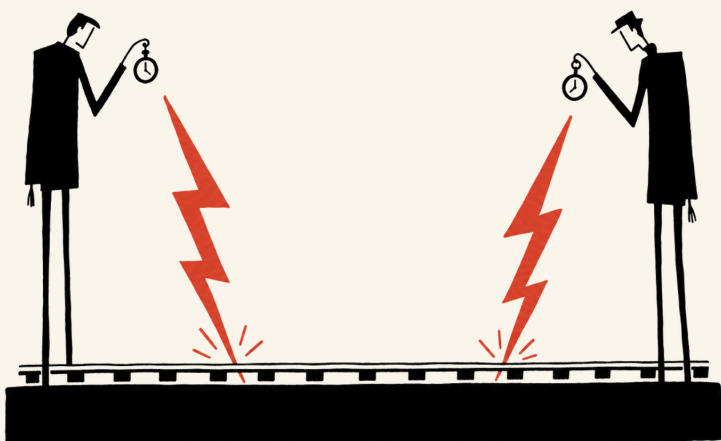


Relativity: The Special and General Theory



Albert Einstein · 1917

Illustrated audio lectures

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From the original: Über die spezielle und die allgemeine Relativitätstheorie
(Gemeinverständlich)

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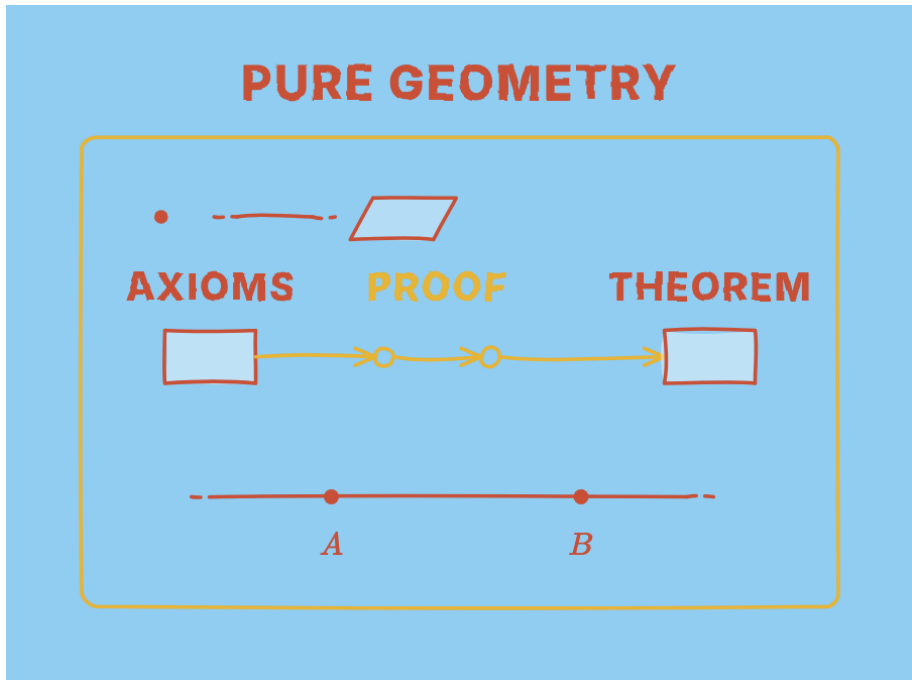
Is Pythagoras True?

Take a sheet of squared paper and a ruler. Draw a right angle in one corner, measure three centimetres along one edge and four along the other, and join the two ends with a straight line. Now measure that slanting line. Before you look, you already know what the ruler will say: five centimetres, because at school you learned that the square on the long side of a right-angled triangle equals the two squares on the short sides, and nine plus sixteen is twenty-five, whose square root is five. The ruler agrees, give or take the thickness of a pencil line. So, was Pythagoras right, and is his theorem true?

Albert Einstein begins his small book on relativity with precisely this question, and he asks it with a smile. Most of us, he says, met Euclid's geometry as children and remember it with more respect than affection, having been chased up its high staircases by conscientious teachers. Out of loyalty to that schooling we would scorn anyone who doubted the humblest of its theorems. And yet our proud certainty might vanish the moment someone asked what we mean by saying that a theorem is true.

Consider how geometry is put together. It starts from a few basic ideas, such as point, straight line and plane, which we picture more or less clearly, and from a few simple statements about them, the axioms, which we accept because the pictures make them feel obvious. Everything else is derived from the axioms by logical steps, and that derivation is what a proof is. So, inside geometry, a theorem is true when it has been properly derived from the axioms, and that is all "true" can mean there. The whole burden of truth then falls on the

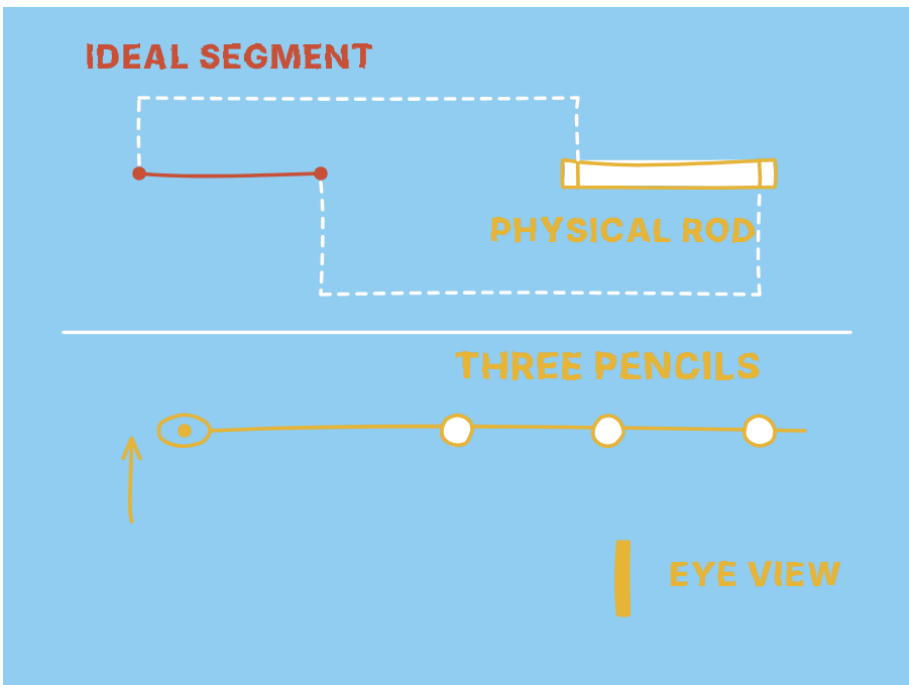
axioms, and here Einstein makes his first surprising point: the question whether an axiom is true cannot be answered by geometry, and in fact it has no meaning at all.



