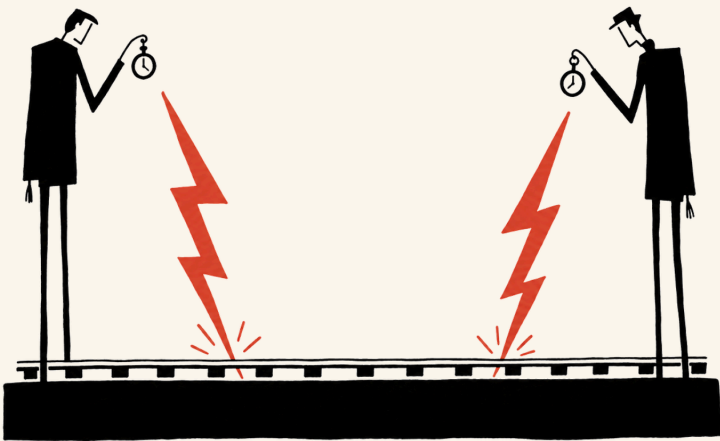


Relativity: The Special and General Theory



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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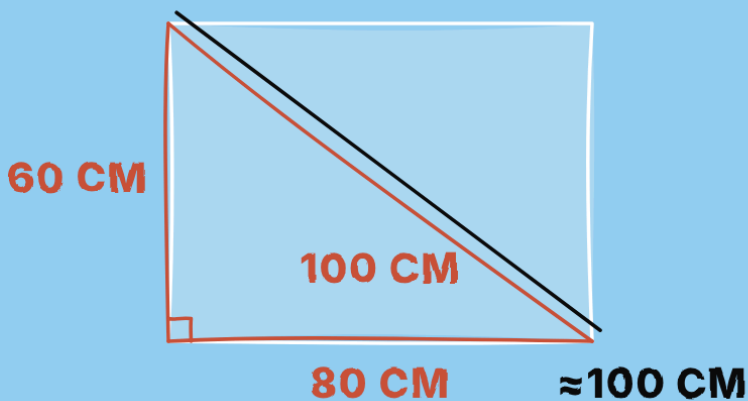
One Stone, Two Paths

Which Reference Bodies Are Allowed?

When Is a Theorem True?

Take a tape measure to the kitchen table. Measure the short side and the long side, then stretch the tape from corner to corner, but before you read it, guess the answer with the one theorem everyone remembers from school, the one about the long side of a right-angled triangle. If the sides were sixty and eighty centimetres, the school rule says the diagonal is a hundred. You look at the tape, and there it is, give or take a millimetre. What exactly have you just confirmed?

WHAT DOES TRUE MEAN?

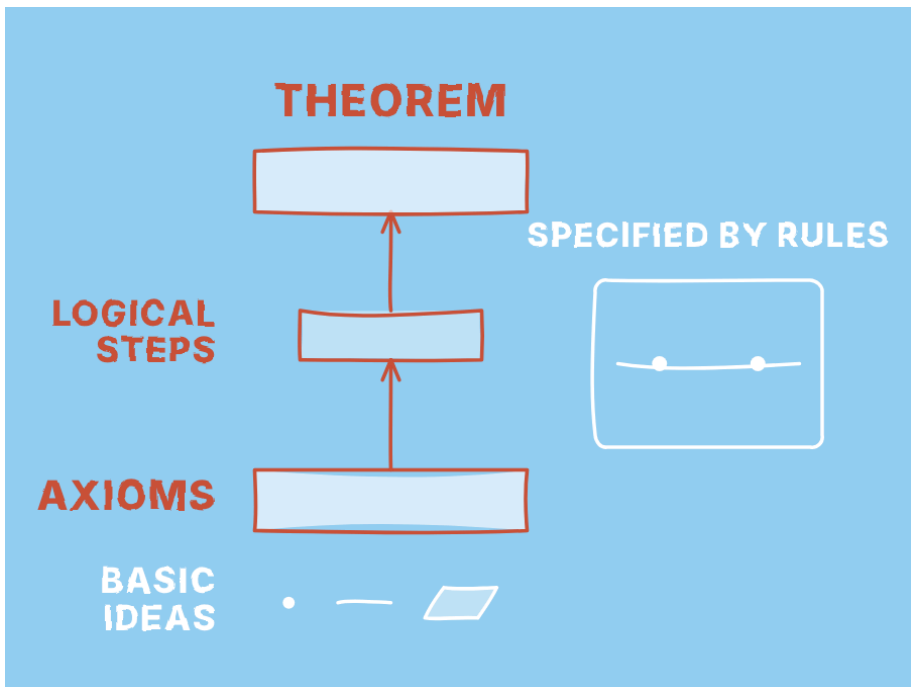


$$60^2 + 80^2 = 100^2$$

Predicting the Table's Diagonal

Most people would say they checked that the theorem is true. Albert Einstein opens his little book by stopping us right there and asking, with some mischief, what we mean when we call such a statement true. He reminds us that most of us met the proud edifice of Euclid's geometry as children, chased up its high staircases by conscientious teachers, and remember it with more respect than affection. Out of loyalty to that schooling we would scorn anyone who doubted the humblest of its theorems; and yet our certainty may evaporate the moment someone asks what "true" means.

