- These effects are irrelevant in most cases, but for speeds approaching that of light, and hence for sub-atomic phenomena (because of the speeds of electrons and other sub-atomic particles), they are measurable.

# Simultaneous Events

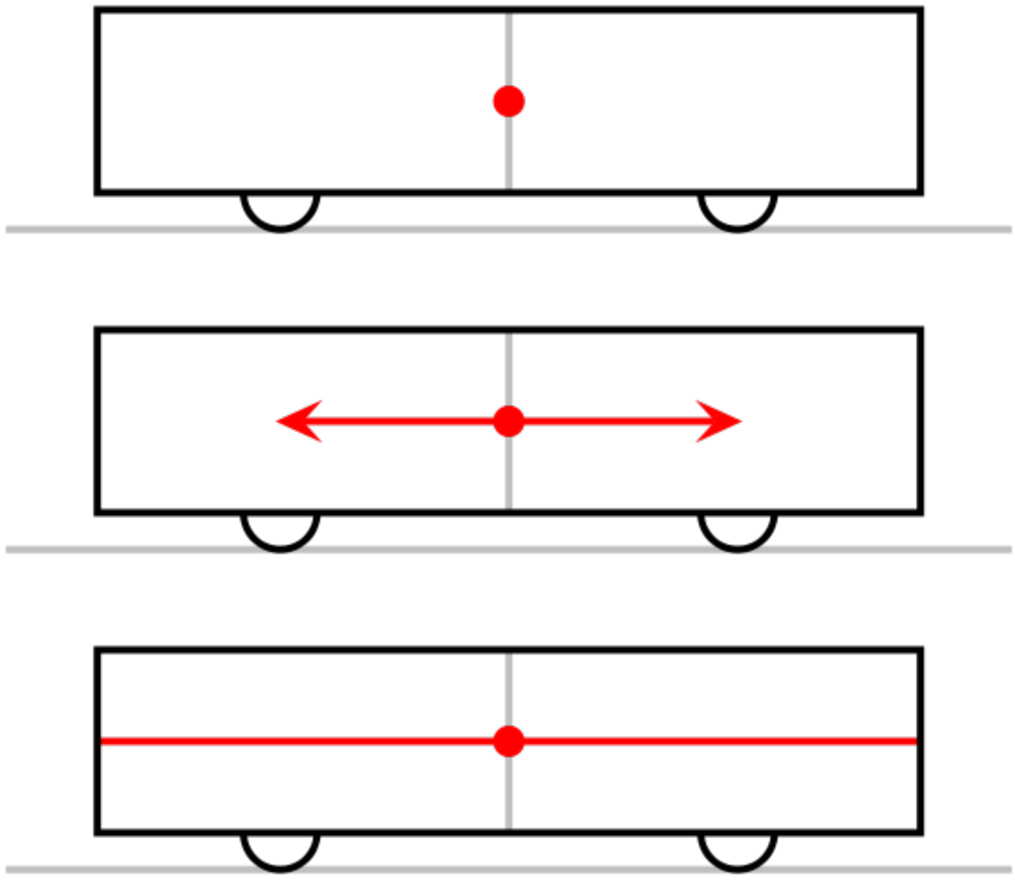
- This theory implies that there are no such things as absolutely simultaneous events. Events which appear to be so in one reference frame will occur at different times in another reference frame.
- If two events appear to be simultaneous to the 'stationary' observer, the 'moving' observer will see the event toward which he is moving as occurring before the other.
- Simultaneity is not frame independent.