What a proof establishes

Try asking whether it is true that only one straight line passes through two points. You cannot, because Euclidean geometry simply deals with certain objects it calls straight lines and gives them, by definition, the property of being fixed by two of their points. The word "true", Einstein observes, always means, in the end, agreement with some real thing. Pure geometry says nothing about real things; it is only about how its own ideas hang together logically. So the word does not fit.

Why, then, do we feel so sure that the theorems are true? Because the ideas of geometry grew out of objects in nature, which correspond to them more or less exactly. Geometry may stand apart from those objects to keep its logic watertight, but the habit of seeing a segment as two marks on a practically rigid body, a ruler or a rod, sits deep in our thinking. We also take three places to lie on a straight line when, looking with one eye from the right spot, we can make them appear to coincide, one hiding the others.



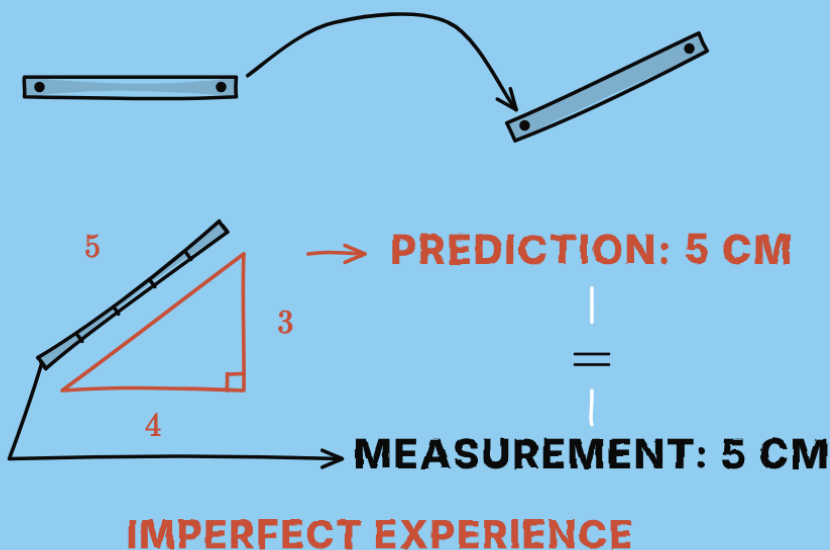
Straightness tested by sight

Try it yourself

Stand three pencils upright in lumps of modelling clay, roughly in a row, and close one eye. Move your head until the nearest pencil hides the other two, so that the three merge into one narrow silhouette. That is a physical test of straightness, made with an eye and real objects, and it is what you really mean when you call three things aligned.

Now comes the decisive step, and it is a single added sentence. To Euclid's theorems we add the statement that two points of a practically rigid body always correspond to the same segment, the same distance, however we move the body about. Nothing in pure geometry says that; it is a claim about rulers and rods and how real matter behaves. Once it is added, the theorems of geometry become statements about the possible arrangement of practically rigid bodies, and geometry so completed is a branch of physics. Now we may rightly ask whether the theorems are true, because now we can ask whether they hold for the real things, the marks and edges and rods, that we have assigned to the geometrical ideas. A little loosely, Einstein says, the truth of a geometrical theorem in this sense means that it holds in a construction with compass and straightedge.

PHYSICAL AGREEMENT



Geometry becomes a physical test

That is what you did on the squared paper. The theorem was true in the physical sense because the ruler, a practically rigid body, agreed with the prediction. The same thing happens, on a grand scale, whenever your phone finds its position: the receiver turns measured distances to several satellites into a place on the map by plain geometry, and the method counts as true because the place it gives agrees with where you actually are. Geometry earns its physical truth the way any physical claim does, by being checked against the world.

Einstein adds one caution, and it is the thread that leads through the whole book. Our conviction that geometry is true in this sense rests on nothing more than rather imperfect experience; a ruler is never perfectly rigid, an eye never perfectly straight. For now, he says, we

will take that truth for granted, and in the last part of the book, when we reach the general theory of relativity, we will see that it has limits, and where they lie.

Remember

Inside pure geometry a theorem is true only because it follows from the axioms, and whether the axioms are true is a question without meaning there. Theorems feel true because the ideas of geometry grew out of real objects, and we are used to seeing a segment as two marks on a rigid body. Add one physical statement, that two points of a practically rigid body keep the same distance however the body is moved, and geometry becomes a branch of physics. Then a theorem is true when real bodies agree with it, in a construction with compass and straightedge, on squared paper with a ruler, or in a satellite receiver. That agreement rests on imperfect experience and is assumed for now; its limits appear in the general theory of relativity.

Questions

1. You draw a 3-by-4 right-angled triangle and the ruler shows the long side is 5 centimetres. In which sense has the theorem been shown true?
 - a. In the sense of pure geometry, because the measurement confirms the axioms

- b. In the physical sense, because a practically rigid body agreed with the prediction
 - c. In no sense, because a ruler is never perfectly rigid
- 2. Why does Einstein say that the question whether an axiom is true has no meaning?
 - a. Because axioms are chosen by convention among mathematicians
 - b. Because "true" means agreement with a real thing, and pure geometry says nothing about real things
 - c. Because nobody has yet found a way to prove an axiom
 - d. Because axioms are too obvious to question
- 3. What does the single added statement about practically rigid bodies accomplish?
 - a. It makes the theorems of geometry statements about real rods and rulers, so geometry becomes a branch of physics
 - b. It proves the axioms of Euclid from experience
 - c. It shows that geometry is independent of all experience
 - d. It replaces the axioms by measurements
- 4. Why is the physical truth of geometry accepted only for now, according to the lecture?
 - a. Because compass and straightedge constructions are never finished
 - b. Because the satellite receiver sometimes gives a wrong position
 - c. Because it rests on rather imperfect experience, and the general theory of relativity will show its limits

Answers

1. **b)** The theorem was true in the physical sense because the ruler, a practically rigid body, agreed with the prediction; inside pure geometry no measurement can bear on a theorem at all.
2. **b)** The word true always means, in the end, agreement with some real thing, and pure geometry is only about how its own ideas hang together logically, so the word does not fit.
3. **a)** Add that two points of a practically rigid body keep the same segment however the body is moved, and the theorems become statements about the possible arrangement of such bodies; geometry so completed is a branch of physics.
4. **c)** Our conviction rests on nothing more than rather imperfect experience; Einstein takes that truth for granted for now and shows in the last part of the book that it has limits, and where they lie.