Think of geometry as a building. Its foundations are a few basic ideas, point, straight line, plane, and a few simple statements about them, the axioms, which we accept because they feel obvious. Every floor above is built from the foundations by logical steps, and that building process is what a proof is. So, inside geometry, a theorem is true when it has been properly built up from the axioms, and that is all the word can mean there. Whether the foundations themselves are true is a question geometry cannot answer, and Einstein says it has no meaning at all.

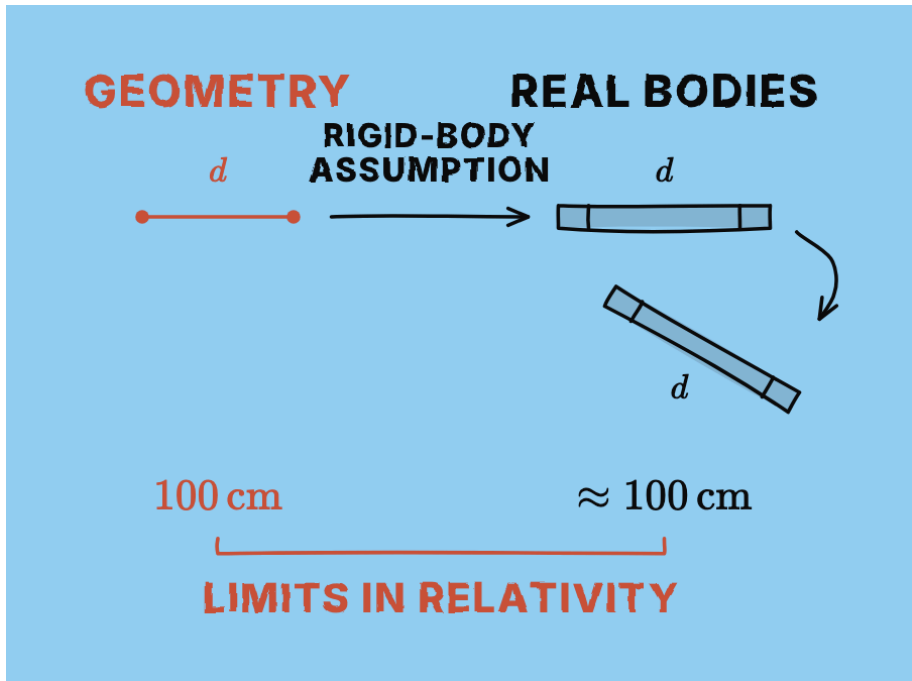


What a Proof Establishes

Here is why. Is it true that only one straight line passes through two points? Geometry does not know; it simply deals with things it calls straight lines and gives them that property by definition, like the rules of chess giving the bishop its diagonal move. Nobody asks whether the bishop's move is true. And "true", Einstein says, always means agreement with some real thing, while pure geometry is only about how its own ideas fit together.

Why then does the theorem feel so true at the table? Because the ideas of geometry grew out of real objects in the first place. We are in the habit of seeing a segment as two marks on a rigid body, a tape, a ruler, a rod, and of judging three things to be in a line when, closing one eye, we can make the nearest one hide the others. That habit is the bridge,

and Einstein makes it explicit with a single added sentence: two marks on a practically rigid body stay the same distance apart however you move the body about. Nothing in pure geometry says that; it is a claim about tapes and rods. Once it is added, every theorem of geometry becomes a statement about how real rigid bodies can be arranged, and geometry has become a branch of physics.



From Geometry to Physical Test

Now the word "true" fits, because now there is something to check. A theorem is true, in this physical sense, when a construction with real things, compass and straightedge or a tape on a tabletop, agrees with it. Your table was such a check, and it passed. The same check is made, on a grand scale, every time 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 agrees with where you really are.

Einstein closes with a caution that runs through the whole book. The conviction that geometry is true in this sense rests on rather imperfect experience; no tape is perfectly rigid and no eye perfectly straight. For now, he says, we take that truth for granted, and at the end of the book, in 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 asking whether the axioms are true has no meaning there, like asking whether the bishop's move in chess is true. Theorems feel true because the ideas of geometry grew out of real objects, and we see a segment as two marks on a rigid body. Add one physical statement, that two marks on a rigid body keep their distance however the body is moved, and geometry becomes a branch of physics. Then a theorem is true when real bodies agree with it, a tape on a table or 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. Inside geometry itself, what makes a theorem true?

