PART I

RELATIVITY

Albert Einstein's theory of relativity has the reputation of being archly difficult and unfathomable, but the basic principles of the special theory of relativity are actually not. They are easy for anyone to understand. The big problem is that they go completely against our intuition. When you first hear them, you immediately think: it can't be! And yet it is. That's the first step you have to take to understand special relativity: accept that sometimes physical reality works very differently from what we encounter in our daily lives.

The basics of the special theory of relativity can be summed up in two sentences. Are you ready for them? Here they come:

1. If you move very fast, time slows down.

2. If you move very fast, lengths get shorter.

Voilà, that was it.

But you probably want a little more explanation. To understand what the hell bo- ving the two sentences below mean, you will have to accept some new rules of physics. Rules that your intuition will be quite opposed to. That's because our sense of reality is based entirely on what we experience as human beings. In our entire evolution we have never encountered speeds of hundreds of thousands of kilometers per second, or gravitational fields like that of a black hole.

So accepting new rules is difficult. Hearing about the special theory of relativity for the first time I like to compare to a soccer team that suddenly finds itself on a rugby field and has to play against a rugby team play. There will be great consternation when the opponent is suddenly allowed to get their hands on the ball, when someone is brutally worked against the ground without a whistle, or when a goal is approved when someone kicks óver the goal. You can then either get very angry, or accept that you are now on a rugby field, adopt the rules, and play along. This also applies to the rules of relativistic theory, which I will explain later.

But first, let's just start on our physics soccer field, with the rules from our own environment. Suppose you have a speedometer. If you are standing still somewhere and a car passes by at fifty kilometers per hour, you can measure that with that. But what if you are on a bicycle and you are going twenty kilometers per hour? Now you are overtaken by a car going fifty kilometers per hour and you measure its speed from your moving bicycle. What will appear on the speedometer's screen? Indeed, thirty kilometers per hour. Simply the difference between the speed of the car and your speed on the bicycle.

It also works in the other direction: you cycle at twenty kilometers per hour, and a car going fifty kilometers per hour crosses you from the opposite direction. Now what speed will you measure when you point your me- ter at the car? Seventy kilometers per hour. In our daily lives, we can simply add and subtract speeds. The old trust- ing rules of our physics soccer field.

But now suppose we travel faster, with a rocket, for example. And from the other direction comes not a car or another rocket, but light. Light travels at a speed of three hundred thousand kilometers per second (actually 299,792,458 meters per second to be precise). Now suppose our rocket flies at a slightly slower speed, say two hundred thousand kilometers per second. To be clear, that is a completely technically unrealistic speed for rockets, which go at most around ten kilometers per second - this is a thought experiment. So we fly at two hundred thousand kilometers per second and are overtaken by a beam of light going three hundred thousand kilometers per second.

send kilometers per second flying. Now if I measure from my rocket at what speed that light passes me, what do I measure?

What do you think, a hundred thousand kilometers per second?

That is indeed what you would expect based on our classic "foot-ball rules. But if you were to measure it in reality, the result would be surprising: three hundred thousand kilometers per second. Strange ... whether you are standing still or moving very fast along with light, it keeps passing you at that same speed of three hundred thousand kilometers per second.

Briefly reversed: we are flying at two hundred thousand kilometers per second and a beam of light crosses us from the opposite direction. We now measure the speed at which the light passes our rocket. What do you think? Five hundred thousand kilometers per second? No, in other words. Again, you would measure three hundred thousand kilometers per second.

Whether you fly very fast toward light or fly along with it, it always passes you and from all directions at the same speed: three hundred thousand kilometers per second.

Chances are your internal soccer player is protesting right now. Impossible! Hands! Penalty! We are now in the physics back by square of special relativity. The rules are different here. Breathe in and out deeply and accept them.

Now I freely admit that just "accepting" is not really enough here, because it also just doesn't seem to make sense. Mathematically, it no longer works out that the speed of such a beam of light relative to you remains the same if you fly along very fast in the same direction. Our classical method in which we were just allowed to add and subtract relative speeds no longer works here.

They also realized this at the end of the 19th century, when this peculiarity of light was discovered. Many physicists pondered this fact, including the young Albert Einstein.