# Simultaneity, Inside the car

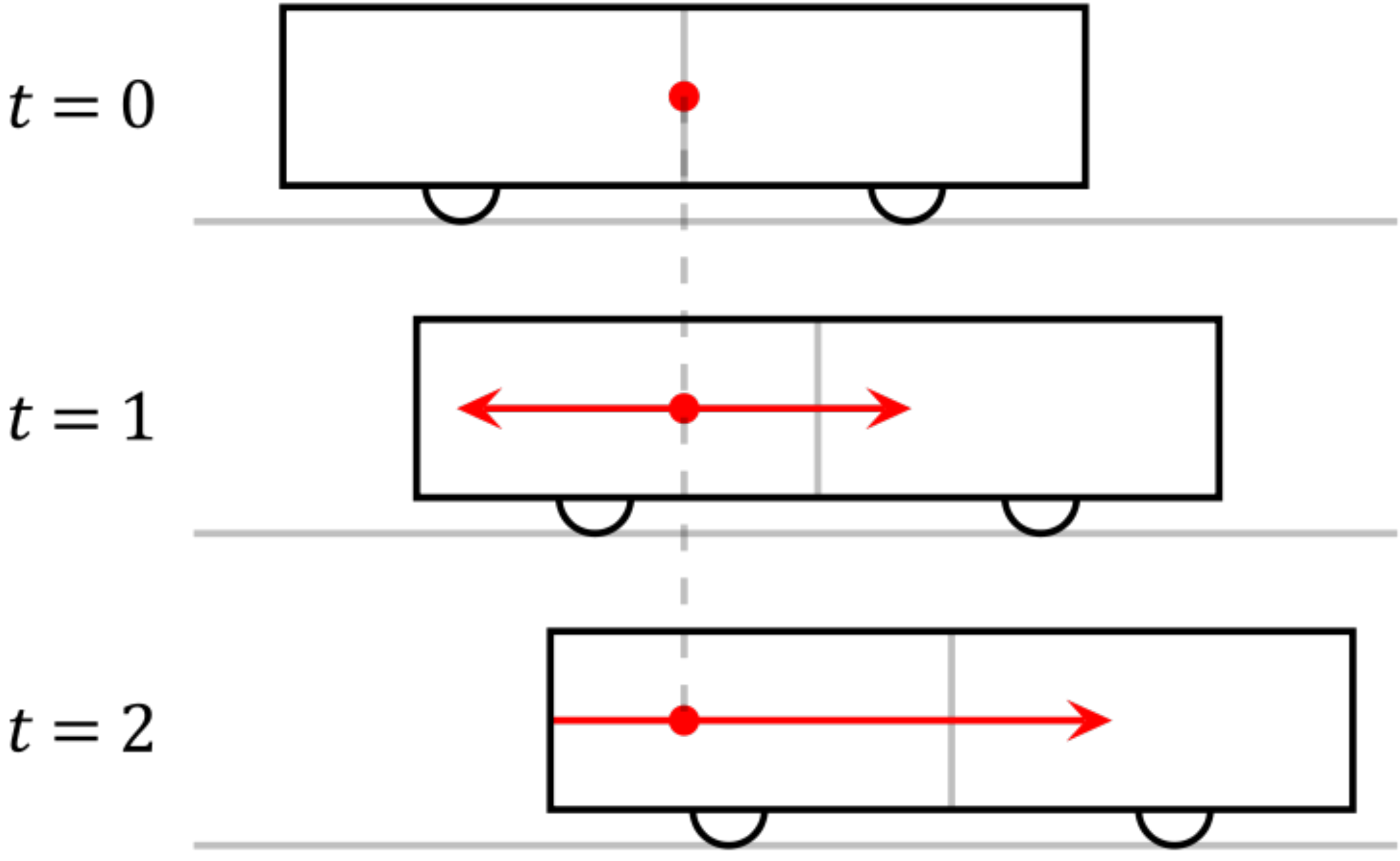
$t = 0$

$t = 1$

$t = 2$



# Simultaneity, On the tracks

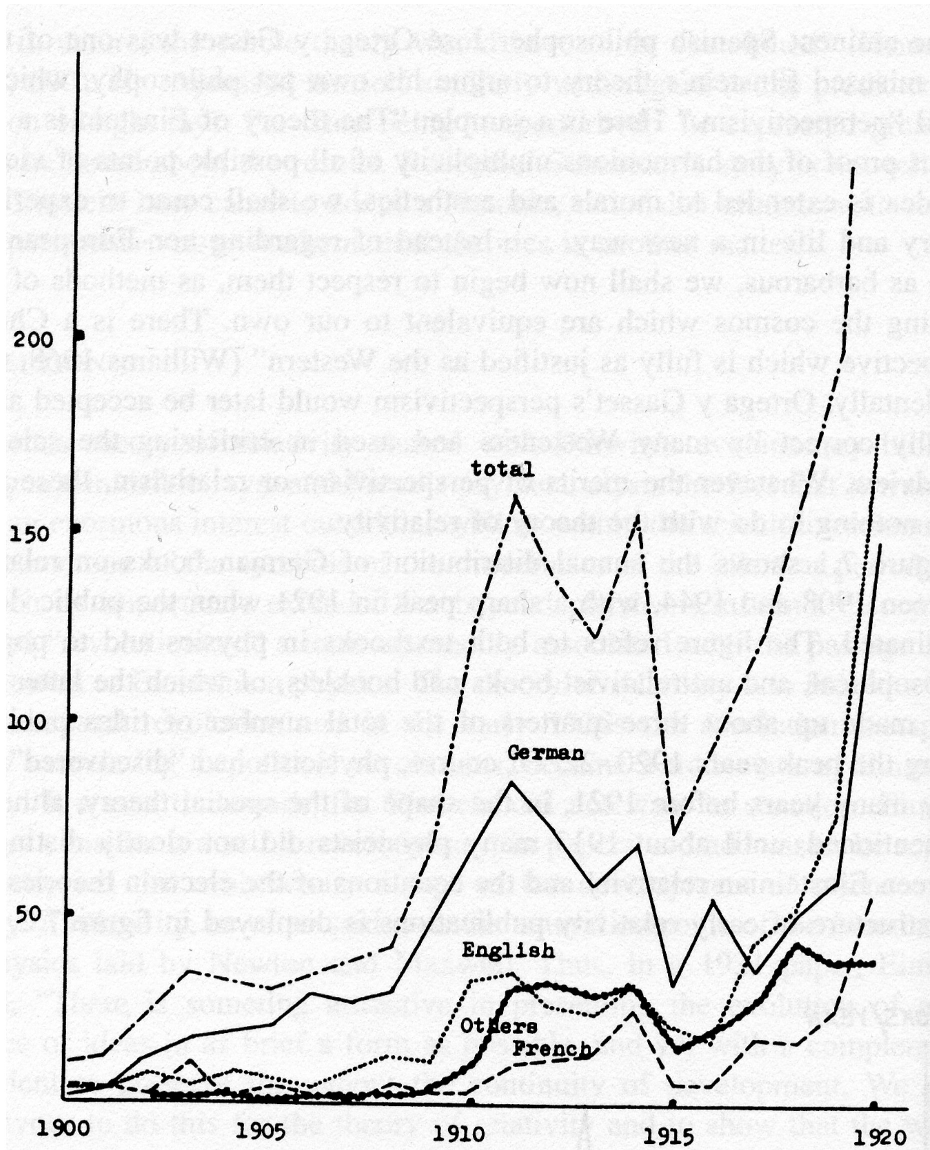


# Einstein's Train

# Reception

- The special theory was only interesting to a small group of specialists. They applied the predictions to experimental results for sub-atomic particles.
- They demonstrated how the mechanical laws of all moving systems could be mapped into one another in a general spacetime geometry. [Minkowski, etc.]
- They determined the invariant spacetime interval between any two events.

# Papers on Relativity



# General Relativity

- Einstein, 1922: “My first thought on the general theory of relativity was conceived two years later, in 1907. The idea occurred suddenly… I came to realize that all the natural laws except the law of gravity could be discussed within the framework of the special theory of relativity. I wanted to find the reason for this, but I could not attain this goal easily… The breakthrough came suddenly one day. I was sitting on a chair in my patent office in Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his own weight. I was taken aback. This simple thought experiment made a deep impression on me.”

# Principles of General Relativity

- *The general principle of relativity*: The laws of physics are exactly the same in every frame of reference, whether stationary, in constant motion, or changing motion.
- *The principle of equivalence:* We have no way of deciding on a privileged reference frame. Hence, to the same effects we must attribute the same causes. (There is no way to distinguish between things like gravity and acceleration, etc. )

# A thought experiment

- We imagine a spacious room in which an observer can perform experiments.
  - If the room is in a region of space with no massy bodies, the observer will experience a lack of 'gravity.'
  - If the room is pulled by something else at the same acceleration with which bodies fall towards earth, the observer will experience the 'law of gravity.'
  - If the room is in freefall towards a massy body, the observer will experience a lack of 'gravity.'
  - If the room is on the surface of the earth, the observer will experience the 'law of gravity.'
- The principle of equivalence tells us that we have no way of knowing what our situation is.