- a. That a tape measure on a table agrees with it
 - b. That it has been properly built up from the axioms by logical steps
 - c. That everyone who thinks about it finds it obvious
2. Why does the lecture compare the axiom about straight lines to the bishop's move in chess?
- a. Because both are hard to learn
 - b. Because both are rules given by definition, so asking whether they are true has no meaning
 - c. Because both were worked out by careful measurement
 - d. Because both can be checked with a ruler
3. What single added statement turns geometry into a branch of physics?
- a. That two marks on a practically rigid body stay the same distance apart however the body is moved
 - b. That the axioms are confirmed by experience
 - c. That a satellite receiver finds its position by geometry
 - d. That a straight line is the shortest path between two points
4. Why does Einstein accept the physical truth of geometry only for now?
- a. Because the theorems have not all been proved yet
 - b. Because tape measures are rarely accurate
 - c. Because it rests on imperfect experience, and the general theory of relativity will show its limits

Answers

1. **b)** Think of geometry as a building: inside it a theorem is true when it has been properly built up from the axioms, and that is all the word can mean there.
2. **b)** Geometry simply deals with things it calls straight lines and gives them their property by definition, like the rules of chess giving the bishop its move; nobody asks whether the bishop's move is true.
3. **a)** Once we add that two marks on a rigid body keep their distance however the body is moved, every theorem becomes a statement about how real rigid bodies can be arranged, and geometry has become a branch of physics.
4. **c)** The conviction rests on rather imperfect experience, no tape perfectly rigid and no eye perfectly straight; he takes it for granted for now and shows at the end of the book where it has limits.

Practice

1. A friend says: "Pythagoras is true, I checked it with a tape measure." In what sense are they right, and in what sense have they checked nothing at all?

Hint: Separate the theorem as something built from axioms from the theorem as a statement about a tape on a table.

Answer: In the physical sense they are right: once we add that a tape is a rigid body whose marks keep their distance, the theorem is a claim about real things, and the table agreed with it. Inside pure geometry they have checked nothing, because there a theorem is true only by being built up from the axioms, and no measurement can bear on that.

2. Explain, with the chess comparison, why the question whether only one straight line passes through two points cannot even be asked, while the question whether a measured diagonal matches the predicted one can be.

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

Answer: The first is a rule of geometry: straight lines are the things that have that property by definition, as the bishop has its diagonal move by the rules of chess, and asking whether a rule is true has no meaning. The second is about marks on a tape and a tabletop, real things, so agreement or disagreement with them can be checked and the word true fits.

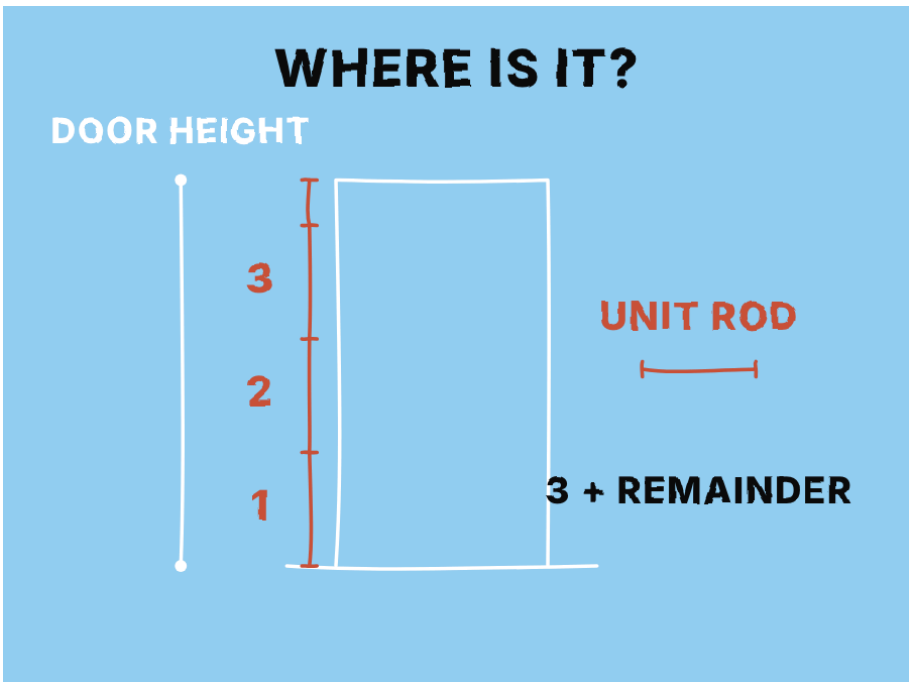
3. Why does the lecture call the habit of seeing a segment as two marks on a rigid body a bridge, and what does Einstein build on that bridge?

Hint: Think about what connects the ideas of geometry to tapes and rods.

Answer: The habit connects the ideas of geometry, which came from real objects, back to those objects. Einstein makes it explicit with one added statement, that two marks on a practically rigid body keep their distance however the body is moved; with it, geometry becomes a branch of physics whose theorems can be checked against real bodies.

Where Is the Cloud?