Practice

1. A friend says: "Pythagoras is true, I checked it with a ruler." Explain in what sense of the word true your friend is right and in what sense they have checked nothing at all.

Hint: Separate the theorem as a statement derived from axioms from the theorem as a statement about a ruler and a sheet of paper.

Answer: In the physical sense your friend is right: once we add that a ruler is a practically rigid body whose marks keep their distance, the theorem is a claim about real segments, and the ruler agreed with it. In the sense of pure geometry they have checked nothing, because there a theorem is true only by being derived from the axioms, and no measurement can bear on that.

2. Why does Einstein say that we cannot even ask whether only one straight line passes through two points, while we can ask whether a measured diagonal matches the calculated one?

Hint: Ask what each question is about: ideas, or real things.

Answer: The first statement belongs to pure geometry, which deals with objects it calls straight lines and gives them that property by definition; asking whether it is true would ask for agreement with a real thing, and pure geometry is not about real things. The second question is about marks on a rigid ruler and a sheet of paper, real things assigned to the geometrical ideas, so agreement or disagreement with them has a meaning.

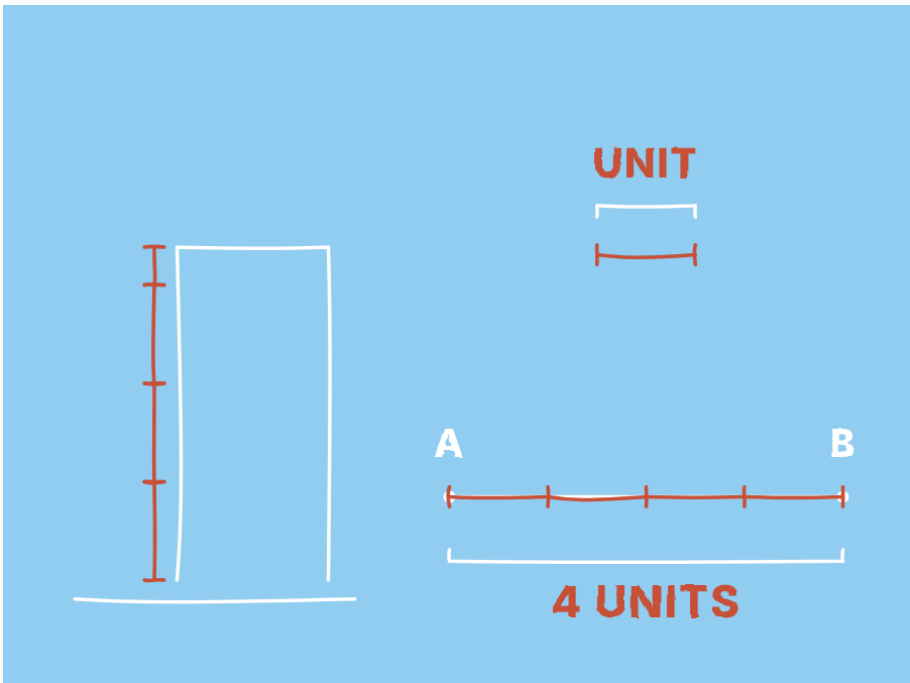
3. Einstein says our conviction that geometry holds for real bodies rests on rather imperfect experience. Give two reasons the experience is imperfect, using the examples of this part, and say what he promises about it.

Hint: Think about what a ruler and a sighting eye really are.

Answer: A ruler is never perfectly rigid, so two marks on it do not keep exactly the same distance; and an eye lining up three pencils is a rough test of straightness, not an exact one. So agreement between geometry and real bodies is only approximate. Einstein promises to assume that agreement for now and to show, in the last part of the book on the general theory of relativity, that it has limits and where they lie.

Where Is the Cloud?

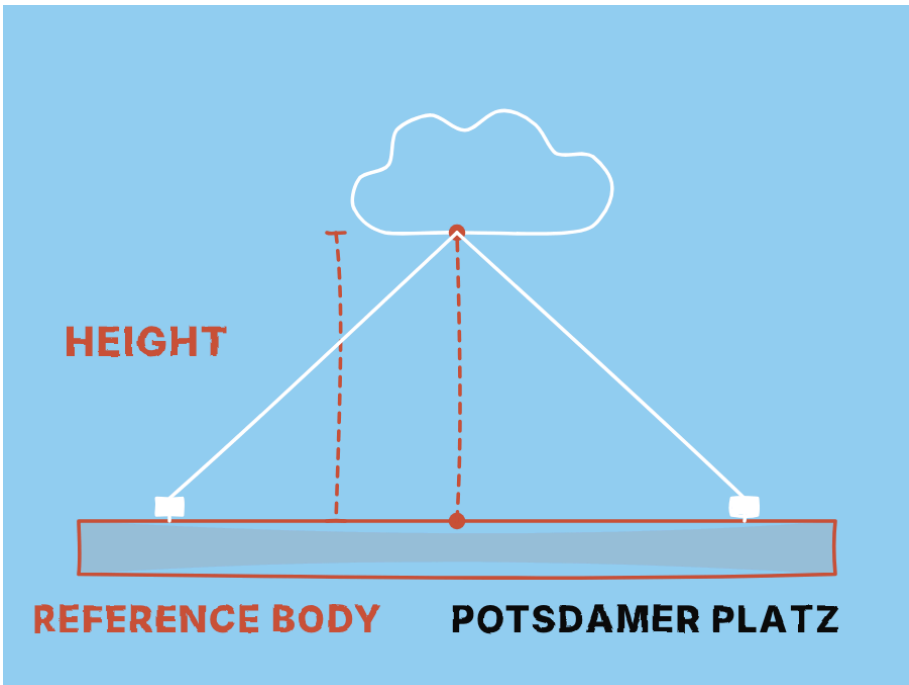
Measure the height of a door with a short wooden ruler. You stand it on the floor against the frame, mark where it ends with a thumb, lift it, stand it on the mark, and count: one, two, three ruler-lengths and a bit over. Nobody taught you this; it is simply what measuring is. Now look up: a cloud is drifting over the house. How would you measure where the cloud is, with that same ruler? Einstein uses exactly this question to show what we are really doing every time we say where something is.