In 1905, he came up with the solution: the special theory of relativity. According to him, why does the speed of light remain the same even if you move in the same direction? Simple: because at high speeds time slows down and distances become shorter. You measure speeds, and thus the speed of light, in distance per time: kilometers per second. But if the distance and time itself change, that three hundred thousand kilometers per second can thus remain nicely the same.

Chances are that you are now firmly furrowing your brow and grumbling, "What kind of a Christmas trick is that, adjusting time and speed ge- live to make the formulas fit? That's what many thought with you when Einstein published his theory. Most scientists in his day believed nothing of it. More to the point: they didn't dare give him the Nobel Prize for it, because they thought the theory was wrong. He received the Nobel Prize for one of his other theories: the photoelectric effect. That is the phenomenon in which some metals can produce electricity when light falls on them. The operation of solar panels is based on this. So although the theory of relativity is much, much more important than this theory, they didn't dare give him a Nobel Prize for it because- that they didn't believe it yet.

Over the past hundred years, the theory of relativity has been tested and confirmed in hundreds of ways. So we can be pretty much sure: no matter how strange, this theory is correct.

1.1 THE DISCOVERY OF THE CONSTANT SPEED OF LIGHT

Light is a wave that travels at a certain speed, like waves on a surface of water or sound waves in the air. Before you can talk about waves, there must be something that waves, a carrier. Without a carrier, there are no waves. In the vacuum, there is no sound because there is no air that vibrates.

But if you assume that light is "something" that vibrates, you immediately get a lot of contradictions. Light comes from the sun to the earth, through the vacuum. If there is no air, people used to think, there must be something else that vibrates. Suppose we have not yet discovered exactly what, but we assume it exists and call it "the ether. The ether must be a very light matter, lighter than air, because the earth moves through it without friction or deceleration. Strangely enough, the ether also under- finds little trouble from the earth passing through it, no vortex, no swirl, nothing. The ether remains so still that one cannot but conclude that the ether is particularly heavy.

The ether cannot be matter as we know it, that much is clear. Is the ether, then, perhaps a kind of "checkered paper," a reference grid through which we move with the earth without interfering with matter in any way, just as you drive a car across a national border or across the equator?

We know that the earth revolves around the sun, that the sun moves within our Milky Way, and that the Milky Way in turn does not stand still either. The only thing really stationary, then, must be the ether. Find a way to measure the speed of the earth relative to the ether, and you know the exact absolute speed of the earth. If you can trace the earth's motion relative to the ether, you know exactly what path the earth is taking in the universe.

That is exactly what Albert Michelson and Edward Morley thought in 1887. With an experiment they tried to find out the objective motion of the earth, the motion of the earth relative to the ether. Send a beam of light back and forth in two directions, and see in which direction the light goes fastest. Michelson and Morley had one problem: No chronometer was precise enough to determine the exact moment a ray of light arrives somewhere, let alone measure the time difference between two arriving rays of light.

To do this, the two devised a brand new instrument: the interferometer. This is a device with which you can compare light waves. If a light ray travels faster in one direction than in the other, the waves of both light rays will be slightly shifted relative to each other. That is exactly what an interferometer can make visible.

Michelson and Morley discovered that light rays, no matter which direction they sent them, always took the same amount of time to return. That could mean only two things. Either the ether was stationary relative to the earth, and the earth was the only fixed point in the universe, or there was no ether at all, but light was a carrierless wave, with a constant speed.

Michelson and Morley didn't realize it yet, but they had just performed one of the most important failed experiments in history. Thanks to their research, an important device like the interferometer now exists, and-much more importantly-physicists came on the trail of one of the most peculiar properties of physical reality.

PART 1: RELATIVITY

Meanwhile, we know that 'the ether' does not exist. There is no 'reference axis' in the universe relative to which you have an absolute speed. All that exists are 'relative' speeds: the speed of something relative to some other object. Hence the term "relativity theory. The ether does live on in our language: 'sending something into the ether' means broadcasting it on radio or TV. This used to be done im- mers via large antennas that sent out electromagnetic "radio waves," which were thought to wave in the ether.

Just back to that speed of light that remains constant even if you move very fast toward it. Our math from everyday life, where we can just add and subtract speeds, we can't use now. To solve this, Einstein used the mathematics of Hendrik Lorentz, a Dutch physicist. With the Lorentz transformations, you can calculate exactly how much time and space change when you move with great speed.