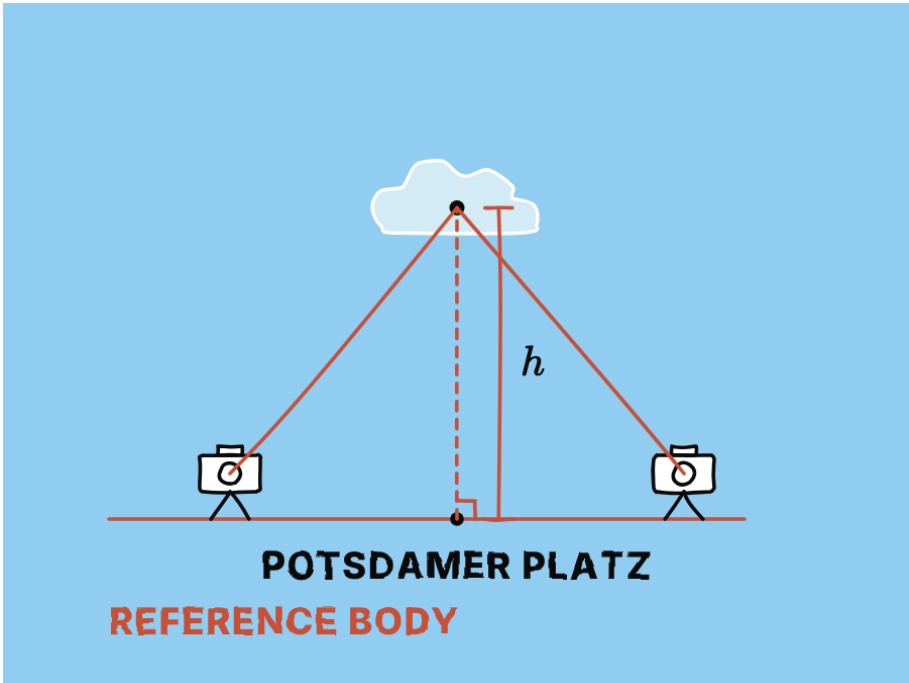
Measure the height of a door with a short wooden ruler. Stand it on the floor against the frame, mark where it ends with a thumb, lift it, stand it on the mark, and count: one, two, three ruler-lengths and a bit. Nobody taught you this; it is simply what measuring is. Now look up at a cloud drifting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



Distance Is Repeated Units

First the ruler. Last time we agreed that a segment is two marks on a rigid body; now pick one such segment, a little rod, and promise to use it once and for all as the unit. To measure the distance between two points of a rigid body, lay the unit rod along the straight line between them, again and again, and count how many times it fits. That count is the distance. Every tape measure 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 something is, Einstein says, names the point of some rigid body that the thing coincides with. That rigid body is the reference body, and everyday speech works this way as much as science does. Say "in Berlin, on Potsdamer Platz": the surface of the Earth is the rigid body, Potsdamer Platz is a named point on it, and the event is at that point. It is like telling a friend you will meet them at the fountain in the park: the park is the reference body and the fountain its named point.



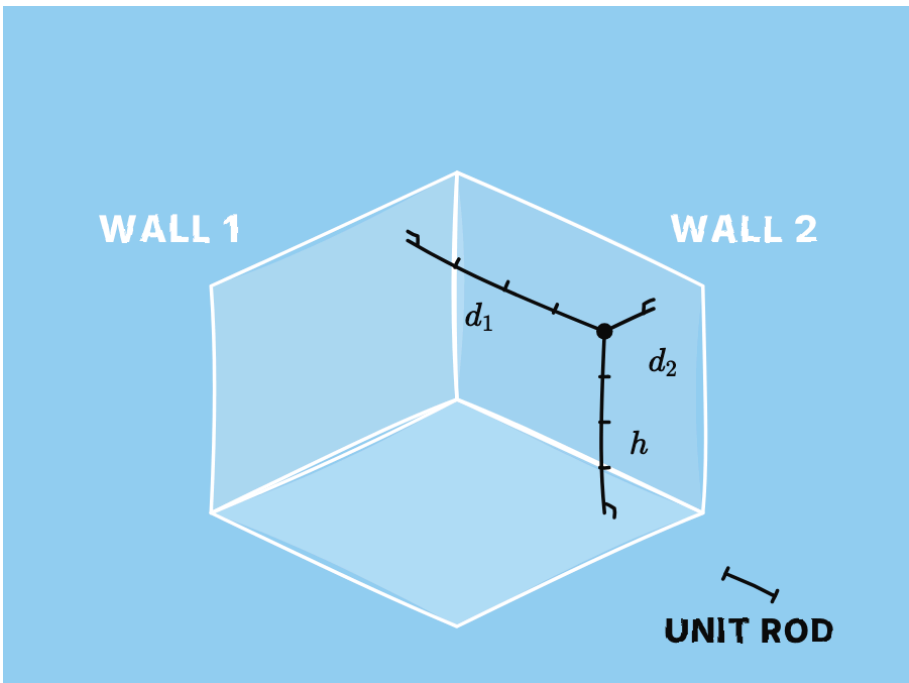
Reaching the Cloud

This way of giving a place has two limits. It can only name places on the surface of a rigid body, and it needs that surface to have landmarks with names. The cloud has neither. So imagine a pole erected 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 its foot, says completely where the cloud is. Nothing has changed in kind: we still name a point of a rigid body, only the rigid body now reaches up to the cloud.