Length by Repeated Units

First the ruler. Last time we agreed that a segment is two marks on a practically rigid body; now take one such segment, a little rod, and promise to use it once and for all as the unit of measure. To measure the distance between two points of a rigid body, construct the straight line joining them, as geometry tells you how, and lay the unit rod along it from the first point, again and again, until you reach the second. The number of times you had to lay it down is the measure of that distance. Every tape measure, every surveyor's chain and every laser rangefinder comes down, in the end, to this counting of a repeated unit.

Now the question of where. Every statement of where an event or a thing is, Einstein says, names the point of some rigid body that the event coincides with. That rigid body is the reference body, and this is how everyday speech works as much as science. Say "in Berlin, on Potsdamer Platz". The surface of the Earth is the rigid body being referred to, Potsdamer Platz is a marked point on it with a name, and the event is at that point.



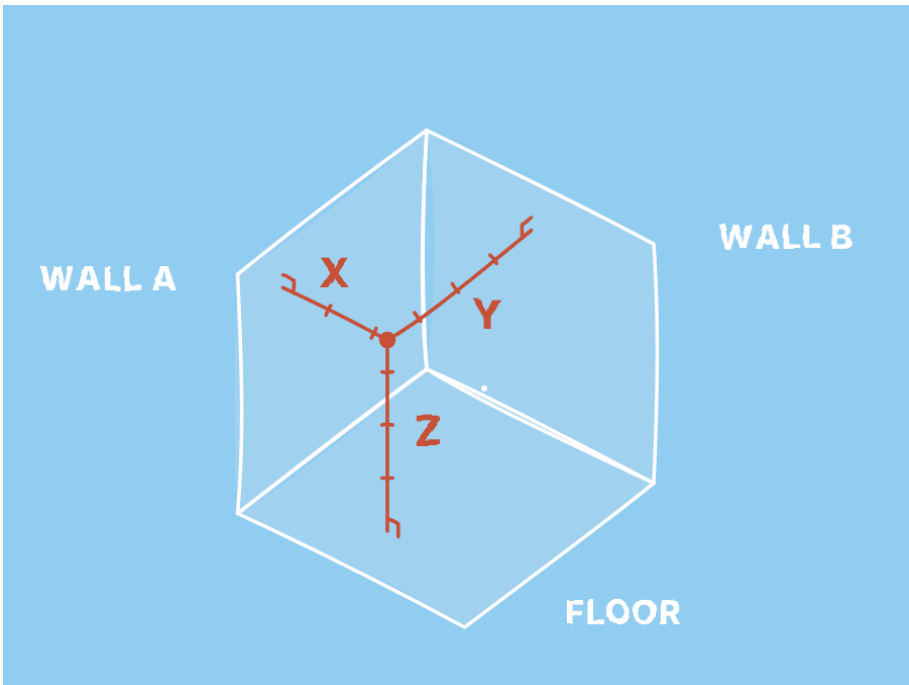
Extending the Reference Body

This primitive way of giving a place has two limits. It knows only places on the surface of a rigid body, and it needs that surface to have distinguishable points with names. Here is where the cloud comes in. To say where it is, imagine erecting a pole on the square, straight up, tall enough to touch the cloud. The length of the pole, measured with the unit rod, together with the place of the foot of the pole, says completely where the cloud is. Nothing about the statement has changed in kind: it still names a point of a rigid body that the cloud coincides with, except that the rigid body has been extended upward by the pole.

Three refinements are hidden in that pole, and Einstein draws them out one by one. The rigid body of reference has been extended until it

reaches the thing to be located. A number, the measured length of the pole, has replaced a named landmark. And we speak of the height of the cloud even when no pole has been built at all: one photographs the cloud from several places on the ground and, knowing how light travels, works out how long the pole would have to be. The pole is imagined, yet its length is measured all the same.

From this Einstein draws the lesson that it pays, in describing places, to free ourselves from named landmarks by using measured numbers. Measuring physics does so with the Cartesian coordinate system, named after Descartes. Picture three rigid flat walls, each at right angles to the other two and joined into one rigid body, like two walls and the floor meeting in the corner of a room. The place of any event is then given by three numbers, its coordinates: the lengths of the three perpendiculars dropped from the event onto the three walls. Each is found, in principle, by laying the unit rod along the perpendicular, a construction that follows the rules of Euclidean geometry.



Three Distances Fix a Place

Try it yourself

Stand in a corner of your room and pick a lamp or a picture hook. Say how far it is from the one wall, how far from the other, and how high above the floor: three distances, three counts with a ruler, and its place is fixed without a single landmark. Move the object, and only the three numbers change; the walls stay what they were.

In practice, Einstein admits, nobody builds the three walls, and the coordinates are hardly ever found with rods; they are found indirectly. A satellite receiver never lays a rod against anything; it measures how

long the signals from several satellites took to arrive and computes three coordinates from those times, just as the cloud's height was computed from photographs. Yet the physical meaning of every such statement must always be the one we have just described, rods laid against a rigid body, or else, he warns, the results of physics and astronomy dissolve into vagueness.

So here is where this section arrives. Every spatial description of events uses a rigid body to which the events are referred. And that reference assumes that Euclidean geometry holds for segments, a segment being two marks on a rigid body. The assumption we accepted on probation last time now carries the whole idea of place.

