Understanding the special theory of relativity

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Abstract

This paper constitutes a background to the paper Quantum mechanics as "space-time statistical mechanics"?, arXiv:quant-ph/0501133, presented previously by the author. But it is also a free-standing and self-contained paper. The purpose of this paper is to give the reader an increased and a deeper understanding of the special theory of relativity, and the spacetime ideas lying behind the above mentioned paper. We will here consider, discuss, define, analyse, and explain things such as, e.g., the constancy of the speed of light, synchronization, simultaneity, absolute simultaneity, absolute space and time, the ether, and spacetime. Albert Einstein’s original version of the special theory of relativity is fundamentally an operational theory, free from interpretation. But the old "Lorentzian interpretation" and the standard "spacetime interpretation" of the special theory of relativity will also be considered. This paper also discusses and analyses aspects of the philosophy of science that in my opinion are relevant for an understanding of the special theory of relativity.

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I. INTRODUCTION

The purpose of this paper is to give the reader an increased and a deeper understanding of the special theory of relativity. There already exist a great amount of literature about the special theory of relativity. Some of more mathematical character, but which are insufficient when it comes to an understanding of the theory. Others are more focused on the understanding, but seldom manage in a satisfactory way to give the reader just that. In my opinion there is missing a more gathering work on the understanding of the special theory of relativity. But also a work that in a satisfactory way explicitly considers, accounts for, defines, analyses and explains things such as, e.g., the constancy of the speed of light, synchronization, simultaneity, absolute simultaneity, absolute space and time, the ether, and spacetime. These concepts and definitions play an important role for the understanding of the special theory of relativity, which is something that seldom comes to light in the literature on theory of relativity.

This paper also discusses and analyses aspects of the philosophy of science that in my opinion are relevant for an understanding of the special theory of relativity. Albert Einstein’s original version of the special theory of relativity is fundamentally an operational theory, free from interpretation. But different interpretations of the special theory of relativity will also be presented. One interpretation is the one that came in connection with a work by H. A. Lorentz, before Einstein presented the special theory of relativity in 1905. Another more familiar interpretation, but which normally is not thought of as an interpretation, is the one that involves the concept of spacetime. This one came, due to Hermann Minkowski, after that Einstein put forward the special theory of relativity in 1905.

This paper is a mixture of, partly, information and knowledge I have obtained in connection to the special theory of relativity, mainly from literature; and,
partly, own analyses and how I myself have understood the special theory of relativity. This paper is the result of several years of thinking about the special theory of relativity, while I have really been working on other things. It has not been completely possible, and I have neither felt it to be really meaningful to try, to label every thought in this paper with a reference to its source. But references to works used, are given in the end of the paper.

This paper does not require that the reader is previously familiar with the special theory of relativity, but it makes it easier for the reader if this is the case.

This is a free-standing and self-contained paper. But it also constitutes a background to the paper [arXiv:quant-ph/0501133](http://www.diva-portal.org/kth/theses/abstract.xsql?dbid=4417) presented previously by the author. ¹

I will begin by giving a background to and an outline of the special theory of relativity. Some undefined concepts will appear in this background, but this will be remedied as we go along.

### II. BACKGROUND TO AND OVERVIEW OF THE SPECIAL THEORY OF RELATIVITY

In the end of the 19th century, physicists tried to understand and unite existing physical theories with observations that were available at that time. There were clues that the existing theories needed to be revised. During the 19th century there were more and more clues that light had wave properties. But wave properties were at this time only something that occurred in relation to a medium of some sort. When it, e.g., comes to sound waves, then they are a

¹ See also pages 39–51 of the author’s thesis, which can be downloaded at [http://www.diva-portal.org/kth/theses/abstract.xsql?dbid=4417](http://www.diva-portal.org/kth/theses/abstract.xsql?dbid=4417)
pressure phenomenon in air, and water waves are water in motion. Therefore it was believed that it had to be the same with light, since this also seemed to be a wave phenomenon.

But there were no observations of such a medium, or the *ether* as it was called. The ether was thought to exist everywhere and to be able to penetrate through all matter. Its nature had many similarities with Newton’s *absolute space*, which also was not directly detectable with any known measurement procedures or observations. There were different variants of theories that described how this ether was supposed to work and interact with other matter. One tried to measure and find signs that such an ether existed, but the attempts turned out to be fruitless or unsatisfactory in one way or the other. E.g., if the ether was a medium for wave motion like any other, then one expected that the velocity of light relative to the source, should be dependent on the velocity of the source relative to the ether. But there were no indications that this was the case. Instead there were indications that the speed of light, relative to *every* observer in constant uniform motion, always was the same, independent of the speed of the light source. These observational indications were hard to reconcile with the ether hypothesis, without at the same time giving the ether more and more strange properties. On the whole, these observational indications were hard to make compatible with everyday thinking and a classical physical description of reality.

The physicist H. A. Lorentz lived and worked during this time, and that before Einstein entered the scene. Lorentz changed the transformation laws for how space and time coordinates change when one changes *inertial reference frame*, i.e., reference frames or reference bodies that are in constant uniform motion, to make these consistent with the laws of electromagnetism. As a matter of fact, Lorentz arrived at *exactly the same* equations, the so-called *Lorentz equations*, as Einstein
later also did in his special theory of relativity. The difference between their presentations was in the way they had come to and interpreted these equations. The Lorentz equations describe how space and time must change for bodies in constant uniform motion. It follows from these equations that lengths are shortened and that time goes slower for bodies in motion.

The most fundamental difference between Lorentz’s interpretation and Einstein’s interpretation of these equations, was that Lorentz assumed the existence of an underlying absolute Newtonian space, whereas Einstein did not do this. According to Lorentz’s interpretation, there are bodies that really, truly, or objectively seen, are in absolute rest relative to the absolute Newtonian space; or relative to the ether, which in many respects plays a similar role to that of the absolute Newtonian space. The ”Lorentzian interpretation” means that for all bodies which move relative to the absolute Newtonian space, time objectively seen goes slower and lengths objectively seen become shorter than for bodies which are in absolute rest.

However, the Lorentz equations at the same time mean and enable that constant uniform motion relative to the absolute space cannot be detected by trying to observe such changes in lengths and time. The only effects which can be observed, are only dependent on the relative velocity between reference bodies. All reference bodies think that it is the time on other reference bodies that goes slowly and lengths are shortened. Below we will come back to how this ”illusion” is possible according to such an interpretation. For bodies in constant uniform motion relative to one another, the situation is thus completely symmetric and the same laws of nature hold for all inertial reference systems. This is in line with the Galilean principle of relativity, because ever since Galilei it has been known that the classical laws of physics are the same for every observer in a state of constant uniform motion. Only the relative velocity can be measured, and not
who "really is in motion" or who "really is at rest".

As time went on, it became more and more clear to Einstein that the ether hypothesis seemed to be superfluous and perhaps even incorrect. Einstein was strongly inspired and influenced by the physicist Ernst Mach, but also by others, e.g., the philosopher David Hume. One can perhaps say that Einstein’s approach to the problems concerning space, time and the nature of light, was an application of Mach’s philosophical ideas and view on science. As Mach did, Einstein also tried to explain physical phenomena without resorting to hypotheses that did not have support in observations. Newton’s absolute space, and the ether, were to Einstein hypotheses that did not have any direct support in observations, so perhaps they did not exist? In the spirit of Mach, Einstein assumed that there was no underlying ether, or absolute Newtonian space. Einstein generalised the Galilean principle of relativity to include Maxwell’s theory of electromagnetism.

However, strictly seen there can only be motion relative to other bodies, if one only wants to define the concept of motion based on what one can observe. But if all motion is relative, what does one really mean when one says that a reference body is in a "state of motion" or in "constant uniform motion", if one does not at the same time specify relative to what the reference body moves?

Einstein was completely clear about and aware of these problems. In spite of this, he kept in the special theory of relativity the idea that bodies can be in a state of constant uniform motion, without one having to specify something that they should be in motion relative to. The special theory of relativity is limited to hold only for inertial reference systems. In a way this means that Einstein kept some sort of absolute space concept after all. Thus, in the special theory of relativity, the concept of absolute motion is still there.
However, motion is only absolute for bodies in accelerated motion. And Einstein did not think of it as motion relative to an absolute Newtonian space, because in the special theory of relativity there is no such thing as an absolute Newtonian space. There are no privileged inertial reference systems in the special theory of relativity, i.e., no inertial reference system can be said to be in absolute rest. But the inertial reference systems can be said to be in a state of ”absolute” or objective constant uniform motion. It was first with the general theory of relativity that there was no absolute motion at all. All states of motion and reference systems are equivalent in the general theory of relativity, no matter how the reference bodies are moving. The difference between the special and general theory of relativity is that the latter one includes acceleration and gravitation, whereas the former does not.

The special theory of relativity must therefore keep an element of absoluteness in the form of constant uniform motion, i.e., inertial reference systems as privileged reference systems when it comes to formulating laws of nature. In the general theory of relativity, inertial reference systems are no longer privileged reference systems. There are no privileged reference systems at all in the general theory of relativity and the laws of nature are the same in every reference system.

III. THE NEWTONIAN WORLD VIEW

An interesting question is whether the idea or notion of the absolute Newtonian space is something Newton invented and since then has indoctrinated all of us with?

Or is it perhaps something biologically given to us all and for that reason we experience it as right? A concept that Newton only refined and then could use to
formulate and make his physical ideas more exact?

Personally I tend to think that the second alternative is the right one, but that also the first alternative has had a great significance and influence on our thinking. The notion of the Newtonian space has become so natural to us that it would be difficult to free ourselves from it, even if we wanted to. I would say that this is because the "Newtonian approach" agree well with our everyday understanding of space and time.