Three steps are hidden in that pole, and Einstein draws them out. The reference body has been extended until it reaches the thing to be located. A number, the length of the pole, has replaced a named landmark. And we speak of the cloud's height even when no pole has

been built: photograph the cloud from several places on the ground, and from the pictures, knowing how light travels, work out how long the pole would have to be. The pole is imagined, but its length is measured all the same.

From this Einstein draws the lesson that it pays to describe places with measured numbers rather than named landmarks. Physics does so with the coordinate system: picture two walls and the floor meeting in the corner of a room, three flat rigid surfaces at right angles, joined into one rigid body. Any point in the room is fixed by three distances, how far it is from one wall, from the other wall, and above the floor. Those three numbers are its coordinates, and each is found, in principle, by laying the unit rod along the perpendicular to the wall.



Three Distances Fix a Point

Try it yourself

Stand in a corner of your room and pick a lamp or a picture hook. Say how far it is from one wall, how far from the other, and how high above the floor: 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 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 meaning of every such statement must stay 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 every description of where things are uses a rigid body to which they are referred, and it assumes that the ordinary geometry of school holds for segments, two marks on a rigid body. The assumption we accepted on probation last time now carries the whole idea of place.

Remember

Distance is measured by laying a chosen unit rod along the straight line between two points and counting how many times it fits. To say where something is means to name the point of a rigid reference body it coincides with, as the fountain names a point in the park. The idea of place is refined by extending the reference body, by replacing landmarks with measured numbers, and by speaking of a length even when the rod that would measure it is only imagined. A coordinate system makes this systematic: three rigid walls at right angles, and the three distances from a point to them are its coordinates. Whether found with rods or computed from satellite signals, a place statement means this, and it assumes that school geometry holds for segments on rigid bodies.

Questions

1. What does measuring the distance between two points actually consist of, in the lecture?
 - 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 between the two points
2. What does "meet me at the fountain in the park" have in common with "in Berlin, on Potsdamer Platz"?

- a. Both give a place as three measured numbers
 - b. Both name a point of a rigid reference body that the event coincides with
 - c. Both need a pole to be erected to work
 - d. Both locate something off the surface of the Earth
3. The cloud's height is worked out from photographs taken at several places on the ground. Which of the three steps is this?
- a. Extending the reference body with a real pole up to the cloud
 - b. Replacing a landmark with a number
 - c. Speaking of a length even though the rod that would measure it was never built
 - d. Treating the cloud as a landmark on 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 satellite signals are less accurate than rods
 - b. Because otherwise the results of physics and astronomy dissolve into vagueness
 - c. Because the three walls of the coordinate system are always built in practice

Answers

1. a) Lay the unit rod along the straight line between the points, again and again, and count how many times it fits; that count is the distance, and every tape and rangefinder comes down to it.

2. b) Every statement of where something is names the point of a rigid body that the thing coincides with; the park is the reference body and the fountain its named point, as the Earth's surface and Potsdamer Platz are.

3. c) We speak of the cloud's height even when no pole has been built: from the pictures, knowing how 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, like the cloud's height from photographs, but the meaning of every such statement must stay rods laid against 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 in your own words what its three coordinates are and how, in principle, each could be measured.

Hint: Think of the two walls and the floor as the three rigid surfaces and ask how far the lamp is from each.

Answer: The two walls and the floor are three flat rigid surfaces at right angles, joined into one rigid body. The lamp's coordinates are its three distances, from one wall, from the other wall and above the floor. Each is found, in principle, by laying the unit rod along the perpendicular to that surface and counting how many times it fits.

2. Name the two limits of giving a place by a landmark, and explain how the pole on the square frees us from each without changing what a place statement is.

Hint: Start from what "at the fountain in the park" can and cannot locate.

Answer: A landmark can only name places on the surface of a rigid body, and it needs that surface to have named landmarks. 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 landmark. The statement still names a point of a rigid body that the cloud coincides with, so its kind is unchanged.