Remember

Length is measured by laying a chosen unit rod along the straight line between two points and counting the repetitions. To say where something is means to name the point of a rigid reference body that it coincides with, as Potsdamer Platz names a point on the Earth's surface. The idea of place is refined by extending the reference body, by replacing named landmarks with measured numbers, and by speaking of a length even when the rod that would measure it is only imagined. The Cartesian coordinate system makes this systematic: three mutually perpendicular rigid walls, and the three perpendicular distances from an event to them are its coordinates. Whether found with rods or computed from satellite signals, a place statement means this, and it assumes that Euclidean geometry holds for segments on rigid bodies.

Questions

1. What does measuring the distance between two points of a rigid body actually consist of?
 - a. Laying the unit rod along the straight line between them and counting how many times it fits
 - b. Timing a signal sent from one point to the other
 - c. Counting the named landmarks that lie between the two points
2. What does "in Berlin, on Potsdamer Platz" mean once we look at it the way the lecture does?
 - a. That the event is a certain distance from the centre of the Earth
 - b. That the event has three coordinates measured from the walls of a room
 - c. That the event coincides with a named point of a rigid body, the surface of the Earth
 - d. That a pole could be erected on the square to reach the event
3. The cloud's height is worked out from photographs taken at several places on the ground. Which refinement of the idea of place is this?
 - a. The reference body is extended by a real pole up to the cloud
 - b. A number stands in for a named landmark
 - c. A length is spoken of even though the rod that would measure it was never built
 - d. The cloud is treated as a point of the Earth's surface

4. Why does Einstein insist that even a satellite receiver's position must mean rods laid against a rigid body?
- a. Because signals are never as accurate as rods
 - b. Because without that meaning the results of physics and astronomy dissolve into vagueness
 - c. Because the three rigid walls are always built in practice

Answers

1. **a)** You construct the straight line joining the two points and lay the unit rod along it from the first point until you reach the second; the number of times you laid it down is the measure of the distance.
2. **c)** Every statement of where something is names the point of a rigid reference body it coincides with; here the Earth's surface is the reference body and Potsdamer Platz a named point on it.
3. **c)** We speak of the height of the cloud even when no pole has been built: from the photographs and the way light travels one works out how long the pole would have to be, so the pole is imagined but its length is measured all the same.
4. **b)** Coordinates are found indirectly, as the cloud's height was from photographs, but their physical meaning must always be the one given by rods and a rigid body, or the results of physics and astronomy dissolve into vagueness.

Practice

1. A lamp hangs in a room. Taking the corner where two walls meet the floor as the coordinate system, explain what its three coordinates are and how each could, in principle, be measured.

Hint: Think of the walls and the floor as the three rigid walls and ask what a perpendicular from the lamp to each one is.

Answer: The two walls and the floor are three mutually perpendicular rigid planes joined into one rigid body. From the lamp drop a perpendicular onto each; the lengths of those three perpendiculars are the coordinates. Each is found, in principle, by laying the unit rod along the perpendicular and counting, a construction that follows Euclidean geometry.

2. Name the two limits of the primitive way of giving a place, and explain how the pole on Potsdamer Platz frees us from each without changing what a place statement is.

Hint: Start from what "Potsdamer Platz in Berlin" can and cannot locate.

Answer: It knows only places on the surface of a rigid body, and it needs named, distinguishable points on that surface. The pole extends the rigid body upward, so a place off the surface can be given; and the measured length of the pole, a number, replaces a named landmark. The statement still names a point of a rigid body that the cloud coincides with, so its kind is unchanged.

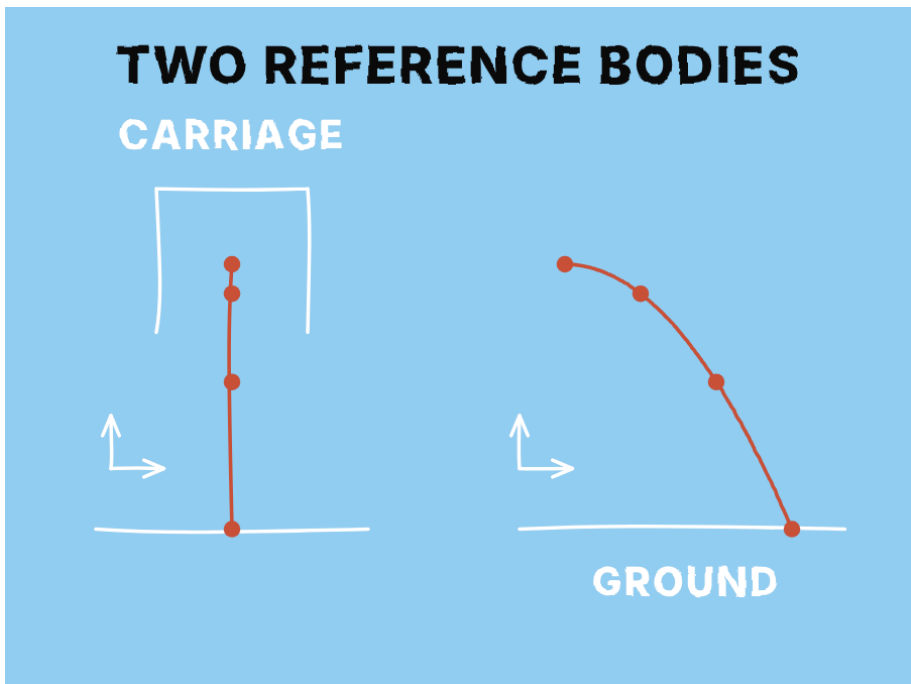
3. A satellite receiver computes its position from signal travel times and never touches a rod. In what sense is its answer still a place statement of the kind described here, and what does it assume about geometry?

Hint: Compare it with the cloud whose height was computed from photographs.

Answer: The receiver finds its coordinates indirectly, as the cloud's height was found from photographs, but their meaning is still the lengths of three perpendiculars to a rigid reference body, lengths a rod could in principle measure. Like every spatial description it assumes that Euclidean geometry holds for segments, a segment being two marks on a rigid body.

One Stone, Two Paths

Sit by the window of a train that runs smoothly along a straight track at a steady speed. Hold a stone out of the window and let it go, without any push. Ignoring the air, you see it drop straight down, as if the train were standing still, and land on the embankment below you. Now a walker on the path beside the track watches the same stone leave the same hand. The walker sees it fall in a curve, a parabola, carried forward with the train while it drops, and landing well ahead of where it was released. One stone, two honest witnesses, two different paths.