What do I then mean by the absolute Newtonian space? Well, one could think of it as a (infinitely) large empty space, room, or void. Like a gigantic box or aquarium without walls that contains a huge empty space. This space has a geometric and metric structure, given by forming a coordinate system consisting of three coordinate axes - height, length and breadth. The coordinate axes are perpendicular to each other and the coordinates are usually denoted by $x$, $y$, $z$; i.e., a Cartesian coordinate system (see figure 1).

Now it is actually not the space in itself one experiences, but instead all the objects that fill up the space, such as galaxies, planets, cars, humans, atoms and light. The space in itself cannot be experienced directly. The existence of an empty space and its hypothetical effect on the objects filling up the space, can only be experienced indirectly by experience the objects themselves and how they move or "want" to move in relation to other objects. The empty space in itself is something one imagines to exist.

One could think of the empty space as something that exists irrespective of if there is something or not which "fills up the empty space". So even if one would remove everything which is "in the empty space", one could still imagine that
there would remain a three-dimensional empty space with a geometric and metric structure that gives the distances between positions in the empty space. (We are here coming in contact with questions having to do with what we consider to be real or unreal, which is something we will came back to below.)

However, the physical objects that are in the empty space, do not just stand still in space, but can also move. It is in particular here that time enters the picture, even if there is also a meaning in speaking of time, and that one can have a subjective feeling of a time in motion, even if one does not see any objects in one’s surrounding which are moving. Time is, of course, measured on a clock, but in the Newtonian world view one imagines that there exists an ideal \textit{absolute time} that ticks on at the same rate independently of what there is, and what is happening, in the absolute Newtonian space. How physical objects are moving
in space, one can describe by giving their space coordinates \( x, y, z \), for every moment in time \( t \) on the absolute time.

The absolute Newtonian space is like a snapshot of the spatial three-dimensional space at a certain point of time on the absolute time. Only the three-dimensional spatial space at the moment of time "right now", i.e., the present or now, has an existence (see figure 2). Thus, for all other points in time the spatial three-dimensional space does not exist. Instead these snapshots of the spatial space belong to the past or the future, which means that they have either previously existed or have not yet come into existence, respectively. In other words, reality exists only "one moment at a time".

There is another property that characterize the absolute Newtonian space. Already Galilei knew that it is not possible to speak about absolute motion for unaccelerated bodies, i.e., for bodies in constant uniform motion. For imagine
that you are on a train which is at a train station and that you look out through the window. If one sees that a train on the neighbouring track moves, it can sometimes be difficult to tell whether it is the train one is on, or if it is the other train which is in motion relative to the train station, if one, e.g., does not feel any vibrations due to the motion of the train one is in, and if one does not see the ground or the train station. In the same way it can be hard to separate the situation in an airplane at an altitude of 10 000 meters flying at 1000 km/h, from a stay in a sofa at home in one’s living room, if it was not for the fact that one, e.g., heard the sound or felt the vibrations from the engines of the airplane and the air friction on the fuselage. Also remember that the Earth is moving around the sun with great speed, and that the solar system in its turn is moving around the Milky way, and so on, without us sensing it.

All the above mentioned, are examples of that only relative motion can be observed when it comes to bodies in constant uniform motion. Therefore, when it comes to unaccelerated motion, one cannot tell who or what, ”actually” or ”really”, is moving or is at rest. Neither is it possible to say who or what, is really moving or at rest, relative to empty space, whatever that would mean?

What is the situation then, when it comes to accelerated motion? Can one in this case tell who or what is really moving? Suppose that two space ships are at rest relative one another. One of the ships starts its engine and thus begins to accelerate, as the passengers experience through that they are pressed against the back of their seats and that things that lie loose, or float freely, are set in motion. The passengers on the other space ship, of course, do not feel any acceleration. Or consider a rotating body in empty space. A person on this body will experience a centrifugal force. These kind of effects can reveal if one’s reference body accelerates or not.
But if there only is relative motion when the motion is uniform, why is there not also only relative motion when the motion is accelerated? Relative to what is, e.g., the spaceship accelerating in the above example? And relative to what is a planet rotating? To be able to handle these kinds of problems, Newton imagined that bodies that are accelerating or rotating, are doing this relative to an underlying empty space which is in absolute rest, which is what we call the absolute Newtonian space. However, all bodies in constant uniform motion relative to this absolute space are equivalent. I.e., reality looks the same and all laws of nature are identical relative to such reference bodies or reference systems, so-called *inertial reference systems*. Only relative to such privileged reference systems, the laws of nature in classical physics hold.

In presenting his general theory of relativity, Einstein generalised this Galilean principle of relativity to also hold for accelerating reference bodies. According to this ”generalised Galilean principle of relativity”, the laws of nature are the same relative to all reference bodies no matter how they move. That Einstein was able to do this, is because he put an equality sign between the effects of acceleration and a gravitational field.

**IV. THE CONCEPTS OF SPACE, TIME, AND SIMULTANEITY**

What is actually meant by ”right now” when one speaks of ”everything that happen right now”? If the speed of light was infinite, then one would *see* something happen in the same instant as it *occurs*. However, it is true that the speed of light is very large, more precisely 300 000 000 meter/second, but it is not infinitely large. This means that if one sees something happen, it does not occur at the moment one sees it happen, but rather it occurred at an earlier moment.
In the same way it is with sound, which also propagates with a finite speed. To hear something, therefore does not mean that what one hears, also happens at the moment one hears it, which the everyday phenomenon of echo clearly demonstrates.

If one, e.g., takes a photo of a mountain from a couple of tens of kilometers distance, then it is not how the mountain really looked when one took the picture, but strictly seen how the mountain looked a couple of ten or hundred thousands parts of a second before one took the picture. In everyday terms this is, of course, a very short time. But on an astronomical scale there is a big difference between that something occurs and that one sees it occurring. The stars and galaxies as we see them, are usually how they looked several years ago. Exactly how many years ago of course depends on how far from us they are. E.g., a supernova that we see in the starry sky, could have happened when Newton lived, but on Earth we did not see it happen until now.

Therefore is, strictly seen, everything that we experience in our surroundings, not something that occur in the moment of time we experience it, but instead something that occurred at an earlier point in time. But when it comes to everyday phenomena which happen here on Earth, and I then primarily think of phenomena which involve light (or more generally electromagnetic radiation), one in practice sees and experiences things at the same moment as they occur. The time it takes for the light to go from where it was sent to where it is registered, as, e.g., an eye or a camera, is so short that for most practical purposes one can ignore it. In practice we can therefore say that, at the moment in time when the picture was taken, the mountain really looked as it does in the photograph.

Perhaps one can in this find an explanation to or support for the idea that absolute simultaneity and a ”Newtonian world view” could be innate notions about
reality. Since the speed of light in practice seems and can be taken to be infinite, evolution could have equipped us with a conception of reality that does not take into consideration the fact that the speed of light actually is finite. What we can see “right now”, could then be something that we also imagine occurs ”right now”. Our subjective or personal present would then not be limited only to ourselves and our closest surroundings, but would include the whole space that we can see; which in principle could be unlimited, i.e., infinitely large.

That we always must take into consideration the fact that the speed of light is finite, to determine whether two events occur at the same time or not, is something we historically seen from relatively modern scientific progress are aware of, but which I think we dismiss as a practical and not as a principal problem. In other words, we imagine that it in principal really is meaningful to speak about the simultaneity of two events, despite the fact that we consciously or unconsciously suspect that we would probably get ourselves into practical problems and difficulties if we actually would try to determine whether two specific events are simultaneous or not.

But if what we see, does not occur at the moment we see it occurring, is it then really meaningful to say that two (or more) events in space occur simultaneously? For what does one really mean when one says that two events occur simultaneously? Concretely, what would you do, if you wanted to determine what happens simultaneously somewhere else in the world or universe? Is it at all possible to determine that? In other words, is it really meaningful to wonder about what happens somewhere else in the world or the universe ”right now”? By ”right now” I mean exactly at that moment when one wonders about what happens somewhere else in the world or universe.

If one thinks that it obviously is meaningful to speak about the simultaneity
of two events, without having to specify more closely what one means by this, one probably has an unconscious notion of **absolute simultaneity** in the back of one’s head. But absolutely simultaneous relative to what? Well, relative to something objective. And what would this objective thing be if not an absolute space, in relation to which events are absolutely simultaneous!? But to make it more clear, and hopefully also more convincing, what I say and mean, let us make an attempt at analysing the origin of the concept of **absolute simultaneity**.

However, before doing this, let me first define what is meant by an **event**. An **event** is defined as a designation of **where** (i.e., the three space coordinates relative to a reference body) together with **when** (i.e., the point in time) something occurs. The three-dimensional (spatial) space we can imagine as a "crystal structure" or "lattice" of perpendicular measuring rods (with some suitable length unit). However, we must be more precise about what we mean by the "point in time" when something occurs, i.e., according to which clock? Well, according to the clock which is at the position in space where the event occurred. In practice there is, of course, no clock, and it would be impossible to place a clock, at every position in space. But in principle we can imagine it to be possible and that we have placed a clock at every position in space where the measuring rods meet in the "lattice" (see figure 3).

