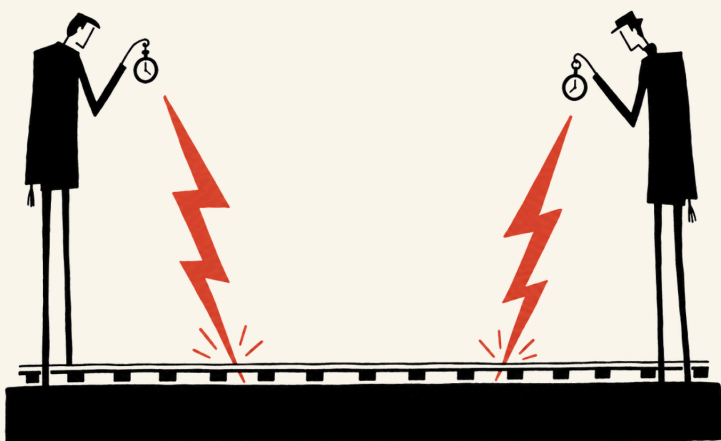


Relativity: The Special and General Theory



Albert Einstein · 1917

Illustrated audio lectures

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From the original: Über die spezielle und die allgemeine Relativitätstheorie
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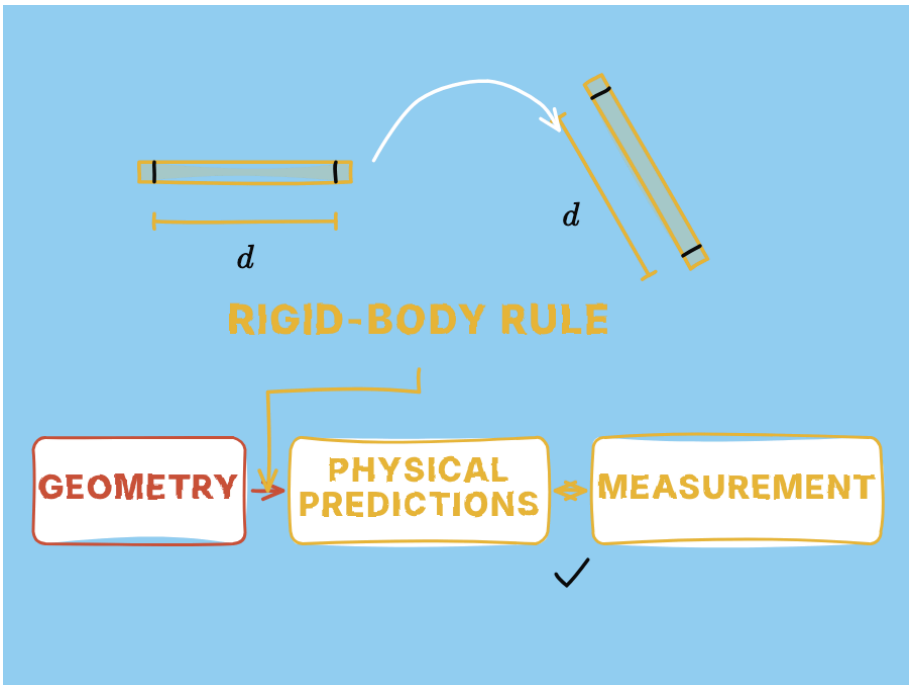
Which Reference Bodies Are Allowed?

What Makes Geometry True

Measure a kitchen table with a tape: sixty centimetres by eighty. Before you stretch the tape across the diagonal, school geometry tells you what it will read: a hundred centimetres. You check, and it does. Everyone says the theorem has just been shown true, and Einstein opens his book by asking what that word can possibly mean.

The question this first section answers is simple to state: in what sense is a statement of geometry true? Inside geometry itself, a theorem is true only because it follows from the axioms, the few starting statements we accept because they feel obvious. Whether the axioms themselves are true is a question geometry cannot answer; Einstein goes further and says it has no meaning at all, because "true" always means agreement with some real thing, and pure geometry is not about real things, only about how its own ideas hang together.