One Stone, Two Reference Bodies

Einstein opens this section with a confession. If he were to say, without further thought, that mechanics has to describe how bodies change their place in space with time, he would commit, in his words, mortal sins against the holy spirit of clarity. The sins hide in two small words, "place" and "space", and the stone is his way of bringing them into the open. Ask the question that seems to demand an answer: do the places the stone passes through really lie on a straight line or on a parabola? And what does it mean to say the stone moves "in space"?

After last time, Einstein says, the answer is plain. The word "space", if we are honest, is a dark word to which we can attach no definite idea at all, so we drop it. In its place we say "motion with respect to a practically rigid reference body", and places with respect to a reference body are exactly what the previous section defined. For the stone there are two reference bodies on offer, the carriage and the ground. With respect to the carriage the places lie one below another, on a straight line; with respect to the ground they lie on a parabola.

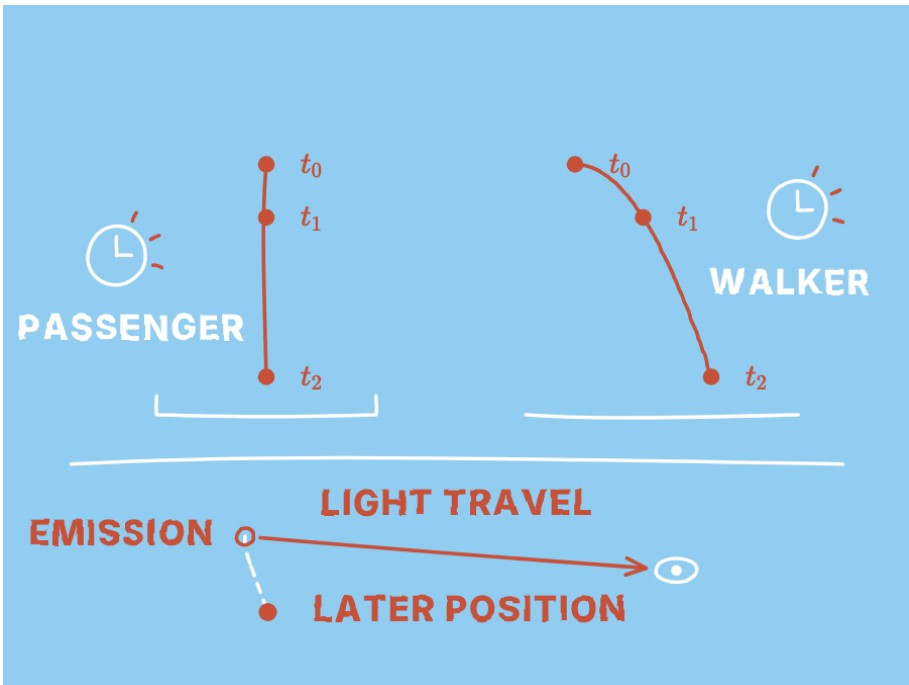
Since the coordinate system, the three rigid walls, is the mathematical form of a reference body, Einstein says it this way: the stone describes a straight line with respect to a coordinate system rigidly attached to the carriage, and a parabola with respect to one rigidly attached to the ground. Neither path is the real one with the other an illusion. Say it twice, because the whole of relativity grows from this seed: there is no path in itself, only a path with respect to a particular reference body. Leave the reference body out of the sentence and the sentence says nothing.

Try it yourself

Next time you ride in a car on a straight, smooth road, let a coin drop from your hand into your lap. It falls straight down and lands in your lap, not behind you. Then picture someone on the pavement watching the coin through the window: it moves forward with the car the whole time it falls, tracing a shallow arc. Both of you are right; you have simply referred the coin's places to different rigid bodies, the car or the road.

A satellite receiver lives by the same rule. It reports your motion with respect to the Earth's surface, so a passenger reading it on a train sees a hundred kilometres an hour while sitting perfectly still with respect to the carriage. Neither number is wrong; each belongs to its own reference body, and the receiver has quietly chosen one for you.

A path with its reference body named is still not a complete description of motion. We must also say how the body changes its place with time: for every point of the path, at what time the body is there. And those times, Einstein insists, must be defined so that they count as quantities observable in principle, results of measurements, not numbers assumed out of the air. On the ground of classical mechanics he does it like this: two clocks, made exactly alike, one in the hand of the passenger at the window, one in the hand of the walker. Each notes at which point of their own reference body the stone is at the moment their own clock ticks. Tick, the stone is here; tick, it is there; and a list of places paired with ticks is a complete description of the motion with respect to that reference body.



Pairing Places With Clock Ticks

Einstein closes with two quiet warnings, left for later. In pairing a tick with a place we have ignored the inaccuracy that creeps in because light travels at a finite speed: the walker sees the stone where it was a moment ago, not where it is. A second difficulty is lurking as well, and he promises to deal with both at length. They are not small: the satellite clocks that feed your receiver, moving at thousands of metres a second high above the ground, would drift by kilometres a day if those difficulties were ignored, and the rest of the book is the story of taking them seriously. So this stretch of the book pauses where Einstein's argument pauses: geometry made physical by rigid bodies, places given by rods against a reference body, and motion that exists only with respect to a reference body and a clock.

Remember

"Motion in space" means nothing until the dark word "space" is replaced by a practically rigid reference body, or its mathematical form, a coordinate system. The stone dropped from the train falls on a straight line with respect to the carriage and on a parabola with respect to the ground, and neither path is more real than the other. There is no path in itself, only a path with respect to a particular reference body. A complete description of motion also needs the time at each point of the path, and times must be observable: the ticks of a clock in the observer's hand, paired with the stone's places on their own reference body. Two difficulties were set aside, the finite speed of light and a second one not yet named, and the rest of the book takes them up.