If one does not have too high thoughts about oneself or is not too philosophical, it is natural to believe that one’s own existence is not more unique or more special than anybody else’s. A reasonable assumption is that other people exist to the same degree and fundamentally in a similar way to how we experience ourselves. Let us therefore assume that other persons experience time in the same way as we ourselves do. I experience the present, remember the past, and the future is something that has not yet come into existence. For me only the subjective or
The personal present is something I experience to exist. I exist in one and only in one moment in time, and that is the personal present. I therefore imagine that others experience time in the same way.
A person’s existence can be connected with the position or place in space where this person is. Because, the place in space where I am at, e.g., the ground under my feet, in principal constitutes a physical extension of my own body, i.e., an extension of myself. I thus experience and imagine that the place in space where I am at, exists in the same way as I myself exist. Hence both I and the place where I am at in space, exist in the personal present.

The personal present corresponds to a specific point in time, which can be read on the clock located in space where I am at. So instead of talking about the personal present, one could just as well talk about the time that a person in his personal present reads on his clock; where by "his clock" is meant the clock located where the person is located in the three-dimensional (spatial) space. Let us call this point in time the local present. The local present is thus the point in time corresponding to the personal present; or in other words, the point in time which the personal present constitutes. Just as the personal present is connected to a certain person, the local present only has a meaning, if one also gives the position in space of the clock that one refers to.

Now there can in principal be a person at every place in the three-dimensional (spatial) space. One can therefore imagine that there is an existence of a personal present at every place in space. But the place in space where one is at, we said that one could regard as an extension of oneself. And the personal present can be replaced by the local present on the clock located where one is at. So instead of speaking about that "a person exists in a personal present at a place in space", one can therefore think away the person’s existence and only speak about "a place in space that exists in the local present".

But how are all these instantaneous existences of places in space related to
one another? We have imagined that every place in space only exists in the local present. The totality or general picture of all these places’ instantaneous existences is one single connected and unitary snapshot of a three-dimensional spatial space.

In this way the notion of *absolute simultaneity* and an *absolute three-dimensional spatial space* could have arisen. So despite the fact that we only experience the space in our closest vicinity or surroundings at a single moment in time, the personal present, we imagine that there exists one single (infinite) three-dimensional (spatial) space which exists at one single moment in time in common to us all - one common personal present. An idea of absolute simultaneity thus seems to be the price one has to pay if one imagines reality in the above described way.

Since the experience that we only exist in a subjective or personal present feels so obvious to us and is so deeply rooted in us, normally it does not even occur to us to contemplate, even less question, this experience or notion. But once we have become aware of this notion and how closely associated it is with the concept of absolute simultaneity and absolute space, we can also begin to question and try to change this conception. This could give us more freedom in forming concepts and thus how we construct our theories that describe reality. By questioning the concept of simultaneity Einstein made it possible for himself to get away from the assumptions of Newton’s absolute space and the ether. Einstein approached the problems connected to the mysterious nature of light from a philosophical point of view that was influenced and inspired in particular by the physicist Ernst Mach’s philosophical approach to science and reality. Einstein eventually arrived at the same equations as Lorentz did, but with a different interpretation of the concepts of space, time and simultaneity.
Einstein was thus clearly influenced by Mach’s philosophical approach (but also by, among others, the philosopher David Hume). Mach denied in principle everything that was not observable or measureable. This lead, among other things, Mach to deny the existence of Newton’s absolute space, since this was immeasureable according to Mach. (It is true that this philosophical approach also lead Mach to deny the existence of the atom, but this is a story in itself which I wont go into here.) According to Mach, it was not meaningful to speak about the motion of a body in relation to an absolute space. He tried instead to explain the inertia of a body, and the effects of acceleration which arise relative to an accelerating reference body, as a consequence of the relative motion of the reference body in relation to all other stars, planets, etc; i.e., relative to the fixed stars.

At first sight, this can perhaps seem to be a rather strange, and maybe even naive, way to approach the problem of inertia and acceleration. But admittedly there is clearly an unsatisfactory element to base physics on concepts such as an absolute space and motion in relation to this space. Because the absolute space is hardly something that can be said to directly correspond to something in our sensations or observations of reality. E.g., one cannot see or experience a black empty space moving. For imagine that you are in empty space without any planets, stars, galaxies, etc, in sight. The black empty space around you looks the same regardless if you are at rest, are in uniform motion, accelerating or rotating. Regardless of your state of motion it is the same black empty space you experience and see before you. Newton’s absolute space is thus hardly something that can be said to correspond to something in our sensations or observations of reality. It only exists in our imagination and in our theories.
According to Einstein’s and Mach’s philosophical approach, we are not allowed - if we are to be consistent - to assume the existence of something that we cannot observe. There is something appealing, not to say obvious, to try to base physics only on things that find support in observations.

For has not the cast of roles been inverted, if it was to be us who should tell reality, which notions and concepts that should have a counterpart or a correspondence in reality, and not the other way around? Is it really our task to tell reality which concepts it should contain, and what should be real or not? For should it rather not be reality that should tell us what it is that exist and do not exist? Instead of trying to describe and explain reality on the basis of concepts we ourselves have created, should we not describe and explain reality only with concepts whose meaning is defined based on, and do not exceed or go beyond, what we can observe and measure?

But then, what about concepts and notions we have acquired or been equipped with through evolution? Because when the human body with its brain was formed through evolution, must not the concepts have been formed based on what was available for and could affect the constituents and building blocks of our brain? Or how could it otherwise have been or come about, seen from an evolutionary perspective? 2

If we speculate that in the brain there was created a notion of absolute simultaneity and an absolute space, did the brain then not go beyond experience and observations of reality? Possibly, but it is not difficult to come up with a

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2 Also our logic or logical reasoning is reasonably the result of evolution, and have been formed by how reality is and functions. But since logic is intimately connected with how we reason, our logic itself is more complicated (and probably partly impossible) to analyse and question, since we need logical reasoning to reason about logical reasoning. However, the aim here is not to get too involved or go too deeply into these sort of questions, so I will not go further into this here.
possible explanation as to why the brain could have done something like that. E.g., it perhaps made the world around it easier to grasp and thereby gave the body, that the brain was in, an evolutionary advantage. And us humans are not necessarily constructed through evolution to be able to experience and understand reality as it really is, but only to understand and control the everyday world in which our bodies for all practical purposes live in.

The hypotheses of the existence of the atom, or strings in string theory, are also examples of concepts that go beyond experience and what can be observered, at least when the concepts were first invented. But in spite of this, they are examples of concepts that have turned out to be successful. At least the atom, which is a hypothesis that has been strengthened more and more as physics has progressed. It should not be very controversial to say, that the hypothesis of the existence of the atom, has been accepted and in practice has been taken to be correct by a majority of scientists, as well as the rest of society. Then it is possible that atoms will never be felt or thought to exist in the same way as a football is experienced to exist. The atom is an example of a hypothesis which is not directly, but rather indirectly, based on observations. It is a concept which was created in order to be able to successfully understand, describe and explain observations. But as things progressed, the atomic hypothesis was supported, strengthenend and confirmed by more and more experiments and theories. The atom hypothesis was finally accepted and atoms thought to be something real. Therefore one cannot reject or discard a concept or notion just because it does not find support in today’s observations, knowledge and theories of reality.

What was described above, one could describe as two different ways of working or philosophies of science. Historically seen science has successfully used both of these approaches. There seems to me, to be a mutual interplay or symbiosis
between these two approaches. When it comes to the situation which was before Einstein and other physicists in the years that preceded the year of 1905, when Einstein presented his special theory of relativity, then with the result at hand, Mach’s and Einstein’s approach seems to have been the right one. But the ether hypothesis could just as well have turned out to be the right one.

Furthermore, is it not so that, what one takes as right or wrong often are after constructions? Because often it is only when one knows the result of something, that one with certainty can say what is right or wrong. Is it not so that, what really decides if we take something to be right or wrong, a matter of how successful this something turns out to be? And if something is successful or not, is strictly seen something that only can be judged afterwards, with the result at hand.

VI. WHAT IS REAL?

When one, as here, discusses philosophical and fundamental questions in physics, one easily comes into questions concerning what one is to consider as real and unreal. It is natural and one can hardly avoid to consider something as real if it directly affects our senses, as, e.g., the sun, a table, a glass of water, or an apple falling from a tree. (But if one wants to play the devil’s advocate for a moment and point out, or rather state, that one from a philosophical standpoint could argue that nothing is real. But on the person arguing for something radical like that, there is also the obligation on him or her to explain what he or she really means by such a statement. Then one could also ask oneself how successful or meaningful such an approach is when it comes to describe, predict, understand and explain what we experience and observe.)

When it comes to such things as, e.g., air, heat, smells, etc, it is hard to not also consider these as real, since they all can be observered with one or more of
our five senses (i.e., eyesight, hearing, smell, taste, and touch). But I would also say that air is not something we experience as real in the same way or to the same degree as we experience, e.g., a table as real. A table we can see, touch and feel, but also hear, taste and smell. It can affect all our senses. It is, e.g., also a more solid object, with a particular shape and position in the room, and it can clearly be separated from its environment. The air, on the other hand, we cannot see, taste or smell, but we can feel it and hear it. It is, e.g., more ephemeral and does not really have any shape, and it is not clearly separated from its environment as, e.g., a table is.

We can go one step further and also consider, e.g., gravitation, magnetic fields and different kind of forces as real. But why and with what right do we do this? One possible answer is that one often considers such, not directly observable, things as real, when they give rise to effects that can be distinguished or separated from "the natural order of things", by which is meant how things usually are and behave under normal circumstances. In the time before us humans freed ourselves from our directly earthbound life and came to look (more closely) at the stars, it probably appeared as obvious and natural that bodies always fall towards the ground. With the limited knowledge of the world one then had, it would not have been strange if one then did think that it was not needed anything real to cause things to fall towards the ground.