On the next page are the formulas for the Lorentz transformations. Those with "math phobia" may just skip them. Mathematicsophobia is a harmless condition in which people go into standby from- onwards the moment a formula appears somewhere. A waiting music then plays in their head until normal words appear again. Don't worry, this in itself is a very simple formula that is easy to calculate with. You should always think: the formula is more afraid of me, than I am of the formula.

By the way, a mathematical formula is a wonderful thing. I think a formula is the closest thing to the concept of "magic spell" that you can get into this reality: a series of mysterious signs, indecipherable to the uninitiated, that if you know them can provide knowledge and possibilities that others do not.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad t' = \gamma \cdot t \qquad L' = \frac{1}{\gamma} \cdot L$$

v is the speed we have relative to the other object

c is the speed of light: 299,792,458 m/s

γ is the Lorentz factor, the number by which times and distances change for the object moving at the speed you enter into the formula.

The new length gets shorter by a factor of $1/\gamma$, and the new time goes slower by a factor of γ.

If an object moves at a certain speed relative to us, then we can enter that speed into the formula above, the lorentz factor formula. With that formula, we can figure out ach- ter how much slower time goes for the moving object.

Suppose a rocket flies by you at half the speed of light, then the Lorentz factor is 1.15. This means that if you see the clock in the rocket flying by ticking 1 second, then for you 1.15 seconds have passed. If the rocket flies at 0.87 times the speed of light (about 260,000 km/s), the Lorentz factor is 2. Flies at 0.99 times the speed of light, then it is already 7.09.

What does that mean in concrete terms? Suppose someone takes a space trip in a rocket that flies at 0.99 times the speed of light, while the rest of the world's population remains on earth. If that person flies around for four years and then lands back on earth, he will find that a period of thirty years has passed on earth in the meantime. So everyone here has aged thirty years, while the person in the rocket has hardly changed at all.

That already sounds very strange, but there is more. Another consequence of the theory of relativity is that objects moving fast become shorter. The faster something moves, the shorter it becomes relative to the observer. A rocket flying by at 0.87 times the speed of light is half as short as if it were just lying still on the ground next to the observer. You can calculate that too with the Lorentz formula. It's not like that rocket is being crumpled. Should you be in the rocket and flying along, you don't notice anything at all and the length of the rocket remains the same for you. But if you are standing still and the rocket passes you, it is only half as long. This is not a trick of sight, but a property of space. It really is. It is also important to know that the rocket is shorter because space itself is shorter. Whoever is in the rocket shortens with it and thus does not notice any difference.

Bon, it is sometimes said that men who drive their pathetic cars too fast have shorter dicks. According to the theory of relativity, that already appears to be true.

You could also conclude that a space trip is the ideal fall- tine gift for married couples: your partner gets thinner, stays young longer, and you also just lost them for thirty years.

MOVE AT LIGHT SPEED

The closer the speed of an object approaches the speed of light, the larger the Lorentz factor becomes. In fact, if you enter the speed of light itself into the formula, the factor becomes infinite. Therefore, no object with mass can reach the speed of light. If you already have a certain speed, the energy required to go even faster increases as you get closer to the speed of light. To reach the speed of light, the energy required is literally "infinite.

Particles without mass can move at the speed of light. More to the point: they cannot move otherwise. Photons have no mass, so light always travels at the speed of light.

For convenience, we assumed two different worlds: the world we know, and a world in which speeds of one hundred five thousand kilometers per second are no exception. We compared one world to a soccer field, in which we, as soccer players, know perfectly well what to expect. The other world with the "relativistic speeds" was the rugby field, where we have to get used to the new rules. But there are actually no two worlds.

The theory of relativity applies not only at very high speeds, but also at speeds we are used to, such as, for example: fifty kilo- meters per hour. The only difference is that when a car overtakes a cyclist, the speeds used are so small (compared to the speed of light), that the Lorentz factor you obtain with that speed difference is very close to 1. Enter fifty kilometers per hour (0.014 kilometers per second) yourself and calculate γ. That's as close as 1. So, does time go slower when you fly in an airplane at nine hundred kilometers per hour? Yes. But so imperceptibly little that you never feel it. An atomic clock, however, which can measure billionths of a second, does notice it. In 1971, in the Hafele-Keating experiment, several atomic clocks were flown around the world in airplanes, and then compared with atomic clocks that had remained in situ. As it turned out, there was effectively a time difference between the clocks, and it perfectly matched the time difference predicted by the theory of relativity.