Questions

1. The stone falls straight down for the passenger and along a parabola for the walker. Which path is the real one?
 - a. The parabola, because the ground is at rest and the train is moving
 - b. The straight line, because the stone was given no push
 - c. Neither: a path exists only with respect to a chosen reference body

2. Why does Einstein drop the word "space" and speak of motion with respect to a practically rigid reference body instead?
 - a. Because we can attach no definite idea to "space", while places relative to a reference body were already defined
 - b. Because space is curved and cannot be measured with rods
 - c. Because the train and the ground move through space at different speeds
 - d. Because rigid bodies are easier to draw than empty space
3. A path with its reference body named is still not a complete description of the stone's motion. What is missing?
 - a. The mass of the stone and the pull of gravity
 - b. The time at which the stone is at each point of the path, given as something measurable
 - c. The speed of the train with respect to the ground
4. How do the passenger and the walker each obtain the times for their description, in classical mechanics?
 - a. They agree on a single master clock on the embankment
 - b. They work the time out from the height the stone has fallen
 - c. Each holds one of two identical clocks and notes where the stone is on their own reference body at each tick
 - d. Each measures how long the light from the stone takes to arrive

Answers

1. c) There is no path in itself, only a path with respect to a particular reference body; the stone describes a straight line with respect to the

carriage and a parabola with respect to the ground, and neither is an illusion.

2. a) Space, if we are honest, is a dark word to which we can attach no definite idea at all; places with respect to a reference body are exactly what the previous section defined.

3. b) We must also say how the body changes its place with time, for every point of the path at what time the body is there, and those times must be observable quantities, results of measurements.

4. c) Two clocks made exactly alike, one in the hand of the passenger and one in the hand of the walker; each notes at which point of their own reference body the stone is at the moment their own clock ticks.

Practice

1. A passenger on a smoothly moving train drops a stone from the window. Describe its path with respect to the carriage and with respect to the ground, and explain why asking which path is real is asking nothing.

Hint: Name the reference body before you describe either path.

Answer: With respect to a coordinate system attached to the carriage the stone falls on a straight vertical line; with respect to one attached to the ground it moves forward with the train as it drops and traces a parabola. There is no path in itself, only a path with respect to a particular reference body, so a question with no reference body in it says nothing.

2. The passenger and the walker each write a list of the stone's places at the ticks of their own clocks. Say what the lists share and how they differ, and why such a list, not the path alone, is a complete description of the motion.

Hint: Ask what a tick adds to a point on the path.

Answer: Both lists pair the same ticks with the stone's place; the passenger's places lie on a vertical line, the walker's on a parabola, each a little farther along the track. The path alone says where the stone passed but not when; the list gives the time at every point, and because the times come from a clock in the observer's hand they are observable quantities, which is what a complete description requires.

3. Einstein admits that pairing a tick with the stone's place ignores an inaccuracy. What is it, and why does he allow himself to ignore it here?

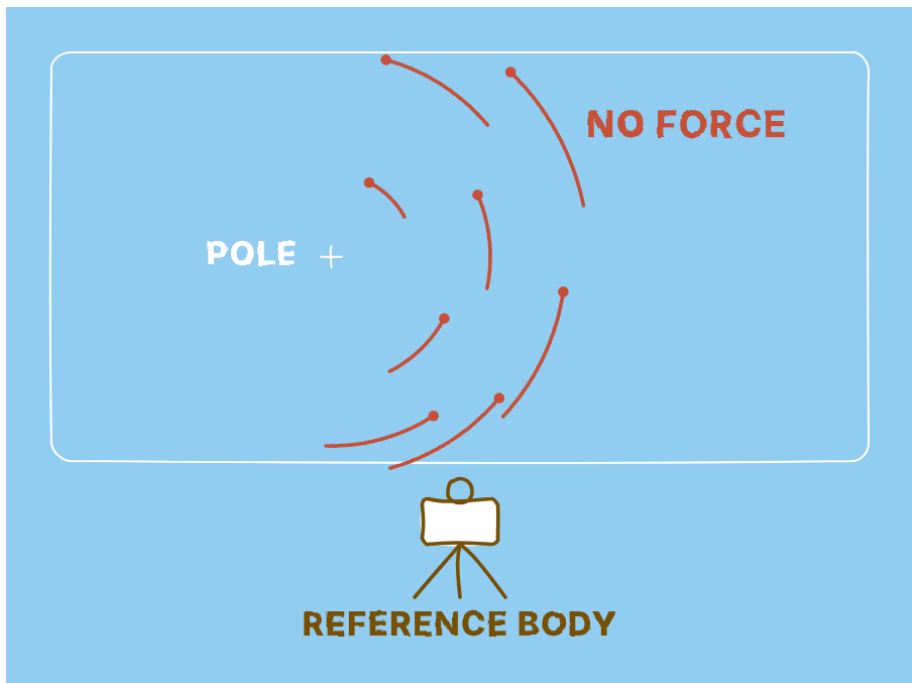
Hint: Ask how the walker learns where the stone is at the instant of a tick.

Answer: The walker sees the stone by light that took a finite time to arrive, so at the tick the stone is seen where it was a moment ago. Einstein sets this aside because he is standing on the ground of classical mechanics for now, and he promises to deal with it, and with a second difficulty, at length later.

Which Reference Bodies Are Allowed?

Put a camera on a tripod on a clear night, aim it at the sky, and leave the shutter open for an hour. The picture shows the stars not as dots but as arcs, pieces of circles drawn around one point in the sky.

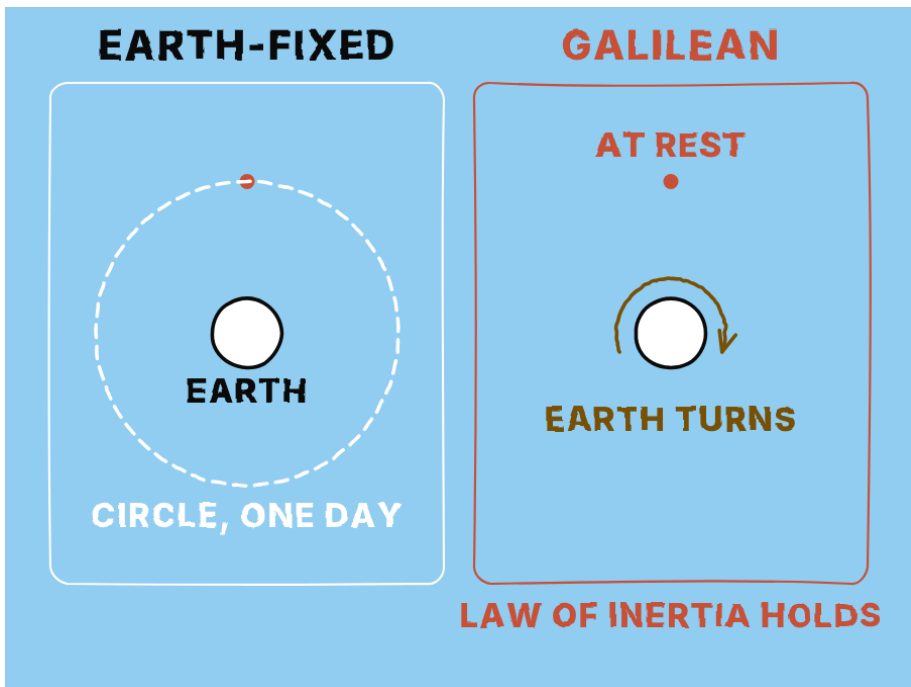
Nothing was pushing those stars; they are so far from everything that no pull worth mentioning reaches them. Yet with respect to the camera and the ground it stands on, every one of them moved along a curve. Einstein uses exactly this to decide which reference bodies physics may use.