Why then does the theorem feel true at the table? Because the ideas of geometry grew out of real objects, and we are in the habit of seeing a line segment as two marks on a rigid body, such as a tape or a rod, and of judging three places to be in line when one eye can make them coincide. Here is the one idea everything rests on. Add to geometry a single physical statement: two marks on a practically rigid body stay the same distance apart however the body is moved. With that addition, every theorem of geometry becomes a statement about how real rigid bodies can be arranged, and geometry turns into a branch of physics.



The Physical Bridge

What follows in practice is that a theorem can now be checked, and so can be true or false in the ordinary sense: it is true when a construction with real bodies, compass and straightedge, or a tape on a tabletop, agrees with it. Your table test was a physics experiment, and it passed. The same thing happens 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 actually are.

Einstein adds one warning that runs through the whole book. The conviction that geometry is true in this physical sense rests on rather imperfect experience, since no tape is perfectly rigid and no eye perfectly straight. He accepts that truth for now, as a working

assumption, and promises to show at the end of the book, in the general theory of relativity, that it has limits. Left out here are the finer steps of Einstein's argument, such as his remarks on our schooling in Euclid and the exact wording of his definitions; they are in the first section of the book.

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. 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 whose theorems can be checked against real things. A theorem is then true when real bodies, a tape on a table or a satellite receiver, agree with it. That agreement rests on imperfect experience; Einstein assumes it for now and will show its limits in the general theory of relativity.

Questions

1. Inside geometry itself, why is a theorem true?
 - a. Because a tape measure on a table agrees with it
 - b. Because it follows from the axioms, the starting statements we accept as obvious
 - c. Because careful people find it convincing
2. Why does Einstein say that asking whether the axioms are true has no meaning at all?

- a. Because the axioms are too simple to doubt
 - b. Because nobody has found a way to test them
 - c. Because "true" means agreement with a real thing, and pure geometry is not about real things
 - d. Because every axiom can be proved from the others
3. What is the one idea everything rests on, according to this part?
- a. That two marks on a practically rigid body stay the same distance apart however the body is moved
 - b. That the axioms of geometry are confirmed by experience
 - c. That a satellite receiver uses geometry to find its position
 - d. That geometry should be kept separate from physics
4. In what spirit does Einstein accept the physical truth of geometry?
- a. As proved beyond doubt by countless measurements
 - b. As a working assumption resting on imperfect experience, whose limits appear later in the book
 - c. As a convention that could be replaced by any other

Answers

- 1. b)** Inside geometry a theorem is true only because it follows from the axioms; whether the axioms themselves are true is a question geometry cannot answer.
- 2. c)** True always means agreement with some real thing, and pure geometry is not about real things, only about how its own ideas hang together.
- 3. a)** Add that single physical statement and every theorem of geometry becomes a statement about how real rigid bodies can be arranged; geometry

turns into a branch of physics.

4. b) The conviction rests on rather imperfect experience; he accepts that truth for now as a working assumption and promises to show, in the general theory of relativity, that 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 that follows 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 following from the axioms, and no measurement bears on that.

2. Explain why a theorem can be checked, and so be true or false in the ordinary sense, only after the single physical statement about rigid bodies is added to geometry.

Hint: Ask what the theorems are about before and after the addition.

Answer: Before the addition the theorems are about ideas and only say what follows from the axioms, so there is nothing real to compare them with. After it they are statements about how real rigid bodies can be arranged, so a construction with compass and straightedge, or a tape on a tabletop, can agree or disagree with them, and the word true applies.