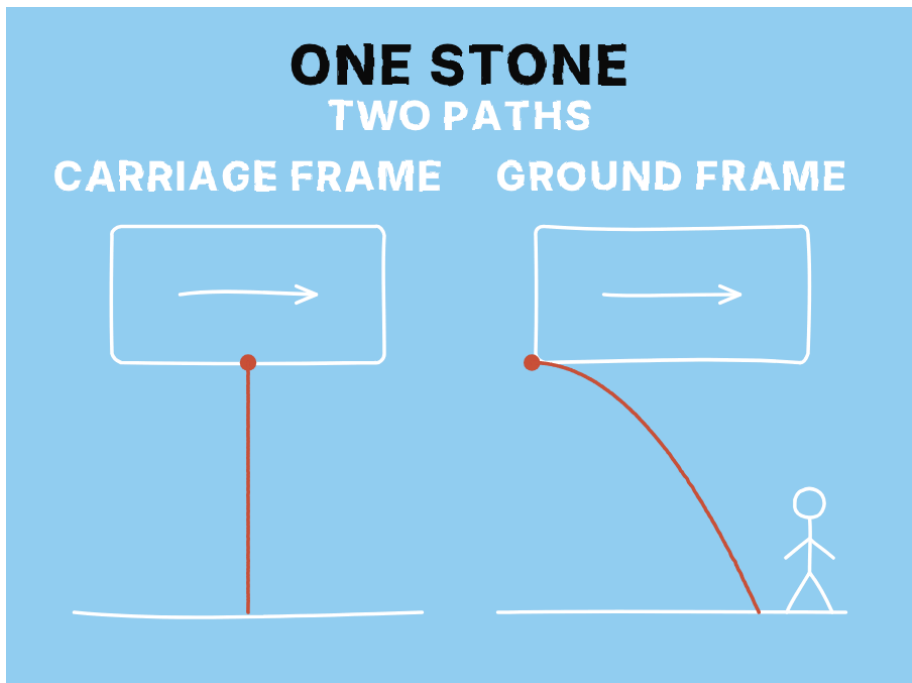
3. A satellite receiver computes its position from signal travel times and never touches a rod. In what sense is its answer still a place statement of the kind described here, and what does it assume about geometry?

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 three distances to a rigid reference body, distances a rod could in principle measure. Like every statement of place it assumes that school geometry holds for segments, two marks on a rigid body.

One Stone, Two Paths

Sit by the window of a train running smoothly along a straight track. Hold a stone out of the window and let it go, without a push. You see it drop straight down, as if the train were standing still, and land on the embankment below you. A walker on the path beside the track sees the same stone leave the same hand, but to the walker it falls in a curve, carried forward with the train while it drops, and lands 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 said that mechanics describes how bodies change their place in space with time, he would be sinning, as he puts it, against the holy spirit of clarity. The trouble hides in two small words, "place" and "space", and the stone brings it into the open. Do the places the stone passes through really lie on a straight line or on a curve? And what does it mean to say the stone moves "in space"?

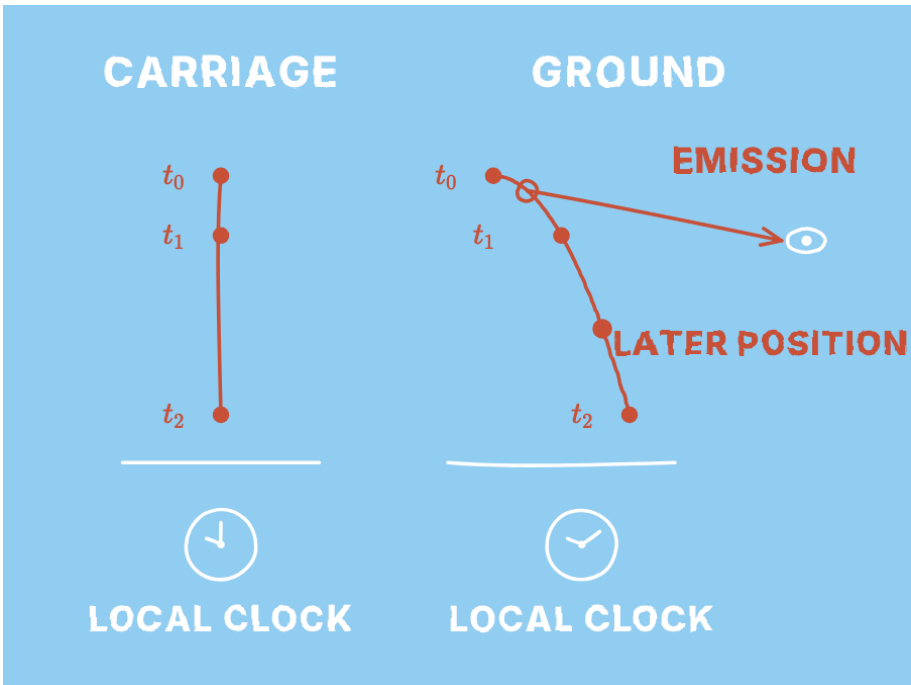
After last time the answer is plain. "Space", if we are honest, is a word we attach no clear idea to, so Einstein drops it and says instead "motion with respect to a rigid reference body". Places with respect to a reference body are exactly what we learned to give last time, and here there are two reference bodies on offer: the carriage and the ground. With respect to the carriage the stone falls on a straight line; with respect to the ground it falls on a curve. Neither is the real path with the other an illusion. There is no path in itself, only a path with respect to a particular reference body, and a sentence that leaves the reference body out 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 through the window: the coin moves forward with the car the whole time it falls, tracing a shallow arc. Both of you are right; you have simply chosen different rigid bodies, the car or the road, to refer the coin's places to.