Einstein was a genius. He was 26 years old when he came up with all this: four brilliant theories in four branches of physics, while not even holding a position at a university. He just had a desk job in a patent office. Fortunately, he lived with a brilliant mathematician and physicist: his first wife Mileva Marić, with whom he could discuss and work out his theories.

THE SPEED OF LIGHT: C

So the speed of light is 299,792,458 meters per second. In physics, this is written with the letter c. If you see c in a physical formula, it stands for 299,792,458 meters per second. For example, in E = mc2.

But actually this physical quantity is much more important than en- kel the speed of light. You could say that c is the maximum allowed speed in the universe, not only for matter but also for force, energy... Actually, it is the maximum allowed speed for any influence.

The consequences of an event can propagate throughout the universe at maximum speed c. Light is such a consequence. If you light a lamp in one place, the light you see in another place is a consequence of it. So that "influence" travels through the universe with the speed c. But the same is true for gravity, for example.

Earth is eight light minutes from the sun. The sun's light takes eight minutes to reach us. But the sun's gravitational force also takes eight minutes. Suppose the sun were to suddenly disappear at this time, the earth would remain in its orbit around the sun for another eight minutes, and only then begin to fly straight ahead.

So the term "speed of light" is actually too specific for such a generally applicable speed limit. Like calling the speed limit in built-up areas the "Ford Fiesta speed" when it applies to all other cars as well.

THE PARADOX1AND VA N2THE

RELATIVITY

When you want to apply the rules of the theory of relativity in certain situations, you sometimes encounter an apparent contradiction; something that doesn't actually seem possible. We call this a "paradox of relativity theory. These paradoxes are not "errors in the theory. In fact, they do not show that the theory contradicts itself, but rather that relativity theory has consequences that contradict what we intuitively perceive as 'logical'.

THE ROCKET IN THE BARN

Suppose you have a twelve-meter rocket that can accelerate to 0.87 times the speed of light (about 260,000 km/s). At that speed, the Lorentz factor is 2, so distances moving at that speed relative to us are only half as long.

You also have a ten-meter-long barn, with a large gate at the front and back. When the gates are open, you can fly the rocket through the barn. There is something else special about these gates: when you push a button, they close for one billionth of a second, and then immediately open again.

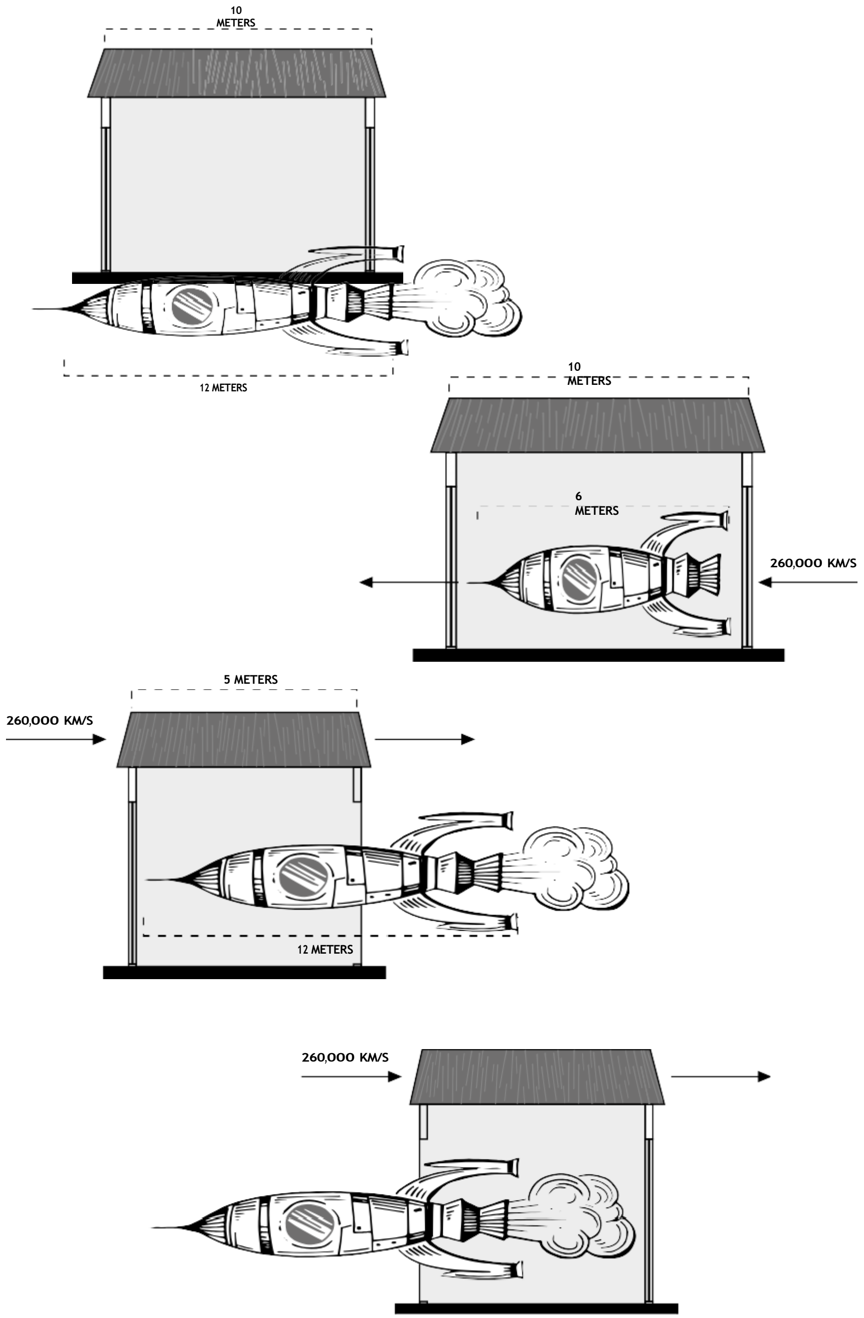
We ask a test pilot to fly the rocket through the open gates of the barn at two hundred and sixty thousand kilometers per second. When we stand next to the barn, that rocket has become shorter for us, by the rules of relativity theory. For us, it is only six meters long. That means that from our point of view there is a moment