Star Trails Over the Camera

He starts from the law of inertia, the first law of the mechanics of Galileo and Newton: a body far enough from all other bodies stays at rest or keeps moving uniformly in a straight line. That sounds like a statement about bodies, but, Einstein says, it is just as much a statement about reference bodies, the coordinate systems mechanics may use to describe motion. After the stone from the train we know why: a path is only a path with respect to a reference body, so "moves in a straight line" says nothing until the body is named.

The visible fixed stars are bodies to which the law of inertia should apply with great accuracy, since nothing is farther from everything else. Take a coordinate system rigidly attached to the Earth, the three walls fixed to the ground. With respect to it every fixed star describes, in one astronomical day, a circle of enormous radius: your photograph. That contradicts the wording of the law, which promised rest or a straight line.



Earth-Fixed Versus Galilean

So one of the two has to give, and Einstein keeps the law. Then motions may be referred only to coordinate systems with respect to which the fixed stars do not move in circles. A coordinate system whose state of motion is such that the law of inertia holds with respect to it, he calls a Galilean coordinate system. The laws of the mechanics of Galileo and Newton claim to be valid only for a Galilean coordinate system. The turning Earth is not quite one; a system that keeps its directions fixed on the distant stars is.

The satellites behind your phone's receiver are tracked in exactly such a system, with axes pointing at the fixed stars, because only there do their motions obey the simple laws; the receiver converts the answer to a place on the turning Earth afterwards. So the first four sections

come to rest: geometry made physical by rigid bodies, places as three numbers on a reference body, motion as a path with respect to such a body and a clock, and now the reference bodies themselves sorted, the Galilean ones admitted and the rest set aside for the moment. That "for the moment" is where the rest of the book begins.

Remember

The law of inertia, that a body far from all others stays at rest or moves uniformly in a straight line, is a statement about reference bodies as much as about bodies. With respect to a coordinate system fixed to the Earth the fixed stars circle once a day, against the law as worded. To keep the law, motions are referred only to coordinate systems in which the fixed stars do not circle: Galilean coordinate systems, those in which the law of inertia holds. The mechanics of Galileo and Newton claims validity only for Galilean coordinate systems, and satellite navigation works in one before translating to the turning Earth.

Questions

1. A camera left open for an hour shows the stars as arcs of circles. What does the lecture draw from this?
 - a. That the stars are pushed along curved paths by some force
 - b. That with respect to a coordinate system fixed to the Earth the fixed stars circle, against the wording of the law of inertia
 - c. That the law of inertia does not hold for stars

2. Why is the law of inertia a statement about reference bodies as much as about bodies?
 - a. Because reference bodies are themselves far from all other bodies
 - b. Because a straight line or rest is only such with respect to a named reference body
 - c. Because the law was found by observing the fixed stars
 - d. Because only rigid bodies can be reference bodies
3. What is a Galilean coordinate system?
 - a. A coordinate system rigidly attached to the Earth
 - b. A coordinate system whose state of motion is such that the law of inertia holds with respect to it
 - c. Any coordinate system built from three walls at right angles
 - d. A coordinate system that moves along with the fixed stars
4. Why are navigation satellites tracked in a system with axes pointing at the fixed stars?
 - a. Because the receiver cannot use Earth-fixed coordinates
 - b. Because only in a Galilean coordinate system do the motions obey the simple laws
 - c. Because the stars are needed to measure the satellites' distances

Answers

1. b) With respect to a system attached to the Earth every fixed star describes a circle of enormous radius in one day, which contradicts the law's promise of rest or a straight line.

- 2. b)** A path is only a path with respect to a reference body, so the law's talk of moving in a straight line says nothing until the body is named.
- 3. b)** Einstein calls a coordinate system Galilean when its state of motion is such that the law of inertia holds with respect to it; the fixed stars do not circle in it.
- 4. b)** The mechanics of Galileo and Newton claims validity only for a Galilean coordinate system, so the orbits are computed in one and converted to the turning Earth afterwards.

Practice

- 1.** Explain in your own words why a coordinate system rigidly attached to the Earth is not a Galilean coordinate system, using the fixed stars.

Hint: Ask what path a fixed star describes with respect to the ground in one day, and what the law of inertia says it should do.

Answer: A fixed star is far from all other bodies, so by the law of inertia it should be at rest or move uniformly in a straight line. With respect to a system attached to the Earth it describes a circle of enormous radius once a day instead. The law does not hold with respect to that system, so the system is not Galilean.

- 2.** Einstein keeps the law of inertia and gives up some reference bodies. State the rule this leads to and name the kind of coordinate system that results.

Hint: What must the fixed stars not do with respect to an allowed system?

Answer: Motions may be referred only to coordinate systems with respect to which the fixed stars do not circle. A coordinate system in which the law of inertia holds is a Galilean coordinate system, and the mechanics of Galileo and Newton claims validity only for such systems.

3. A friend says the law of inertia must be false, since the stars plainly circle every night. Answer them with the ideas of this part.

Hint: Separate the statement about bodies from the statement about reference bodies.

Answer: The circles are the stars' paths with respect to the turning Earth, and a path exists only with respect to a reference body. The law claims validity only for Galilean coordinate systems, in which the fixed stars do not circle; the Earth-fixed system is not one, so the night sky contradicts the choice of reference body, not the law.