But with astronomy and the idea that Earth and the Sun are not the centers of the universe, and that bodies do not always fall towards the ground, one started to question one’s previous view and knowledge of reality. The natural order of things instead became that a body moves uniformly in a straight line, until it is acted on by forces, such as in a collision, or by frictional or gravitational forces. Forces could then be viewed as real since they constituted a deviation from how things normally
behave. With generally applicable laws and mathematical equations, Newton could with precision describe and explain the motion of bodies, planets, and stars, as a consequence of action of forces. It thus became convincing and natural to consider gravitation and gravitational forces as something real. However, nothing forces us to view gravitation or gravitational forces as something real, since they do not affect our senses directly. We observe gravitation only indirectly through its thought or hypothetical effect on something that does directly affect our senses and which we therefore can perceive.

Consider, e.g., an apple falling towards the ground. We do not here perceive, experience or observe gravity in itself, but only the apple and its motion relative to other objects. Gravity is something we imagine exists and that it pulls the apple towards the ground. It is true that we can feel that something pulls us towards the ground. But if I, e.g., feel that gravity pulls my hand towards the ground, I do not really feel gravity itself, but rather that the hand pulls the muscles in my wrist. And if one finds oneself in free fall under the influence of gravity, one does not experience or feel any gravitational forces at all.

Furthermore, in the classical theories of physics one does not normally consider such things as, e.g., air, heat, pressure, energy, and momentum as something directly real, but as a composition or consequence of something else which in turn is considered to be real. If one, e.g., assumes that atoms exist, then air becomes just a big swarm of atoms (molecules), and pressure becomes the total force and macroscopic effect of many atoms colliding with other objects. Energy and momentum are examples of quantities defined in terms of other quantities, such as mass, position, time, and velocity. The latter quantities are normally considered as something real, unlike energy and momentum which are mathematical compositions of quantities such as mass, position, time, and velocity.

It is true that the quantity velocity is a mathematical composition of position
and time. But since velocity, unlike energy and momentum, has a direct counterpart among our sensations, with the property "to be in motion", I here choose to consider velocity as something real; but since this does not have any real significance for the rest of this paper, I wont go into this any deeper than that.

Generally seen there is hence some room for interpretation and we have a certain degree of freedom, when it comes to choosing what we consider to be real or not, and exactly what this something should be once we have decided to consider it as real. As is well known, Newton explained gravitation as a force that acts between massive objects. However, in Einstein’s general theory of relativity there are no gravitational forces. Instead gravity is there an effect of how spacetime curves.

In the case of atoms, one cannot observe atoms directly. (Remember that a scanning tunnelling microscope only gives an indirect image of atoms via the theory of quantum mechanics.) But by assuming that atoms exist, many pieces fall into place. The multitude of different things that one can explain, understand and predict by assuming that atoms exist, are so overwhelming and convincing that it is hard to deny the existence of atoms. Since the atomic hypothesis is so successful, it is in the current situation rather on those who deny the existence of atoms to, in addition to explaining why he or she does not believe that atoms exist, try to find a better and more satisfactory underlying explanation or hypothesis than the atomic hypothesis.

By this is not meant that the understanding and description of atoms will not need to be revised in the future. This is something that (directly or indirectly) happens all the time, as one comes to understand more and more about reality and its most fundamental constituents.

Before we continue, I just briefly want to explain what my own personal thoughts are on such words as "to exist", "real" and "reality". I have an on-
tological approach to the world. I imagine that there is an objective world "out there", which we are a part of, but which exists independently of us humans. As I see it, we humans are just a product of that which exists objectively and is "out there".

For me, the ultimate goal and ambition of science is, as well as we possibly can, to describe and understand this objective reality we all find ourselves in, and are a part of. I therefore imagine that some things are objectively real, while other things are only effects or compositions of things that are objectively real. E.g., for me fields and elementary particles are more natural candidates to be something fundamental and objectively existing, than I, e.g., believe that probability or energy is. I do not imagine probability or energy as things which have objective counterparts "out there". For me they are just abstract, mathematical quantities and concepts that exist only as a thought in our brains. And a brain is for me only a sophisticated biological machine which is a result of evolution, which in its smallest constituents consists of elementary particles and fields. Particles and fields (perhaps also strings, membranes, and other variants of fundamental building blocks) are for me the most fundamental building blocks of reality, at least that we know of in the present-day situation.

VII. THE CONSTANCY OF THE SPEED OF LIGHT

Observations confirm that the speed of light in vacuum is approximately 300 000 000 m/s, in agreement with what Maxwell’s equations predict. But if Maxwell’s equations hold for all observers in constant uniform motion, does this not mean that same light beam moves at the speed of 300 000 000 m/s relative to each observer?

If it were so, this would not be consistent with how we normally perceive our
everyday world. Because if I am on a train and throw a stone in the direction that the train travels, then the stone does not move relative to the ground with the same speed as the stone moves relative to the train. Relative to the ground the stone instead moves with the speed of the stone relative to the train plus the speed of the train relative to the ground, i.e., with a speed that is greater than the speed of the stone relative to the train. Suppose further that the horn on the train emits a soundwave in the direction that the train travels. Since the sound medium, i.e., the air, is at rest relative to the ground, the sound wave travels relative to the ground with the speed of sound (about 340 m/s), and that regardless of the speed of the train. But relative to the train, the sound wave travels with the speed of sound minus the speed of the train, i.e., with a speed that is lower than the speed of sound.

That the same light beam would travel with the same speed regardless of which observer measures the light beam’s speed, is remarkable if one considers what classical physics predicts, or simply what our everyday experience tells us. So how can one explain that light moves with the same speed relative to all inertial reference systems?

But what does one really mean when one says that light moves with the "same speed" relative to all inertial reference systems? For one cannot measure the speed of light by sending a light signal between two clocks located in two different places in space and then divide the distance with the time difference on the clocks, if one does not also have synchronized clocks. To calculate the time difference, the clocks need to show the same time at the same time, i.e., simultaneously. This means that the clocks must be simultaneous or, in another word, synchronized.

Simultaneity and synchronization of clocks are important and key concepts
for the understanding of the special theory of relativity. We therefore need to be careful what we mean by these concepts. One needs to do synchronization in a systematic and reliable way. Einstein chose to synchronize clocks by sending light beams between the clocks. Since he had postulated that the speed of light is constant, he could use this to synchronize clocks. (It seems perhaps more natural, simpler and more intuitive to simply synchronize clocks at the same place in space and then distribute them out to the places in space where one wants them to be. But if one starts to move around clocks in this way, one will have practical problems, e.g., with the fact that time passes more slowly for clocks in motion, which we know is the case on the basis of experiments and observations.)

The speed of light one determines by sending a light beam from a transmitter $T$ to a reflector $R$, e.g., a mirror, which reflects the light back to $T$ (see figure 4). Let $x$ be the distance between $T$ and $R$, both of which are at rest relative to a single reference body $X$. The distance $x$ is measured by placing measuring rods on $X$ from $T$ to $R$. The time interval $t$ between that the light was send out and returned is then measured by the same clock $C$, which is at rest next to $T$ on the reference body $X$. The distance back and forth, i.e., twice the distance $2x$ between $T$ and $R$, is then divided by the time interval $t$ measured on $C$. The speed $c = 2x/t$ one then obtains, is defined as the speed of light. Defined in this way, the speed of light can be measured and is thus a meaningful concept in the spirit of Mach and Einstein. It is this speed that Einstein postulated to be
Note that one cannot prove that a postulate is true. One can only convince oneself of its correctness by testing the postulate in more and more different situations. And so far the postulate has never turned out to be wrong, so in that sense it is a satisfactory postulate.

Once one has defined and measured the speed of light $c$ with the above described method, one can then use it to synchronize clocks. Assume that one has two clocks $C$ and $C'$ that one wants to synchronize relative to a reference body $X$. Both clocks must then be at rest relative to $X$. The clocks are at a distance $x$ apart on $X$. At a given time $t$ on $C$, say $t = 0$, a light beam is sent from clock $C$ to $C'$. When the light beam reaches $C'$, one sets $C'$ to show the time $t' = x/c$. In this way one can synchronize any clocks at rest on a single reference body (inertial reference system).

What does it mean then that two events are simultaneous? Simultaneity is defined as follows: Assume that we have clocks that are synchronized relative to an inertial reference system $X$. Further assume that two events, such as two lightning strikes, occur at two different places in space. If the synchronized clocks of $X$ at these two places in space show the same time for the events, one says that the events are simultaneous relative to the inertial reference system $X$.

But how does one know that the light beam really arrives at the reflector after ”half the time” when one synchronizes two clocks with the above described method of synchronization? For could the light speed not be higher in one direction and lower in the other?
That depends a little bit on what one means. Assume that one on a reference body $Y$ already has synchronized clocks with the above given method. Assume further that on a reference body $X$ one intends to synchronize two clocks, where $X$ moves relative to $Y$ with velocity $v$ (see figure 5). The synchronization situation in $X$ is observed from the reference body $Y$. Relative to $Y$ the reflector $R$ moves either towards or away from the light beam, depending on how $X$ is moving relative to $Y$. According to the clocks on $Y$ the light beam will not arrive at the reflector when the clock $C$ shows half the time, i.e., $t/2 = x/c$. This means that observers on $Y$ do not think that $C$ and $C'$ on $X$ have become synchronized. But according to the clocks $C$ and $C'$ on $X$ the light beam will, by definition, arrive at $R$ after half the time. We have thus demonstrated that with the above definition of simultaneity, it becomes a relative concept. If two events are simultaneous relative to one inertial reference system, these two events in general will not be simultaneous relative to other inertial reference systems in motion relative to the first inertial reference system.