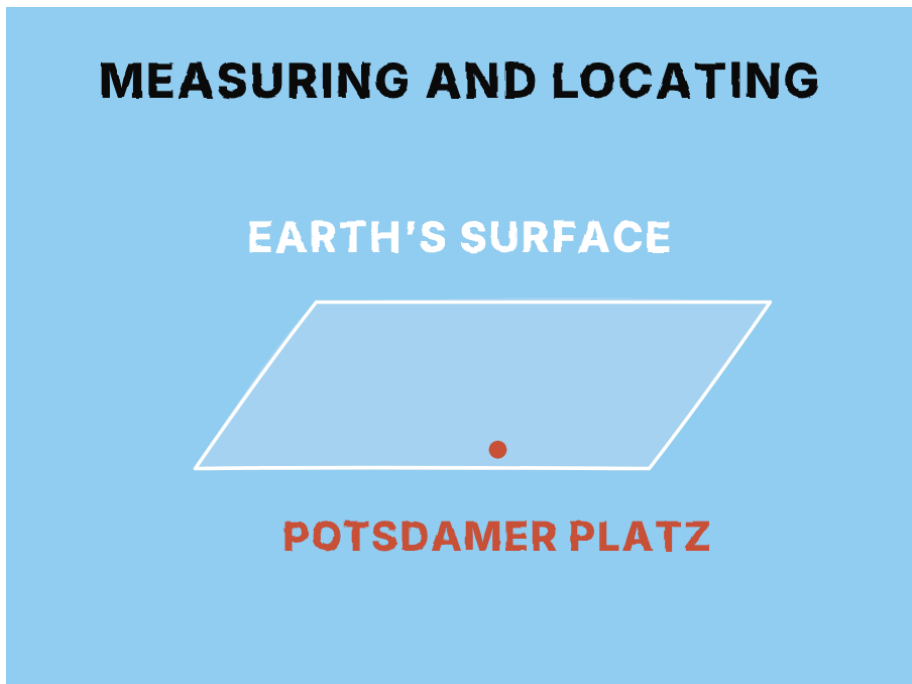
3. Why does Einstein call our conviction of the truth of geometry a matter of imperfect experience, and what does he promise about it?

Hint: Think about what a tape measure and an eye really are.

Answer: The conviction rests only on experience with real things, and no tape is perfectly rigid and no eye perfectly straight, so the agreement is approximate. He assumes that truth for now and promises to show at the end of the book, in the general theory of relativity, that it has limits.

Saying Where Something Is

Measure a doorway with a short ruler: lay it against the frame, mark where it ends, lay it down again from the mark, and count. Three ruler-lengths and a bit, and that is what measuring is. This section answers one question: what are we really doing when we measure a length or say where something is?

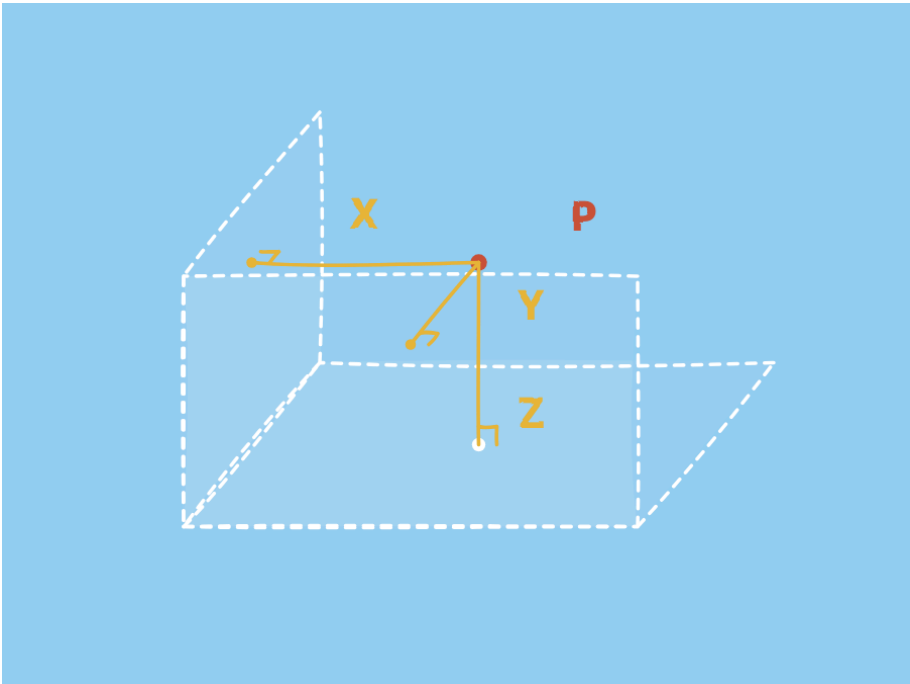


Measuring and locating

Two ideas carry everything. The first is the unit rod: choose one segment, two marks on a rigid body, once and for all, and the distance between any two points is the number of times that rod must be laid