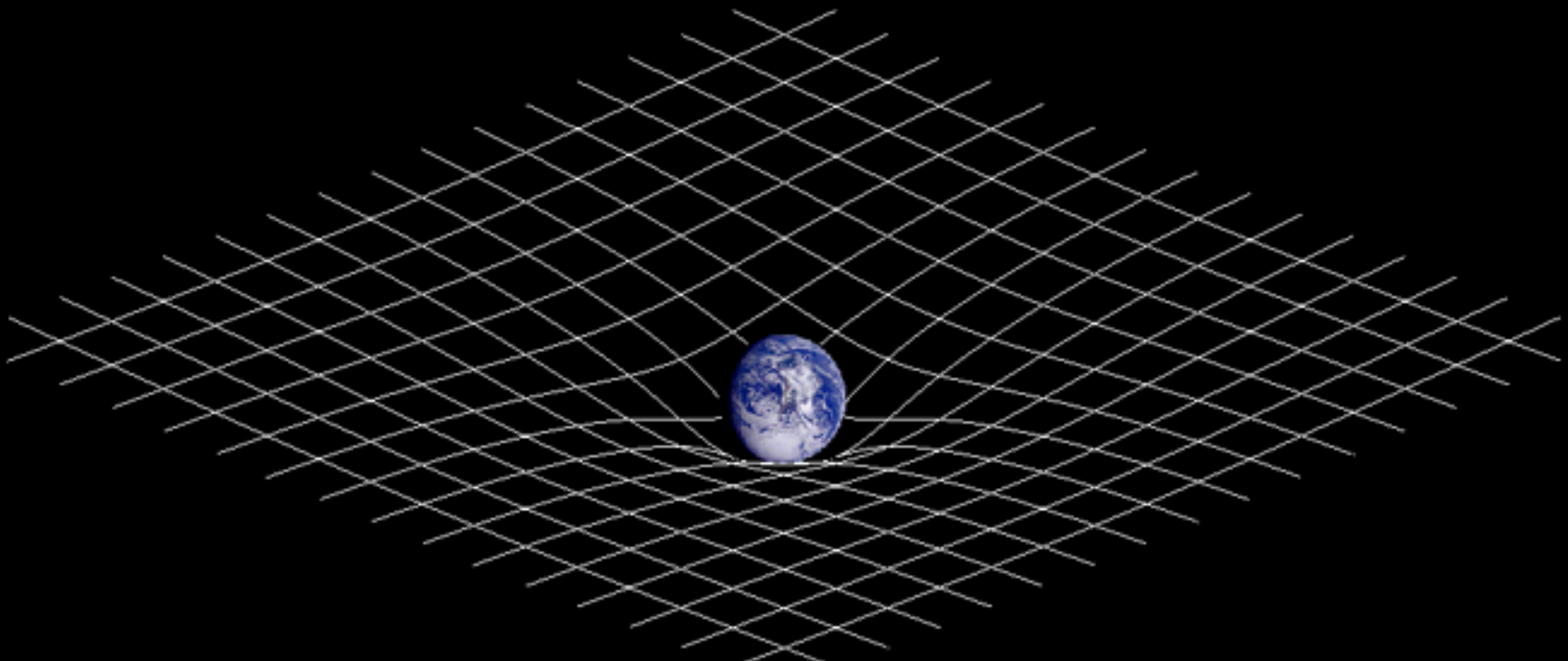
# A New Field Theory

- Einstein set out to make a field theory in which gravitation was the result of the spacetime field in the same way that electromagnetic force was the result of the electromagnetic field.
- The theory was an elegant extension of Maxwell's style of physics.
- The claims were even stranger than those of the special theory.

# General Relativity

- Published in 1915, in the middle of WWI.
- Space and time make up a continuous (4D) field analogous to an electromagnetic field.
- Massy objects distort this field in a regular way, producing the gravitational effect. [Gravity well.]
- Light is subject to this effect and will be 'bent' in the vicinity of large objects.
- Time elongates (clocks run slower) near large objects.