But now I do not think this is what one really thinks of and means with the above question, but whether the light beam really hits the reflector after "half the time." One asks how it really or truly is, i.e., if the light beam arrives at the reflector after half the time objectively seen?
However, this is a question that we strictly seen cannot answer. The only thing we can do is to make use of synchronized clocks to check whether this is the case or not. Because, we use the definition of the speed of light to synchronize clocks. This definition involves a time-interval on one and the same clock $C$ located at $T$. In other words, the definition of the speed of light does not involve the clock $C'$ at $R$. *First* we define and determine the speed of light using clock $C$. *Then* the speed of light is used as a tool to synchronize clock $C'$. In that moment when the light beam is reflected on $R$, the clock $C'$ is set to show the time $t' = x/c$. But $t' = x/c$ is half of the time $t = 2x/c$, where $t$ is the time interval between the emission and the return of the light beam at $T$, and $t$ was measured on $C$. Clock $C'$ is thus set to show half the time, i.e., $t'/2$, when the light beam is reflected on $R$. The light beam therefore hits the reflector after half the time by definition.

The only thing we can do is to define the speed of light and then synchronize clocks with the above described method. Then there are no guarantees that this systematic and consistent way of synchronizing clocks will work in practice. That is up to experimental tests to settle. But so far, this way of synchronizing clocks, and to define space and time, has proven to work excellent in practice. If this had not been the case, then one would have had to try something else.

Then it may be the case that one perhaps could in different ways motivate why it would be highly unlikely that it should not work, or that there would have been severe consequences for one’s concepts, theories and understanding of reality if it had not worked, and that one therefore expects that it should work. But we are not in the position to tell reality how it should work. Our job is, on the basis of empirical tests and investigations, to find out how reality works.

From the *postulate* on the constancy of the speed of light and the *postulate* that all laws of nature are the same in all inertial reference systems, one can now derive the special theory of relativity. From only these two postulates follows
exactly the same equations that Lorentz arrived at, i.e., the Lorentz equations, but with a different conceptual and philosophical basis.

From the Lorentz equations it follows, among other things, that time goes slower, and that bodies become shorter in the direction of motion, for bodies in motion relative to other bodies. But also that simultaneity becomes a relative concept. In addition to these relativistic effects, there are several other things that follow from the special theory of relativity, e.g., that quantities such as momentum and energy are changed. The famous equation \( E = mc^2 \) was presented by Einstein in the wake of the special theory of relativity. However, we will here mainly focus on how the notions of space, time and simultaneity came to change with the special theory of relativity.

VIII. A LORENTZIAN INTERPRETATION OF THE SPECIAL THEORY OF RELATIVITY

How should one then explain and understand the above mentioned relativistic effects? That depends on how one interprets the special theory of relativity. Let us first do as Lorentz did and assume that for all observers that are in motion relative to Newton’s absolute space, or the ether, time and length change according to the Lorentz equations. The faster one moves relative to the absolute space, or the ether, the slower time goes and lengths become shorter in the direction of motion. The combined effect of these two effects, is that the speed of light becomes the same relative to all inertial reference systems.

But if time is goes slower and distances become shorter, as seen from one inertial reference system at rest relative to Newton’s absolute space, or the ether, does that not mean that time goes faster and that distances become longer when
seen from all other inertial reference systems in motion relative to Newton’s absolute space, or the ether? And if this is the case, would one then not be able to determine who actually is in motion and who is not, in violation with one of the postulates of the special theory of relativity?

Well, if this was the case, then one would have a means of detecting absolute motion. But in fact the situation will be completely symmetrical for all inertial reference systems. What enables this, apart from the fact that time and length change, is that also simultaneity has become a relative concept. Also in the ”Lorentzian interpretation”, we use the above definition of simultaneity. All inertial reference systems, regardless whether they are in absolute rest or not, will find that their clocks are synchronized and therefore simultaneous. But as we have already seen, if two inertial reference systems are in motion relative to one another, it generally holds that two events that are simultaneous relative to one of the inertial reference systems, are not simultaneous relative to the other inertial reference system. No observers on these inertial reference systems can therefore distinguish between constant uniform motion relative to the absolute space, from being at rest relative to the absolute space. From the observers’ point of views, their situations are completely symmetrical or equivalent.

But according to the ”Lorentzian interpretation”, or ”Lorentzian approach”, it is only seemingly so. Because, as seen from ”the point of view of reality”, or objectively seen, their situations are in fact asymmetrical. This asymmetry has its origin in the fact that it matters who objectively seen moves or does not move relative to the absolute Newtonian space, or the ether. For the observer who happens to be in absolute rest, two events that are simultaneous for this observer are also absolutely simultaneous. I.e., only for observers in absolute rest, will events that they observe to be simultaneous, also be simultaneous objectively seen. For
all other observers in motion relative to the absolute space, the events that they
observe to be simultaneous, will objectively seen only seemingly be simultaneous.
Because, having adopted a "Lorentzian interpretation" of the special theory of
relativity, one has hence also assumed **absolute simultaneity**.

But that is not to say that the observers who live in a reality where
absolutely simultaneity prevails, can distinguish, based on the definition of
simultaneity which they themselves have created, between events which are
absolutely simultaneous and events which objectively seen only are seemingly
simultaneous. The light beam used in the synchronization method described
above, will *objectively seen* reach the reflector after half the absolute time it takes
for the light beam to go from and come back to the transmitter, only if the
transmitter and reflector are in absolute rest (relative to the absolute Newtonian
space). But even with a Lorentzian interpretation, this is not something that
can be measured by an observer, since also in the Lorentzian interpretation all
inertial reference systems are equivalent; i.e., there is no way for an observer to
find out who really is in absolute rest or who really is in a state of absolute motion.

With a Lorentzian interpretation one can thus *explain* and *understand* how the
speed of light, but also how all other laws of nature, are, or appear to be, the same
relative to all inertial reference systems. But to do so, one needs to "go outside
reality" and "see it from the outside", i.e., from a meta perspective. However, this
is not a perspective that is accessible to observers, who are (by definition) limited
to observe reality "from within". The Lorentzian explanation of the constancy
of the speed of light, therefore includes assumptions and concepts which are not
based on observations. One is forced to introduce an abstract idea of an absolute
Newtonian space which cannot be observed. Events are only truly simultaneous
in relation to this absolute space. For all observers that move relative to this
absolute space, time goes *objectively seen* more slowly and distances become
objectively seen shorter in the direction of motion.

At first sight, the Lorentzian interpretation may seem radical. But it is a natural interpretation to do, when trying to adapt our everyday experiences and the classical theories, to the observational facts that the speed of light and the natural laws are the same for all inertial reference systems, if one at the same time wants to maintain a Newtonian approach to reality. Instead of a "Newtonian approach to reality", one could also say an "everyday-experience-based world view." That would make it more clear that the Lorentzian interpretation is closely and intuitively connected with everyday concepts and the possibility to translate the predictions of the special theory of relativity to something more intuitive and understandable for us human beings. Because the Newtonian and Lorentzian conception of the world enable us to create and imagine a more understandable and intuitive internal mental picture or model of reality.

IX. THE LORENTZIAN INTERPRETATION - A TRAIN EXAMPLE

To make what have been said above more concrete, we will now, by considering an example, look more closely at how a Lorentzian interpretation provides an explanation of how the speed of light and the laws of nature can be the same for all observers in constant uniform motion. For the sake of simplicity we restrict ourselves to consider only one space dimension $x$. We lose nothing in generality by doing so, because we can always turn the three space coordinate axes $x, y, z,$ so that the motion is only in the $x$-direction.

On board one of the cars on a train, is a person at the rest in that car's rear end, in relation to the direction that the train moves. This person sends a beam of light towards the front end of the car, where it is reflected back by a mirror.
The person measures with a clock $C$ the time interval from the point in time when the light beam is sent out until it comes back again. The length of the car $x$ can be measured by the person on board by placing measuring rods along the floor of the car.

We assume now that the embankment is in absolute rest relative to the absolute space. Relative to the embankment the light beam objectively seen thus moves with the speed of light, i.e., $c = 300\,000\,000$ m/s. Assume that the train is travelling at a speed $v$ which is close to the speed of light. Seen from the embankment, the mirror is moving away from the light beam (see figure 6).

If nothing would happen with the lengths or with the time on the clocks on board the train, then a simple calculation shows that it would take a longer time for light to travel back and forth along the car of the train, \emph{as seen both from the embankment as well as from the person on board the train}. (This even though the person and the clock $C$ on board the train move, as seen from the embankment, towards the light beam after it has been reflected on the mirror.) This means that the person on the train would have to wait a longer time for the light beam to come back. Since we have assumed that lengths on the train do not change, this would mean that the person on the train would

Figure 6: Train-embankment inertial reference systems.
have measured a lower value on the speed of light than 300 000 000 m/s. This would contradict the postulate that the speed of light is to be the same relative to all inertial reference systems, as we know from experiments that it must be.

This means that lengths and/or time must change in some way to compensate for the longer time the light beam takes to travel back and forth along the car of the train. If lengths become shorter and the time on the clocks on board the train moves slower, relative to the embankment, precisely in the way that the Lorentz equations prescribe, then one can by a simple calculation show that this exactly compensates for the longer time that the light beam takes to go back and forth along the car of the train. The result or combined effect of this, is that the person on board will measure the speed of light to be 300 000 000 m/s after all.

The faster the train moves, the shorter lengths on the train will become, and time will go slower and slower, relative to the embankment. And if the person on the train instead would be in the front end of car and sends the beam to the rear end of the car, where it is reflected, a similar reasoning would give the same result or conclusion, i.e., the speed of light remains invariant.