along the straight line between them. Every tape measure and every laser rangefinder comes down to this counting. The second is the reference body: to say where a thing is means to name the point of some rigid body that it coincides with. "In Berlin, on Potsdamer Platz" names a point on the surface of the Earth, and the Earth's surface is the rigid body the statement refers to.

Einstein then shows how this simple idea stretches without changing its nature. A cloud over the square has no landmark of its own, so imagine a pole erected on the square, tall enough to reach it; the measured length of the pole, with the place of its foot, says where the cloud is. Three things have happened: the rigid body has been extended to reach the cloud, a number has replaced a named landmark, and we may even speak of the cloud's height when no pole exists at all, computing from photographs how long it would have to be.



From landmarks to coordinates

What follows in practice is the coordinate system: three rigid flat walls at right angles, like two walls and the floor meeting in the corner of a room, and any point is fixed by its three distances from them, its coordinates. Nobody builds the walls, Einstein admits, and the numbers are found indirectly; a satellite receiver in your pocket computes its three coordinates from how long the signals from several satellites took to arrive, as the cloud's height was computed from photographs. Yet the meaning of every such number must stay what it was: rods laid against a rigid body, or 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 ordinary geometry holds for

segments on rigid bodies, the assumption accepted on probation last time. Left out here are Einstein's remarks on how the coordinates are found by rod constructions prescribed by Euclidean geometry; they are in the second section of the book.

Remember

Distance is the number of times a chosen unit rod fits along the straight line between two points. To say where something is means to name the point of a rigid reference body it coincides with. The idea stretches by extending the reference body, by using measured numbers instead of landmarks, and by speaking of a length even when the rod is only imagined. A coordinate system, three rigid walls at right angles, turns any place into three numbers, and even a satellite receiver's position means rods against a rigid body. All of it assumes that ordinary geometry holds for segments on rigid bodies.

Questions

1. What is the distance between two points, according to this part?
 - a. The number of times the chosen unit rod fits along the straight line between them
 - b. The time a signal takes to travel from one to the other
 - c. The number of landmarks between them
2. What does "in Berlin, on Potsdamer Platz" mean when we take it apart?

- a. That the place has three coordinates measured from walls
 - b. That the event is a certain distance from the centre of the Earth
 - c. That the event coincides with a named point of a rigid body, the surface of the Earth
 - d. That a pole on the square would reach the event
3. A cloud's height is computed from photographs, with no pole built at all. Which stretching of the idea of place is this?
- a. Extending the rigid body with a real pole
 - b. Speaking of a length even though the rod that would measure it only exists in imagination
 - c. Treating the cloud as a landmark on the ground
 - d. Replacing the Earth by a different reference body
4. Why must a satellite receiver's coordinates still mean rods laid against a rigid body?
- a. Because satellite signals are less exact than rods
 - b. Because the three walls of the coordinate system are always built
 - c. Because otherwise physics and astronomy dissolve into vagueness

Answers

1. a) Choose one segment once and for all as the unit rod; the distance between any two points is the number of times that rod must be laid along the straight line between them, and every tape and rangefinder comes down to this counting.

2. c) To say where a thing is means to name the point of some rigid body it coincides with; here the Earth's surface is the reference body and Potsdamer Platz a named point on it.

3. b) We may speak of the cloud's height when no pole exists at all, computing from photographs how long it would have to be; the pole is imagined, the length is measured.

4. c) The numbers are found indirectly, as the cloud's height was from photographs, but the meaning of every such number must stay what it was, rods laid against a rigid body, or physics and astronomy dissolve into vagueness.

Practice

1. Explain in your own words what the three coordinates of a lamp in a room are, taking the corner where two walls meet the floor as the coordinate system, and how each could in principle be measured.