# Spacetime Curvature



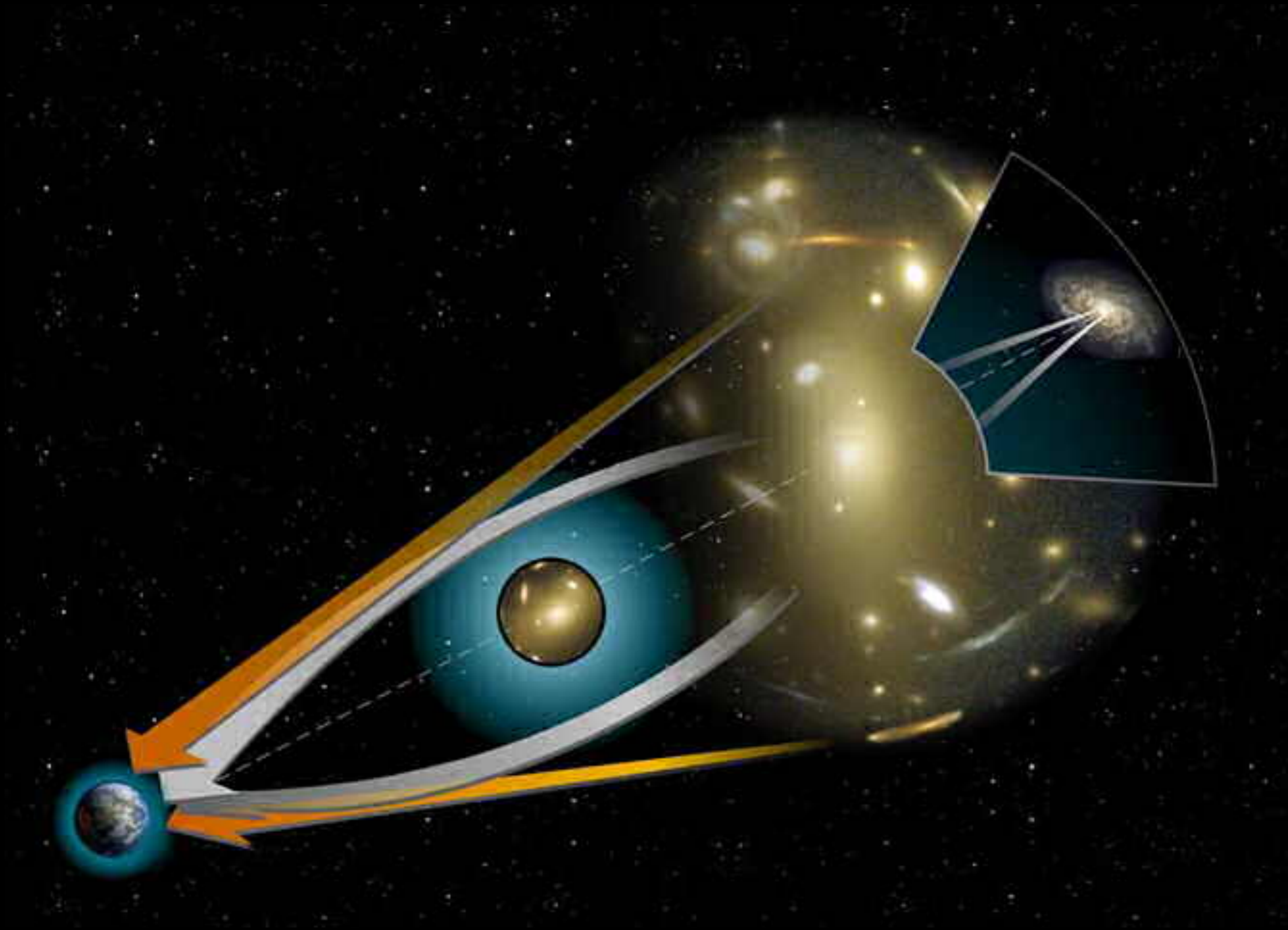
# Predictions

- The orbit of Mercury (perihelion) could not be exactly modeled with Newton's laws, but could with Einstein's.
- Gravitational redshift. [Difficult to detect.]
- The deflection of light by the sun should be detectable in a solar eclipse.