is that the rocket fits completely inside the shed. Thus, if we push the button at that moment, for a billionth of a second we have a twelve-meter-long rocket locked in a ten-meter-long barn. That is bizarre, but it is not yet a paradox.

Let's look at that same situation from the pilot's eyes. He is sitting still relative to the rocket, so it remains twelve meters long in front of him. But in front of him, the barn passes by at two hundred and sixty thousand kilometers per second. So for the pilot, the barn is not ten meters long, but ... five meters long. That's crazy, because we pushed a button, and then those gates closed and opened with the rocket in the middle of the barn. From the pilot's point of view, this doesn't seem possible.

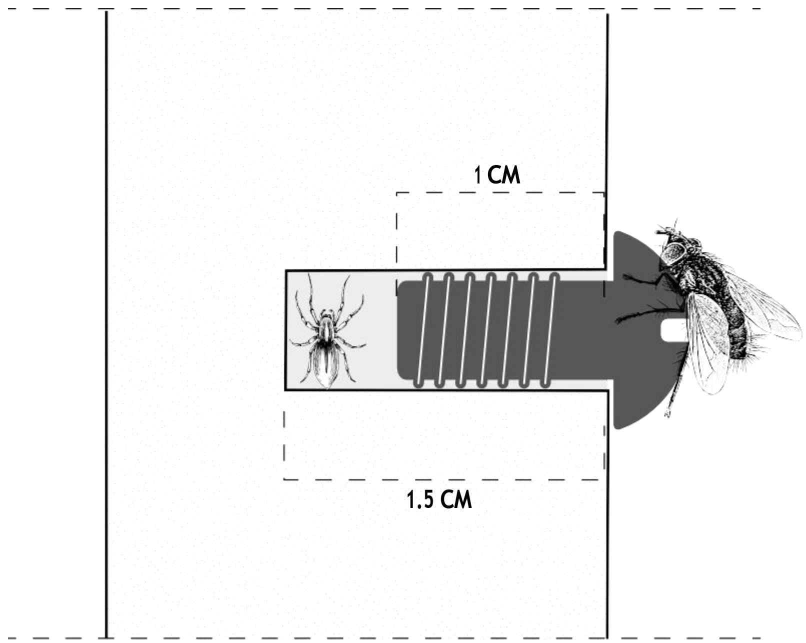
The solution to this paradox? Actually, we forgot to mention a third effect of the theory of relativity, besides slower time and shorter lengths: things that happen simultaneously for someone standing still do not happen simultaneously for someone moving very fast. For us, both gates were closed simultaneously, but not for the pilot. He saw the front gate close just before he went through it, and a little later only the rear gate when he had just passed through it, and the head of the rocket was already sticking out of the front gate for some distance.