Hint: Think of the walls and the floor as three rigid surfaces at right angles.

Answer: The two walls and the floor are three rigid flat surfaces at right angles, joined into one rigid body. The lamp's coordinates are its three distances from them, and each distance 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 three things that happen when a pole is used to say where a cloud is, and say why the nature of a place statement has not changed.

Hint: Start from what a landmark on the ground can and cannot locate.

Answer: The rigid body is extended by the pole to reach the cloud; a number, the measured length of the pole, replaces a named landmark; and we speak of the height even when no pole exists, computing it from

photographs. The statement still names a point of a rigid body that the cloud coincides with, so its nature is unchanged.

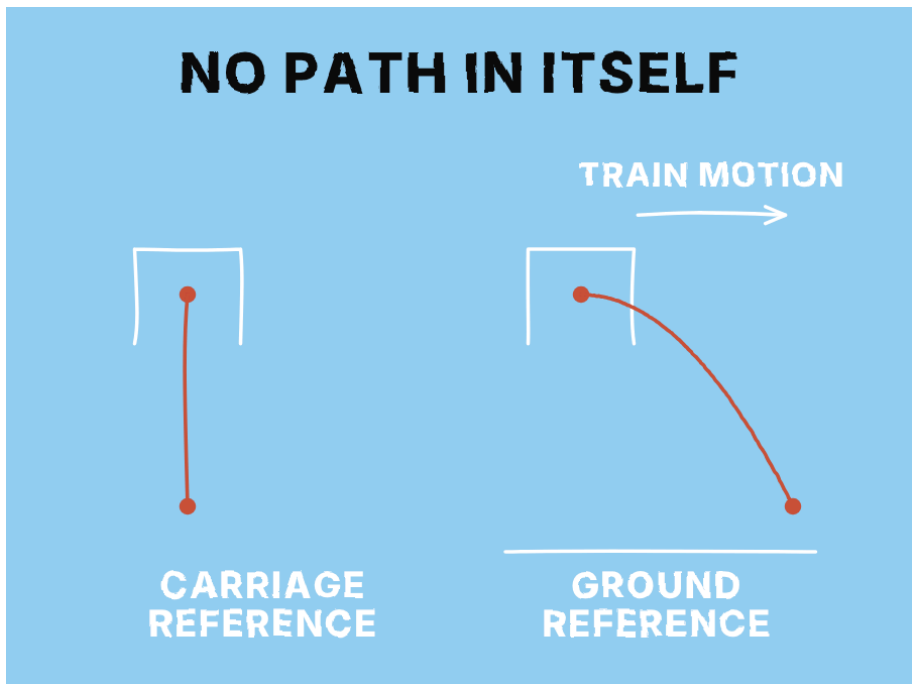
3. What assumption about geometry underlies every description of where things are, and where did this course first meet it?

Hint: Recall what was accepted on probation in the first part.

Answer: Every such description refers events to a rigid body and assumes that ordinary Euclidean geometry holds for segments, two marks on a rigid body. That is the physical truth of geometry accepted on probation in the first part, resting on imperfect experience, whose limits appear in the general theory of relativity.

No Path in Itself

Sit by the window of a smoothly running train and let a stone drop from your hand. You see it fall straight down to the embankment. A walker beside the track sees the same stone fall in a curve, carried forward with the train while it drops. One stone, two witnesses, two paths, and this section asks which of them is real.