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.

A path with its reference body named is still not the whole story of a motion. We must also say when the stone is at each point of the path, and those times, Einstein insists, must be things that can be measured, not numbers assumed out of the air. He does it simply: two clocks made exactly alike, one in the hand of the passenger and one in the hand of the walker, and each notes where the stone is on their own reference body at each tick of their own clock. Tick, here; tick, there; and a list of places paired with ticks is a complete description of the motion with respect to that reference body.



Places Paired With Clock Readings

Einstein closes with two quiet warnings, left for later. Pairing a tick with a place ignores that light takes time to travel, so the walker sees the stone where it was a moment ago; and a second difficulty is lurking that he does not yet name. They are not small: the satellite clocks that feed your receiver would drift by kilometres a day if such things 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 real 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 vague word "space" is replaced by a rigid reference body. The stone dropped from the train falls straight down with respect to the carriage and along a curve 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 full description of motion also needs the time at each point, taken from a clock in the observer's hand and paired with the stone's place on their own reference body. Two difficulties were set aside, the travel time 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 curve for the walker. Which path is the real one?
 - a. The curve, 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 rigid reference body?

- a. Because we attach no clear idea to "space", while places relative to a reference body were defined last time
 - 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 picture than empty space
3. A path with its reference body named is still not the whole story of a motion. What is missing?
- a. The weight of the stone and the pull of gravity
 - b. When the stone is at each point of the path, given as something that can be measured
 - 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?
- a. They share a single clock on the embankment
 - b. They work the time out from how far 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; neither path is the real one with the other an illusion.
- 2. a)** Space, if we are honest, is a word we attach no clear idea to; places with respect to a reference body are exactly what the previous part taught us to give.

3. b) We must also say when the stone is at each point of the path, and those times must be things that can be measured, not numbers assumed out of the air.

4. c) Two clocks made exactly alike, one in the hand of the passenger and one in the hand of the walker, and each notes where the stone is on their own reference body at each tick of their own clock.

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 the carriage the stone falls straight down; with respect to the ground it moves forward with the train as it drops and traces a curve. There is no path in itself, only a path with respect to a particular reference body, so a question that leaves the reference body out 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 kind of ticks with the stone's place; the passenger's places lie on a vertical line, the walker's on a curve, 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 measured, which is what a complete description needs.

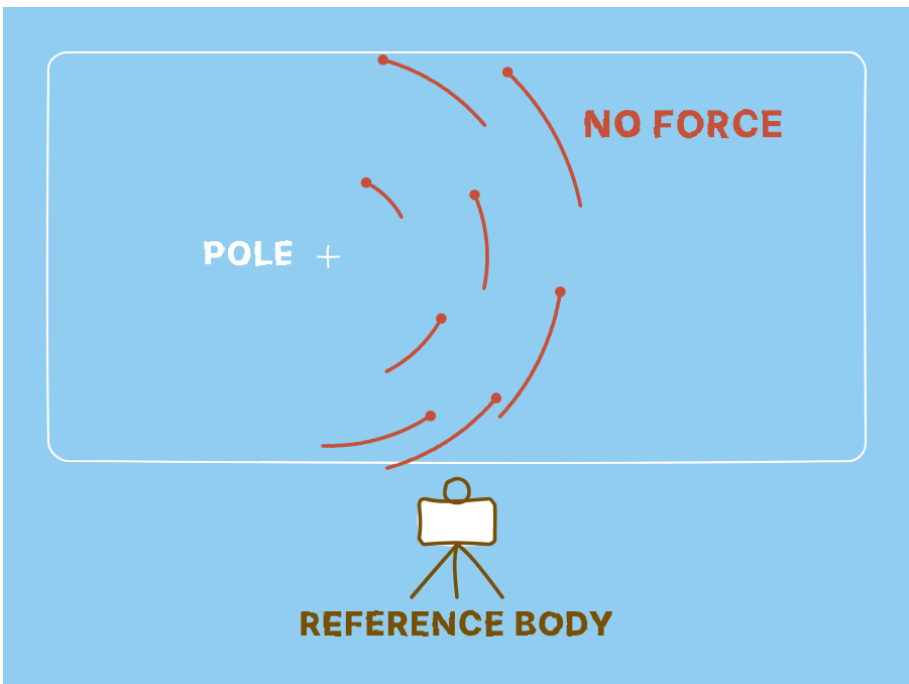
3. What does pairing a clock tick with the stone's place ignore, and why does Einstein allow himself to ignore it here?

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

Answer: It ignores that light takes time to travel, so the walker sees the stone where it was a moment ago, not where it is. Einstein sets it aside because he is standing on the ground of ordinary mechanics for now, and he promises to deal with it, and with a second difficulty, later in the book.

Which Reference Bodies Are Allowed?