That's why it's called "relativity"; you have to view everything relative to the observer.



THE SPIDER AND THE FLY

In a wall there is a hole and in it lives a spider. The hole is one-half inch deep. We also have a nail that fits exactly into the hole, to a depth of one centimeter. It doesn't get any further, because it ends on a head wider than the hole. The spider is in the last half-centimeter of the hole, and so is not bothered by the nail. Now a fly passes by with a nefarious plan: it wants to squash the spider. That doesn't seem to work with the nail, because it doesn't get deep enough into the hole.



But what if the fly takes a run-up, and flies together with the nail to the wall at two hundred and sixty thousand kilometers per se- conde? Relative to the fly, the hole is now no longer one and a half centimeters deep, but only 0.75 centimeters! Hooray, thinks the fly, that spider is going to die. But what does the spider see? It sees a fly and a spider coming towards it. They move so fast that they are shorter for the spider.

have become. For the spider, the nail is not one, but only half an inch long. Ha, thinks the spider, nothing can happen to me in my hole one and a half centimeters deep.

Again: an apparent paradox. Is the spider crushed or not? In retrospect, it cannot be both dead and alive. That is only allowed in quantum mechanics, and that is for another chapter.

The answer: the spider is dead. From the fly's point of view, it already was. But what happens from the spider's point of view? The fly moves toward the hole with the nail until the head of the nail touches the side. That is the signal for the nail to stop flying. But that signal, that "influence," can only be transmitted at the speed of light to the rest of the nail. And that itself is already flying at 87 percent of the speed of light. So before the 'influence' of the head of the nail has caught up with the end of the nail, it has had enough time to still get to the bottom of the hole and crush the spider.

And actually even more happens: coming to a standstill from two hundred and sixty thousand ki- lometers per second is a gigantic deceleration. With very large acceleration (and thus deceleration, which is "negative deceleration"), a new theory of relativity comes into play: the general theory of relativity, which Einstein published in 1916.

PART 1: RELATIVITY

THE GENERAL1E REL AGIMYHORY

The special theory of relativity is about the things that happen when you move at high speeds relative to each other, thousands to a hundred thousand kilometers per second. It was published by Einstein in 1905. It assumes that we cannot distinguish between motion and rest: if I am moving relative to you, you might as well say you are moving and I am standing still. Everything moves 'relatively ' relative to each other; there is no absolute zero point. The only thing that is fixed is the constant speed of light in vacuum, which is the same for all observers.

In 1916, however, Einstein published another theory of relativity: the general theory of relativity. Here we are not only talking about high speeds, but also about acceleration, i.e. change of speed, and about great gravity. With acceleration and gravity, very other effects occur, such as curvature of space. With great acceleration and great gravity, time also slows down. At the edge of a black hole, gravity is so great that time stands still there.

General relativity is a lot more complicated mathematically than special relativity, so unfortunately it doesn't fit in this booklet. But we do have to deal with it every day: the GPS satellites orbiting the earth feel a lower gravity at that altitude than we do here on earth. As a result, for these clocks, time runs faster. The difference is very small, but the electronics of GPS systems calculate so quickly that they are affected. A GPS satellite's clock is constantly adjusted according to the rules of general relativity, otherwise the GPS in our car or on our phone would locate us many miles away.

If you would prefer a directly observable proof of the general relativity theory, that also exists: the orbit of Mercury around the sun. Planets have elliptical orbits around the sun, and this elliptical shape itself rotates slowly through the ages. This can all be perfectly predicted by classical Newtonian mechanics. But the orbit of Mercury, the planet closest to the sun, shows a systematic deviation from that calculation. As it turned out, due to the sun's great gravity, time goes slightly slower there, and space is slightly curved. The deviation corresponds perfectly to what is predicted by the theory of relativity.

SCIENCE COMEDY

A few years back, I toured for a while with a comedy show about the special theory of relativity. So if you want to get the whole explanation a little more elaborate, with bits of stand-up comedy in between, you can find this show on my YouTube channel, under the title *The Special Relativity of Einstein*.