But if time goes slower and distances become shorter on the train relative to the embankment, does that not mean for the person on the train, that time goes faster and distances become longer on the embankment? If this was the case, that would contradict the postulate which says that reality must look the same from all inertial reference systems. This means that the situation as seen from the train, must be identical to the situation as seen from the embankment, apart from the fact that the embankment moves in the opposite direction. (The size of the relative speed must however be the same, seen from both of the reference bodies. For if this were not the case, then the two reference bodies would not be
equivalent, which again would violate one of the postulates of the special theory of relativity.)

Therefore, seen from the train, time on the embankment must go slower than on the train, and lengths on the embankment must become shorter in the direction of motion. But this is also possible, thanks to the fact that *simultaneity* has become a relative concept. For in the case with the train described above, there is an asymmetry between the situation on the train and the situation on the embankment. The asymmetry has to do with how times and distances are measured. As have already been said, the person on the train measures lengths on the train by placing measuring rods along the floor of the car of the train. Furthermore, this person measures time on his clock in the rear end of the car. Therefore, as seen from the train, the point in time of the emission of the light beam, as well as the point in time of its return, are both measured at the *same place* in space.

The measuring situation *seen from the embankment* is however different. To measure, e.g., the length of the car of the train from the embankment, one cannot place measuring rods along the ground from one end of the car to the other. The reason for that is that the train is moving and therefore would have moved while one did this. One would then not have measured the length of the car, but simply something else. Nor is the time between the emission and return of the light beam possible to measure from the same place on the embankment. Because the event when the person on the train emits the light beam and the event when the beam comes back to the person on the train, occur at *two different places* along the embankment.

Therefore one must use two different clocks for these two places on the embankment. It is here that the concept of simultaneity comes in, since the clocks
must be synchronized. And synchronization and simultaneity are basically the same thing. According to what have been said above, the observers on the two reference bodies will not agree on which events are simultaneous and which are not. Since they move relative to one another, two events that are simultaneous relative to the train, will not be simultaneous relative to the embankment; and vice versa. The same thing holds for synchronized clocks. Two clocks that are synchronized relative to the train, will not be synchronized relative to the embankment; and vice versa. And this again because they move relative to one another.

Let us see how the synchronization situation becomes in the case with the train. Again we assume that a clock $C'$ is located by the mirror. When the light beam is reflected on the mirror, then $C'$ is set to show the time $t' = x/c$, where we have assumed that the light beam was sent at the time $t = 0$ on clock $C$. The time $x/c$ is, according to clock $C$, precisely half the time it takes for the light beam to go back and forth along the car of the train.

But as seen or measured on clocks that are at rest on the embankment, the light beam is not reflected after half the time between it was sent and returned. According to times measured by clocks at rest on the embankment, the reflection occurs after a time which is longer than half of the time interval between the emission and the return. The reason for this is that clock $C'$, as seen from the embankment, is moving away from the light beam before the reflection, while the clock $C$ is moving towards the light beam after the reflection. According to the embankment, it therefore takes a longer time for the light beam to reach $C'$ from $C$, than it takes for the light beam to return back to the $C$ from $C'$. Relative to the embankment clock $C'$ is hence not synchronized at the right time. Because relative to the embankment, the clock $C$ does not show half the time, i.e., $x/c$, at
the same time that the light beam is reflected. According to the embankment, the light beam has not yet reached the mirror when clock $C$ shows the time $x/c$. As seen from the embankment, once the light beam reaches the mirror and clock $C'$ is set to show the time $x/c$, then clock $C$ shows a time which is later than $x/c$. As seen from the embankment, the clocks on board are thus not synchronized.

But observers on board the train insist that the clocks $C$ and $C'$ are synchronized. The observers on board the train instead consider the clocks on the embankment as not synchronized. Hence observers on the train and observers on the embankment, do not agree on whose clocks are synchronized and therefore not which events that are simultaneous. Both inertial reference systems consider their clocks to be synchronized, which they also are completely entitled to think. The thing is that there is no way for observers on board the train or the embankment to determine which of them really are right. Thus they cannot through measurements determine who really are in absolute rest. Now we happen to know, since this was assumed above, that it is the embankment which really is in absolute rest. But that is only because we view the situation from an objective perspective which is not available for the observers on the train or the observers on the embankment; or for any observer at all for that matter. This meta perspective is possible thanks to that we have assumed that the "Lorentzian interpretation" or "Lorentzian world view" is true. This interpretation thus offers an explanation for how reality manages the feat to get all observers in constant uniform motion to agree that the speed of light is always the same.

If one on the embankment wants to measure, e.g., the length of the car of the train while it is in motion, one uses clocks that are synchronized relative to the embankment’s inertial reference system. The length of the car is measured by measuring the position of car’s rear and front end, according to these synchronized
clocks, *simultaneously in two different places along the embankment*.

In a similar way one determines, in the embankment’s inertial reference system, the time between the event when the light beam leaves $C$ and the event when it returns to $C$. First one identifies the two places along the embankment where the light beam left and came back to clock $C$. The points in time of these two events, one reads from clocks that are synchronized relative to the embankment. The time between these two events is then obtained by simply taking the difference of these two points in time. Seen from the embankment, it is true that these two points in time are not measured simultaneously, but with clocks that are synchronized relative to the embankment.

However, observers on board the train do not consider the clocks along the embankment to be synchronized relative to one another. According to the train’s inertial reference system, the clocks on the embankment have therefore measured where the front and rear of the car of the train are *at two different points in time*. So observers on the train do not consider it to be the length of car that the observers on the embankment have measured up, but something else.

According to the ”Lorentzian interpretation” of the Lorentz equations, it is thus only for those observers who are in absolute rest that the speed of light *really* or *objectively seen* is 300 000 000 m/s, regardless of the speed of the light source and regardless of the direction in which the light travels. For all other observers, who are in motion relative to the absolute space, it is only *seemingly* so. This ”illusion” is thus made possible by the fact that time *really* goes slower and that lengths *really* become shorter, relative to the time and lengths of the absolute space, for reference bodies that *really* move relative to the absolute space. The relativity of the concept of simultaneity enables observers on board the train
to perceive the situation as if they are at rest and that it is the embankment which moves relative to them (with the same relative speed as seen from the embankment). Space and time will thus change in the same way for all observers who are in constant uniform motion relative to each other. One can demonstrate this through the systematic use of the Lorentz equations and by applying the definitions of space, time, and simultaneity, on the one hand relative to the embankment, and on the other hand relative to the train.

Does then the Lorentzian interpretation give any explanation as to why time goes more slowly and why lengths become shorter for observers who are in absolute motion? No, the Lorentzian interpretation simply says that this is how reality works. On the other hand, if we assume that this is how reality works, then it would not be very difficult to come up with all kinds of reasons and explanations to why it could be like that. Since we have already assumed an existence of an absolute space which we cannot observe, why should we then also not be able to give this absolute space characteristics or properties that would make bodies, moving through this space, shorter and time on them go slower? But it does not necessarily have to be properties of the absolute space. One could imagine all sorts of properties of reality, which would be the reasons why time on clocks goes slower and why distances become shorter for bodies in absolute motion. It is, of course, not impossible that such characteristics of reality one day might be observed. On the other hand, since we already have assumed the existence of an abstract absolute space that we cannot observe, it is not even sure that we feel, or consider it to be necessary, that we should actually be able to observe everything which according to our models and theories are assumed to exist in reality.

Once again we here touch upon questions having to with the philosophy of science. However, let me just conclude by saying that, despite its abstract and non-
observable nature, I do not feel or consider the concept, and the assumption of the existence, of an absolute space to be something far-fetched or arbitrary. Instead I consider it, together with the concept of absolute simultaneity, in many respects to be something natural, and intuitive. Because remember that we had perhaps not even questioned the notion of absolute space, time, and simultaneity, if it were not for philosophers and physicists such as Mach and Einstein. For it was thanks to that Mach questioned and criticized the concept or idea of absolute space, and that Einstein was working on the basis of, and applied, this philosophical approach to problems directly and indirectly connected to the nature of light, which enabled the development of the theory of relativity, and much of modern physics as we know it today.

X. OPERATIONAL SPECIAL THEORY OF RELATIVITY

But now it was not a "Lorentzian interpretation" that Einstein did of the special theory of relativity. Einstein was critical of, what we here have called, the "Lorentzian interpretation". It was not length contraction and time dilation in itself that Einstein considered to be unsatisfactory, for these phenomena are also found in the special theory of relativity. It was the interpretation or explanation of these phenomena that Einstein found unsatisfactory. He thought that Lorentz’s explanation, that lengths become shorter and time goes slower as a result of their movement relative to the absolute space, or ether, was unsatisfactory. In the Lorentzian interpretation the length contraction and time dilation are absolute in a Newtonian sense, while Einstein had a different approach on the whole thing with the special theory of relativity. Einstein wanted to get away from Newton’s absolute space, the ether hypothesis, and more generally concepts and hypotheses that do not have its basis in observations. He realized that it was the notions of space, time, and simultaneity, that needed to be changed, if one wanted to
get away from the assumption of an existence of a non-observable and abstract concept such as the absolute Newtonian space, or the ether.

Einstein attacked the problems having to do with space, time, simultaneity, the invariancy of the speed of light and the other laws of nature, in an operational way. In its original form the special theory of relativity is an operational theory, which is important to remember when trying to understand the special theory of relativity and its predictions. By operational I mean, that one does not explain natural phenomena in terms of non-observable and abstract concepts, in a way similar to how one explains the pressure of a gas by assuming the existence of atoms, or the wave nature of light by assuming the existence of an ether. Instead one starts from observations of reality and describes how other natural phenomena can be described using these observations. All concepts in the theory are defined on the basis of something which in a concrete way can be observed and measured, and predictions from the theory only have a meaning if they can be observed and measured. The theory does not go, so to speak, beyond experience.