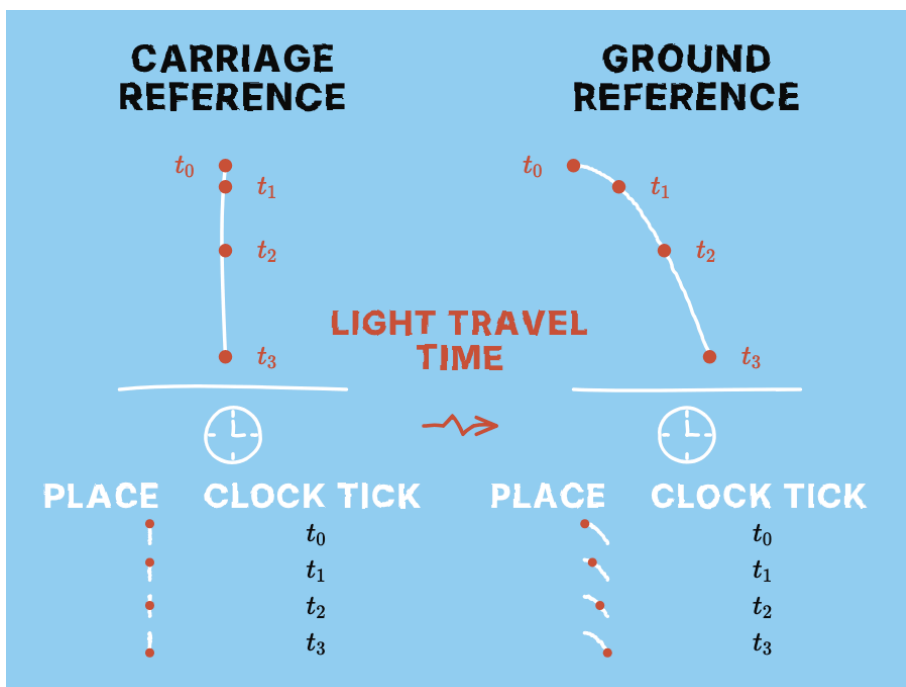
One Stone, Two Reference Bodies

Einstein begins by confessing that the usual statement of what mechanics does, describing how bodies change their place in space with time, sins against clarity. The trouble hides in the words "place"

and "space". Do the places the stone passes through really lie on a straight line or on a curve, and what does moving "in space" even mean?

One idea answers both questions. "Space", if we are honest, is a word we attach no clear idea to, so Einstein drops it and says "motion with respect to a rigid reference body" instead. Places with respect to a reference body are what the previous section taught us to give, 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, 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. Leave the reference body out of the sentence and the sentence says nothing. A satellite receiver lives by this rule; it reports your motion with respect to the Earth's surface, so a train passenger reads a hundred kilometres an hour while sitting still with respect to the carriage, and neither number is wrong.

What follows in practice is a second requirement. A path is not yet a motion; we must also say when the stone is at each point of it, and those times must be things that can be measured, not numbers assumed out of the air. In ordinary mechanics Einstein 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. A list of places paired with ticks is a complete description of the motion with respect to that reference body.



Pair Each Place With Time

Einstein closes with two warnings left for later: pairing a tick with a place ignores that light takes time to travel, 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 takes them seriously. Left out here are Einstein's notes on how a straight line is defined by least distance on a rigid body and on divided measuring rods; they are at the end of the third section. So this stretch of the book pauses where his 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 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. 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
 - b. The straight line, because the stone was given no push
 - c. Neither: there is no path in itself, only a path with respect to a reference body
2. Why does Einstein replace "motion in space" by "motion with respect to a rigid reference body"?
 - a. Because we attach no clear idea to the word "space", while places relative to a reference body were already defined
 - b. Because space is curved and cannot be measured
 - c. Because the train moves through space faster than the walker

- d. Because rigid bodies are easier to draw
3. What second requirement turns a path into a description of motion?
- a. The mass of the stone and the force on it
 - b. Saying when the stone is at each point of the path, as something that can be measured
 - c. The speed of the train with respect to the ground
4. How are the times obtained in ordinary mechanics, in Einstein's example?
- a. From a single clock on the embankment
 - b. By calculating from the height the stone has fallen
 - c. From two identical clocks, each observer noting where the stone is on their own reference body at each tick
 - d. By timing the light coming from the stone

Answers

1. **c)** Neither path is the real one with the other an illusion; there is no path in itself, only a path with respect to a particular reference body.
2. **a)** Space, if we are honest, is a word we attach no clear idea to; places with respect to a reference body are what the previous section taught us to give.
3. **b)** A path is not yet a motion; we must also say when the stone is at each point of it, 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 with the passenger and one with the walker, and each notes where the stone is on their own reference body at each tick of their own clock.