Leave a camera pointed at the night sky with the shutter open for an hour. The stars come out not as dots but as arcs, pieces of circles around one point in the sky. Nobody is pushing those stars; they are so far from everything that nothing reaches them. Yet with respect to the ground, every one of them travelled along a curve.

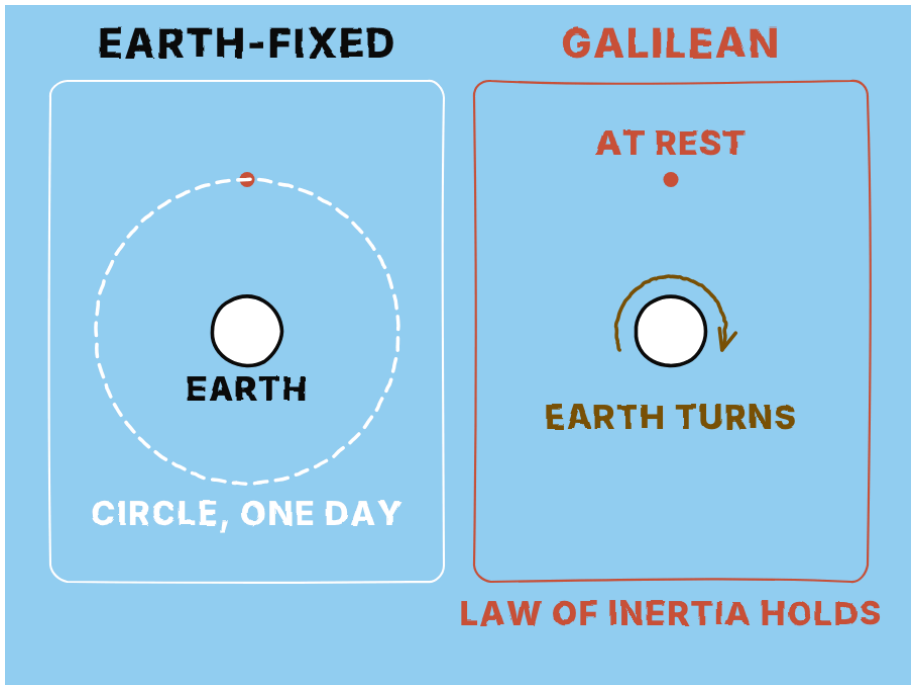


Star Trails Over the Camera

Einstein starts from the law of inertia: a body far from all other bodies stays at rest or keeps moving in a straight line at a steady pace. That sounds like a rule about bodies, but after the stone from the train we

know it is just as much a rule about reference bodies, because "straight line" means nothing until we say with respect to what. The fixed stars are the bodies the law should fit best, and with respect to the Earth they circle once a day. So either the law goes, or the Earth goes as a reference body, and Einstein keeps the law.

Motion may then be referred only to reference bodies with respect to which the fixed stars do not circle. Such a reference body, one in which the law of inertia holds, he calls a Galilean coordinate system, and the mechanics of Galileo and Newton claims to be valid only for those. The satellites behind your phone's receiver are tracked in exactly such a system, one that keeps its directions fixed on the stars; the receiver converts the answer to the turning Earth for you. So the first four sections close with the reference bodies sorted: the Galilean ones admitted, the rest set aside for the moment, and that "for the moment" is where the rest of the book begins.



Earth-Fixed Versus Galilean

Remember

The law of inertia says a body far from all others stays at rest or moves uniformly in a straight line, and it is a rule about reference bodies as much as about bodies. With respect to the Earth the fixed stars circle once a day, so the Earth is not a reference body in which the law holds. A reference body in which the law of inertia holds is a Galilean coordinate system, and the mechanics of Galileo and Newton is valid only for those.

Questions

1. With respect to a coordinate system rigidly connected with the Earth, what does a fixed star do in one astronomical day?
 - a. It stays at rest, as the law of inertia requires
 - b. It describes a circle of enormous radius, against the wording of the law of inertia
 - c. It moves uniformly in a straight line
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 rest or uniform straight-line motion 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 connected with the Earth
 - b. A coordinate system whose state of motion is such that the law of inertia holds relative to it
 - c. Any coordinate system built from three walls at right angles
 - d. A coordinate system moving along with the fixed stars
4. For which coordinate systems do the laws of the mechanics of Galileo and Newton claim validity?
 - a. For every coordinate system

- b. For Earth-fixed coordinate systems only
- c. For Galilean coordinate systems only

Answers

1. **b)** Relative to a system rigidly connected with the Earth every fixed star describes, in one astronomical day, a circle of enormous radius, in contradiction with the wording of the law of inertia.
2. **b)** The law says something not only about the motion of bodies but about which reference bodies or coordinate systems may be used in mechanical description, since motion is always motion with respect to a reference body.
3. **b)** A coordinate system whose state of motion is such that the law of inertia holds relative to it is called a Galilean coordinate system; the fixed stars perform no circular motion relative to it.
4. **c)** Only for a Galilean coordinate system do the laws of the mechanics of Galileo and Newton claim validity.

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.