In its original form, the special theory of relativity is, e.g., not dependent on the concept of spacetime. The theory is free from interpretation and its predictions are very concrete. One could describe the special theory of relativity as taking a step back from the Lorentzian interpretation, in the sense that it assumes less and is therefore more general than the Lorentzian interpretation. The Lorentzian interpretation can be seen as one possible interpretation of the special theory of relativity. This is not to say that the special theory of relativity needs an interpretation, because strictly seen it does not.

So Einstein did not really try to interpret, or to explain how or why the speed of light and the laws of nature are invariant with respect to all inertial reference
systems. He simply *postulated* that it was so, i.e., he took it as an observational fact and assumed that it was true. The concepts of space, time, and simultaneity, he *defined* what they should be. Distances in space are measured with measuring rods, relative to a reference body at rest, i.e., an inertial reference system. Time is what one measures with ordinary clocks. When measuring time in the special theory of relativity, in general one does not move the same clock around in space. Instead one places a clock at every position in space, which in principle is possible to do. The clocks are assumed to be of identical construction. Furthermore, one assumes that time goes at the same rate (i.e., equally fast) on every clock in space.

In the special theory of relativity, are thus space, time, and simultaneity, operationally defined concepts. Strictly speaking the theory offers no explanations of *how* reality objectively seen (ontologically) actually works, or *why* it works as it does. The only thing the theory says is that, if we define space, time, simultaneity, and the speed of light in the above described way, and assume that the speed of light and all laws of nature are invariant with respect to all inertial reference systems, then it follows that one will measure and observe that space and time in different inertial reference systems are related in the way that the Lorentz equations prescribe. Why and how reality manages the feat to make the speed of light and the laws of nature to be invariant with respect to every inertial reference system, are questions that the special theory of relativity strictly speaking does not answer. As have already been said, it assumes or postulates that this is the case. And these two postulates have been verified in countless experiments and observations.

It is true that the special theory of relativity strictly speaking requires no interpretation. However, personally I think that it is difficult to stop at an
An interesting comparison can here be made with what Einstein himself thought of quantum mechanics, i.e., as unsatisfactory because it did not provide a complete ontological description of reality. Bohr is said to have been inspired by the operational character of special theory of relativity when he participated in and contributed to the development of quantum mechanics. He therefore thought that Einstein would like quantum mechanics, since also this was an operational theory. But it seems as if Einstein in the years between the creation of the special
theory of relativity and the creation of quantum mechanics, had partly changed attitude, or philosophy. From being more operational, in the spirit of Mach, to becoming more accepting of more not directly observable elements and concepts in the theories, such as the spacetime concept.

But probably had there in Einstein always been certain notions and opinions that he was not prepared to alter or give up on. Philosophically seen, Einstein seems to fundamentally have had an ontological approach to reality. He was, e.g., not willing to give up on an objective description and understanding of reality when it came to quantum mechanics. Maybe one also could take the finiteness of the universe as an example of something that Einstein for a while had a difficult time to accept, despite the fact that his own general theory of relativity rendered such a universe possible. Probably because it was contrary to his inner beliefs and convictions of how reality reasonably should be.

If one wants to, one can thus refrain from trying to interpret the special theory of relativity. This is in some sense similar to how many physicists in the present-day situation approach quantum mechanics. But for me this approach is unsatisfactory. I find quantum mechanics as unsatisfactory as a final description and explanation of reality. Although I personally do not believe so, at the moment quantum mechanics may be adequate, and perhaps even inevitable. But it does not agree well with what I think should be the ultimate ambition and final goal of science, and that is to understand how reality objectively or ontologically seen is and works. Then it is possible that this ambition and goal never will, or cannot be accomplished. But science should not give up on this ambition until there are very good and convincing reasons for doing this. And any such reasons I cannot remotely see in the present-day situation.
XI. THE SPACETIME INTERPRETATION

One way to look at the concept of *spacetime*, is as a practical way to illustrate what happens in space and time. E.g., at train traffic supervision centers one uses a kind of *spacetime diagram* to facilitate the monitoring of the trains. Such a diagram has two perpendicular axes, where space is on one axis and time on the other axis. A train’s movement is represented by a line, where the slope of the line gives the speed of the train. An intersection of two lines corresponds to a meeting between two trains. If the trains did not meet each other on two separate tracks, it means that a collision between the trains has occurred. A spacetime diagram of this kind is, of course, nothing mysterious or fundamentally new, but it is just a practical way to illustrate the movement of trains (see figure 7).

Figure 7: An example of a ”spacetime diagram” at a train traffic supervision center.
Instead of trains, one could just as well illustrate the motion of atoms in this way. The motion of atoms would then be shown as lines in the diagram, and if two lines intersect it means that a collision between the atoms has occurred. If the atoms can move in two space dimensions, the spacetime diagram would be three-dimensional, i.e., two space axes and one time axis. And if the atoms can move in three space dimensions, the spacetime diagram instead becomes four-dimensional. Although it in practice is a greater challenge to illustrate a four-dimensional space in a pedagogical way, there is nothing strange with a four-dimensional space. We all live in a four-dimensional world, i.e., with three space dimensions and one time dimension.

If I say that I am at the main entrance to the Turning torso in Malmö, at 12:00 on the 1st of January 2009, I have in principle described where I am with four coordinates, i.e., three space coordinates (giving the location in space) and one time coordinate (the point in time when it happens). If one would place the space origin at the main entrance to Turning torso, then my spacetime coordinates would be 

\[(x, y, z, t) = (0, 0, 0, 12)\].

It takes four coordinates to describe the motion of an object in space. One could, e.g., describe the motion of a 200-meter runner when he or she runs on the finishing stretch as 

\[(x, y, z, t) = (v \cdot t, 0, 0, t)\],

where \(v\) is the runner’s speed and \(t\) is the time the runner has been on the finishing stretch. Since the motion on the finishing stretch in practice takes place along a straight line in space, one can illustrate the runner’s motion as a line in a two-dimensional spacetime, with one space axis and one time axis. With this two-dimensional spacetime the coordinates would then be 

\[(v \cdot t, t)\].

Again, the spacetime concept used in this way, is not or does not involve anything mysterious or fundamentally new. It is just a convenient and alternative way to illustrate the motion of bodies.

When it comes to the spacetime concept in the special theory of relativity,
there is nothing that prevents one from limit oneself to consider and use spacetime in the above described manner, i.e., as a practical and useful way to illustrate what happens in space and time. It seems to me that many physicists, to a large extent, perceive and understand the spacetime concept only in this way. I think that has to do with the fact that they either are not aware of any other way to understand the concept of spacetime, or because they simply do not have a clear understanding of the meaning of spacetime concept that we will consider below.

Admittedly, the special theory of relativity requires no other interpretation of the spacetime concept other than the one described above. But there is another interpretational possibility of the concept of spacetime that is natural to adopt, if the special theory of relativity is to go from a purely operational theory, to a complete and ontological theory. The general theory of relativity suggests that one uses the ”spacetime interpretation” of the spacetime concept presented below, although not even the general theory of relativity strictly speaking requires one to interpret the spacetime concept in that way. In the general theory of relativity, spacetime is considered to be something real, and it plays a central and active role in the physical course of events. Spacetime interacts with that which fills up spacetime, such as particles and fields. The curved geometry of spacetime dictates not only how a body is to move, but the body in turn dictates how spacetime should curve.

This other possible interpretation of the concept of spacetime, is that it can be understood as a merge of the two separate concepts space and time, into a single entity called spacetime.

According to what has been said above, in the Newtonian world view, is what exists a three-dimensional (spatial) space at single point in time, the present. Time is there absolute and is ticking at the same rate regardless of what is going on in the
As time goes, one present is replaced by its subsequent present, which in turn is replaced with its subsequent present, and so on. Neither all those present moments which have been, the so-called past, nor all those present moments which not yet have come into existence, the so-called future, exist. Only the present moment exists. The present corresponds to a snapshot of a three-dimensional space, together with everything in this space at this moment in time.

Some examples of things or events that can occur in the present, can, e.g., be a person on Mallorca who drops a coin, a bullet which leaves the muzzle of a rifle on the north pole, a meteorite colliding with a satellite above the earth surface, or a star exploding in another galaxy. All these events occur in an objective and absolute present. In the next moment on the absolute time, this present moment does not exist anymore, but instead belongs to the past. The past has no existence in itself, but is just a name on those present moments which previously have existed. In the same way, the future is not something that exists, but is just a name on those present moments which are yet to come. In the Newtonian approach, the past and the future are really only something which exist in relation to a brain existing in the present.

Spacetime is instead a four-dimensional space which exists. Three of these four dimensions constitute the usual three-dimensional (spatial) space and the remaining dimension is the usual time. Instead of reality being a three-dimensional present which is constantly being replaced by a new present as time goes, spacetime is instead a four-dimensional "present". Since time is included in the four-dimensional spacetime, there is no time in motion. Instead the four-dimensional spacetime, together with all its contents (such as particles and fields), is something which only is. Thus, it is not only what one in a Newtonian approach to reality calls the present which exists. Instead the past, present, and future all exist to the same degree. All three are a part of spacetime, and exist all at once. In fact, what we have called the past, present, and future in
the Newtonian approach, have no direct counterparts, or absolute meaning, in spacetime.