Practice

1. Describe the stone's 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 describing 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. Why is a list of places paired with clock ticks a complete description of the motion, while the path alone is not?

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

Answer: The path alone says where the stone passed but not when. The list gives the time at every point, and because each time is a tick of a clock in the observer's hand it is something measured, which is what a complete description requires.

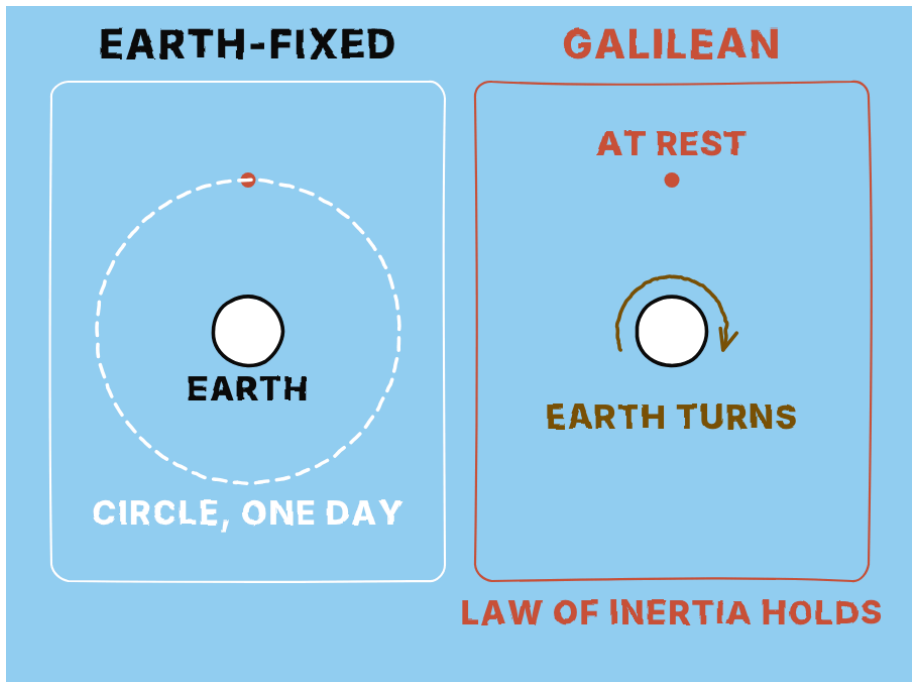
3. What two difficulties does Einstein set aside at the end of this section, and why can he afford to for now?

Hint: Think about how the walker sees the stone at the instant of a tick.

Answer: Pairing a tick with a place ignores that light takes time to travel, so the stone is seen where it was a moment ago; and a second difficulty is lurking that he does not yet name. He sets them aside because he is standing on the ground of ordinary mechanics for now, and promises to treat both at length later in the book.

Which Reference Bodies Are Allowed?

A camera left open on the night sky for an hour shows every star as an arc of a circle, though nothing is pushing the stars at all. This section answers one question: which reference bodies may physics use to describe motion?



Circles Or Rest

Everything rests on the law of inertia: a body far from all other bodies stays at rest or moves uniformly in a straight line. Since a path is only a path with respect to a reference body, the law is also a rule about reference bodies. With respect to a system fixed to the Earth, the fixed

stars circle once a day, against the law as worded; Einstein keeps the law and gives up the Earth as a reference body.

What follows in practice: motion may be referred only to reference bodies with respect to which the fixed stars do not circle. Such a system, one in which the law of inertia holds, is a Galilean coordinate system, and the mechanics of Galileo and Newton claims validity only for those. Satellite navigation computes its orbits in such a system, axes fixed on the stars, before translating to the turning Earth. Left out here is only Einstein's phrasing of the law itself; it is in the fourth section of the book. So the first four sections end with the reference bodies sorted, and that sorting is where the rest of the book begins.

Remember

The law of inertia is a rule about reference bodies as much as about bodies. The Earth is not one in which it holds, since the fixed stars circle with respect to it. Reference bodies in which the law holds are Galilean coordinate systems, 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.