# Solar Eclipse of 1919

- Expeditions were organized in 1917, but there were political and weather problems. The gravitational deflection of sunlight was observed by Dyson off the west coast of Africa and Eddington in Brazil.
- The evidence was messy and some of it had to be discarded. The photos were interpreted to agreed with Einstein' theory.
- Dyson, reporting to Royal Society: "A very definite result has been obtained that light is deflected in accordance with Einstein's law of gravitation."
- When Einstein was told he was "unperturbed" and said, "I knew that the theory is correct. Did you doubt it?" But actually, he had been anxious.

# Gravitational Lens



# Reception

- The result of this announcement was that first the theory, and then its inventor, became world famous. Particularly in the US and Britain.
- This fueled anti-Semitic feelings among many Germans who felt that Einstein was intentionally garnering foreign attention for his “Jewish” theories.
- In fact, Einstein’s fame in the States requires some explanation.

# Headlines

- JJ Thompson is reported to have called the discovery “one of the most momentous, if not the most momentous pronouncements in human history.”
- The press got carried away with statements like this and they peppered their articles with intriguing phrases that were composed of simple words but seemed to make no sense, “curved space,” “four dimensions,” “finite universe,” etc.

# "Revolution"

- *London Times:* "Revolution in Science."
- *Washington Post:* "Fundamentals of Physics May be Revolutionized."
- *New York Times:* "Bolshevism in Science."
- A *Current Opinions* writer wrote that Einstein had "knocked out Euclid and driven Newton in to a corner."
- Physicists, like Max Planck and Oliver Lodge, were quoted as supporting these views.
- Einstein himself repeatedly claimed that his theories were built on the work of his predecessors, but no one listened to him.

# “Relative”

- *London Times:* “The ideals of Aristotle and Euclid and Newton which are the basis of all or present conceptions prove in fact not to correspond with what can be observed in the fabric of the universe… Space is merely a relation between two sets of data, and an infinite number of times may coexists. Here and there, past and present, are relative, not absolute, and change according to the ordinates and coordinates selected.”
- Einstein again insisted it would be better to speak of the theory of “covariance” or “invariance,” but of course no one listened to him.

# “Destroyer of Space and Time”

- *New York Times* incorrectly attributed to Einstein the statement that “from this time hence time by itself and space by itself are mere shadows.” [Minkowski.]
- *New York Times* editorial called Einstein the “destroyer of space and time.”
- The idea that time and space had actually been changed disturbed many people and there was even the idea that the scientific elite had some power over these things.

# "The Twelve Men"

- *Manchester Guardian* started the rumor that Einsein had claimed that there were only 12 men who would understand his theory. "When he offered his latest work to the publishers he warned them that there were not more than 12 men in the whole world who could understand it. Nevertheless, they took the risk."
- *New York Times:* "A Book for Twelve Wise Men."
- Einsein, when asked, at first thought they were joking, and then denied it. But it was too late; the 12 men became a central myth.
- The idea of such an elite science was held to be undemocratic and, in fact, un-American.

# Un-American

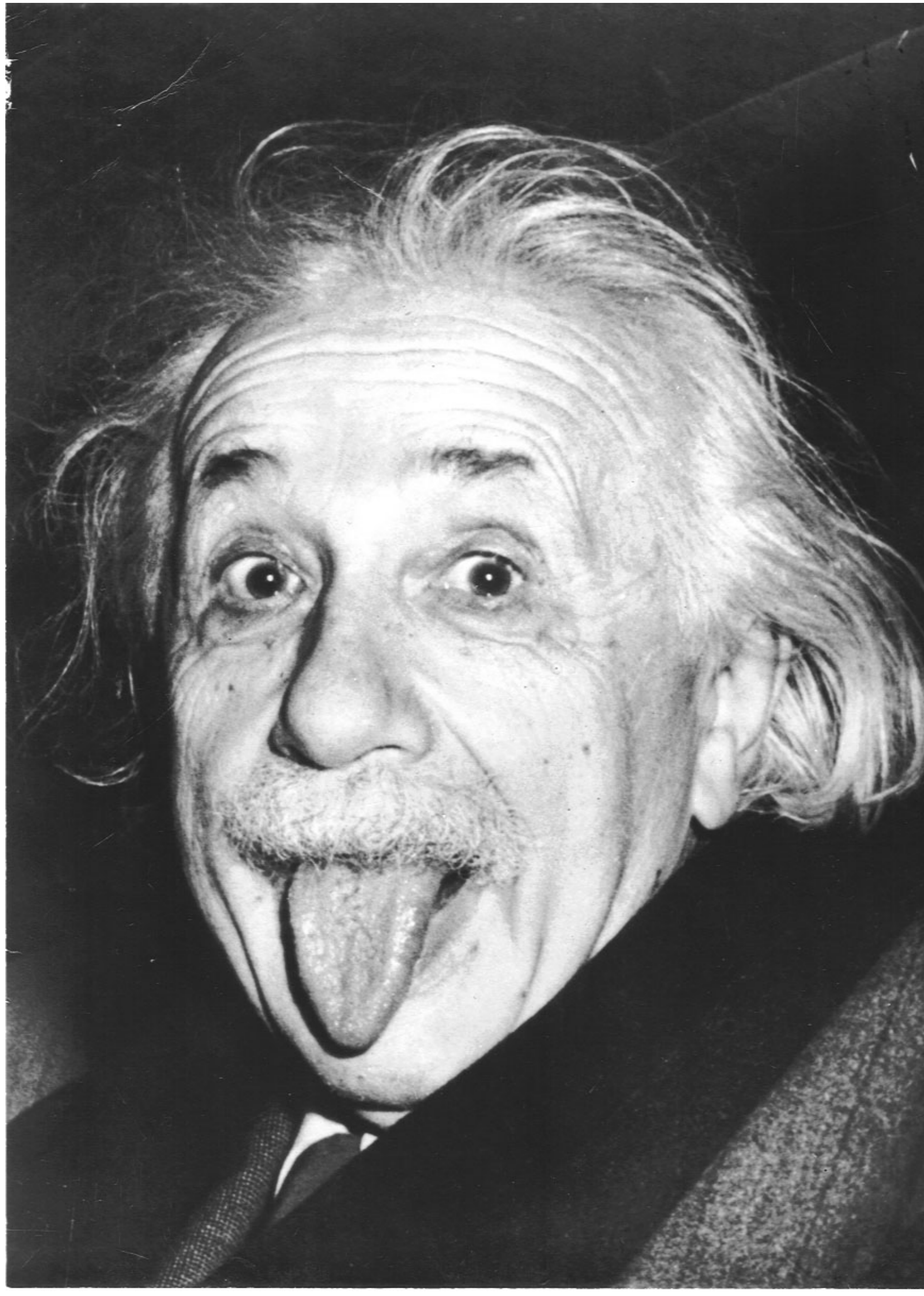
- *New York Times*, editorial, 1919: “As Professor Einstein remarks, the ‘man in the street’ has felt the foundations of belief in upheaval. He has an explanation of the fact, regarding it as ‘psycopathological.’ It is an interesting theory, but to one who knows our man in the street, it is not plausible. The true answer is Democracy. The Declaration of Independence itself is outraged by the assertion that there is anything on Earth, or in interstellar space which is understood by only a chosen few.”

# Einstein’s Visit

- Just as interest in the theory was dying down, Einstein himself visited the US.
- He came as part of a Zionist delegation, hoping to raise money for the Hebrew University in Jerusalem. The delegation was met in NYC by huge crowds of cheering fans.
- The gentile press wrongly assumed all this cheering must be for Einstein.
- They assumed he was an international celebrity receiving a “hero’s welcome.”

# Einstein’s Image

- Einstein turned out to be the opposite of what the press was expecting. Far from the “frightening Dr. Einstein, destroyer of time and space,” he was informal, friendly, humorous, goofy and spoke in sound bites.
- The US press fell in love with him. The European press reacted to this.
- The anti-Semitic press especially considered that he was currying favor abroad for his outlandish, and altogether too “Jewish” ideas.
- The mainstream press accepted his celebrity.



- “You imagine that I look back on my life’s work with calm satisfaction. But from nearby it looks quite different. There is not a single concept of which I am convinced that it will stand firm, and I feel uncertain whether I am in general on the right track.”

Einstein, Letter to Solovine, 1949