This is what is meant by *spacetime* in the "spacetime interpretation". But how can a consciousness and an experience of the passage of time arise from such a timeless and "frozen" spacetime? How can one reconcile the spacetime concept, interpreted according to the "spacetime interpretation", with the experience all of us have of a time in motion, a time that goes, and that the personal present is the only moment in time which exists for us, one personal present at a time?

If spacetime is real in the way described above in the "spacetime interpretation", then the only possibility I can see to reconcile, on the one hand, the timeless concept of spacetime with, on the other hand, the emergence of a consciousness, an experience of a time in motion and that we exist only in a single unique personal present, is that the latter is some sort of "illusion". ("Illusion" is not a really satisfactory word, but it is the best word I can come up with, that comes closest to describe and capture what I mean.) By the word "illusion", I do not mean that the spacetime events underlying the illusion are unreal. I mean that the personal experience that the brain creates of a time that goes, a time in motion, and a reality that only exists *one moment at a time*, is an "illusion".

How, and why, our brains could or would be designed to operate in this way, is something I do not want to speculate too much about. But perhaps it could be a kind of "side effect" of a four-dimensionally existing brain? Perhaps some evolutionary advantage might lie behind? An evolutionary successful four-dimensional brain of our kind could perhaps more easily have arisen if this kind of "side effect" also arises? That some four-dimensional formations in spacetime have been equipped with the ability to create an experience of a time
in motion, that events have a time order, and a reality existing one moment at a
time, etc, is perhaps something that gives these four-dimensional formations the
right conditions and advantages needed for them to arise?

Bear in mind that we do not really have a completely clear picture, or
understanding, of how thoughts, and an experience of a consciousness, can arise
even if we were to adopt a Newtonian world view. We understand, or imagine,
that thoughts, and consciousness, probably have to be a product or effect of the
particles and fields that constitute our brains. But exactly how this experience
or effect arises from these building blocks, is something that we only partly
understand. So our inability in the present-day situation to understand how an
experience of a consciousness and the passage of time, may arise from the timeless
spacetime concept, is in itself no argument for rejecting a timeless interpretation
and description of the concept of spacetime.

Let us simply assume that it is possible for an experience of a consciousness,
and a ”time in motion”, to arise from such a timeless thing as spacetime. If one
looks at how we perceive reality and our everyday world, it probably seems very far-
FETCHED, speculative, and unlikely that it could be like this. But another consistent,
 systematic, and coherent way to understand the concept of spacetime on, I cannot
see if one wants to get away from a notion of absolute simultaneity. So if this is the
consequences of what is thought and worked out from a consistent, systematic, and
logical reflection of reality as it appears to us humans, perhaps we need to find us
to accept these consequences, although they may seem strange or unbelievable to
us. That reality, seen from a larger perspective, may seem unintuitive, remarkable,
and unlikely, is in itself not something strange, or an argument for that it would not
be possible for it to be like that. Because reasonably our brains are of evolutionary
reasons only constructed to understand the aspects of reality which constitutes our
"closest or most immediate reality", or, put in another way, our everyday world.

XII. THE VARIOUS INTERPRETATIONS COMMENTED AND COMPARED

Why is it really wrong to imagine reality in a Newtonian or Lorentzian way? The "spacetime interpretation" is perhaps more in line with what we strictly seen can say about reality. But does it not also move the description of reality in physics further away from our everyday world, and thereby from an intuitive understanding and conception of reality? Cannot the assumption of an abstract absolute space be compensated by the fact that reality then becomes easier to grasp? It may be difficult to understand, and perhaps seem bold, that Einstein discarded an intuitive and comprehensible notion of space and time, and replaced it with an operational description of space and time. And this just to not be forced to assume the existence of an absolute space or an ether, or?

It is even more remarkable that Einstein did this without "going all the way" and coming up with the concept of spacetime. For it was only in and with the spacetime concept that I can see that one could give a satisfactory explanation, obtain an overall picture and a deeper understanding of the special theory of relativity and its predictions. Because the spacetime concept was not in the original version of the special theory of relativity as presented by Einstein. It came instead after that Minkowski, who was Einstein’s former teacher in mathematics, reworked Einstein’s special theory of relativity to a different mathematical form (up to the point that not even Einstein for a while recognized his own theory). The spacetime concept was a product of this reworking. Initially Einstein disliked the concept of spacetime, but eventually took it to his heart. It was later to enable and become the foundation of his general theory of relativity.
So what is most satisfactory: 1) To understand how reality works at the price of the having to assume an abstract concept which has no direct support in observations, but which feels as intuitively obvious, and gives us an opportunity to visualize and understand reality based on everyday concepts and everyday thinking, i.e., by ”common sense”? Or 2) to stop at an understanding and description of reality that only use concepts which are defined on the basis of something that can be measured and observed?

These questions are related to what is really meant by to understand something. Even if we understand something logically and operationally, this does not necessarily mean that we experience it as if we ”truly understand” this something. Because, how do we know or decide that we really understand reality, if we cannot imagine and explain reality in terms of everyday concepts and everyday thinking? For what other criteria should we have on a theory, for us to truly think that it explains and describes reality in an ontological way? Or is perhaps the ambition to understand and describe how reality is objectively, a naive, unrealistic, and hopeless dream? Should one perhaps let go of this ambition and be content with trying to create theories that are as successful as possible when it comes to describe existing, and predict new, observations in an operational way? How one views and responds to these questions, have to do with one’s attitude towards, and opinion of, what the role and final goal of science should be. The above questions are, e.g., related to how one looks at a theory such as quantum mechanics, which some claim gives us a complete description of reality.

If alternative 2) above seemed obvious to the reader, then remember that, e.g., the atomic hypothesis has no, or at least originally had no, direct support in perception and observations. Originally the atomic hypothesis only indirectly had support in observations, since it predicted, described and explained, e.g., the
behaviour of gases, the structure of the periodic table, Brownian motion, etc. To me approach 2) also has a sense over it of giving up too easily or too early.

But in practice, there will probably always be spokesmen and representatives of both these two different alternative approaches and ways of working, among scientists and other thinkers. Not only in different individuals, but also in one and the same individual.

The "Lorentzian interpretation" offers an explanation of how the special theory of relativity fundamentally works. It explains how reality manages the feat of making the speed of light and the laws of nature to appear invariant, since time really slows down and distances really become shorter, for observers in motion relative to the absolute space. But this comes at the price of having to assume the existence of an absolute space which cannot be observed, and this can be seen as a science-philosophical deficiency or weakness in this interpretation.

But perhaps there could be other ways to interpret the special theory of relativity, that do not involve an absolute space, ether, or a spacetime? It is, of course, not inconceivable that there could be. But as long as these ideas are the best we have, what else can we do other than to believe in and use these ideas?

However, now it is not in any way the case that the spacetime concept is a pure invention or something purely made up. It is a consequence of a logical, systematic, and consistent scientific and philosophical thinking. A reasoning containing a minimum of assumptions that are not supported by observations. And how else can we build our theories about reality, if we do not want to get into metaphysics and speculations?
Moreover, if it really would be the case that there are no such things as an underlying absolute Newtonian space, or absolutely simultaneity, then we would be forced to accept that the Newtonian way to imagine space and time would be incorrect. And if we have given up this idea, what other choice do we then have, other than to create a conception of space and time from what we really know about reality, i.e., what we can observe?

Now the criticism of the spacetime concept would perhaps be more justified, if it had not turned out to be successful in some other way than in the special theory of relativity. But the spacetime concept enabled and led to the general theory of relativity, which is a successful, deep and conceptually satisfactory theory. It contains Newton’s law of gravity as a special case, and in the cases it has been tested it has also been confirmed by observations. The theory has led to an increased understanding, and given rise to new theories, of reality. And is not being successful, strictly seen, the only criterion one can have on the correctness of a theory? At least from an evolutionary perspective this seems to be the case.

Then there are, of course, many other guiding principles, and criteria, on a theory that enter. E.g., that it should contain a minimum of unfounded assumptions and concepts that do not find support in observations. It also should, as far as possible, be consistent with other already existing theories. But preferably also with our everyday thinking, for it is when a theory is this, that we feel that we really understand it and we can visualize reality.

In the future it may, of course, turn out that the spacetime concept ceases to be successful and is therefore not quite right. It is not at all inconceivable that the idea of an ether, or an absolute space, could make a comeback. However, the tendency is rather the opposite, if one considers how the theories of physics look like in the present-day situation. The concept of spacetime
is certainly accepted and taken to be correct by the physics community. At the same time, it seems to me that the spacetime concept not always is being interpreted in the manner I have described above in the "spacetime interpretation". Many still seem to view space and time in a more absolute Newtonian way, even though they know about the theory of relativity and the concept of spacetime.

My impression is that the more fundamental research area one looks at, the more is spacetime a more known, recognized, embraced, and used concept among physicists in this field. I am here thinking of such areas as, e.g., particle physics, astrophysics, and string theory. However, when it comes to the scientific community at large, my impression is, at the same time, that the concept of spacetime is unclear to many. Or that they do not consider spacetime as something real, but rather a useful abstract concept. The majority are aware of the consequences of the special theory of relativity, such as time dilation and length contraction, and they know about the concept of spacetime. But not many seem to have a deeper insight, or understanding of the special theory of relativity, or the concept of spacetime. Or is it perhaps the lack of same from my side, that makes me experience the situation in this way?

XIII. SPACETIME DIAGRAMS

A spacetime diagram is a good way to visualize and understand the special theory of relativity and the spacetime concept on. It is enough to consider the case of a two-dimensional spacetime, i.e., with one space dimension and one time dimension. It is easy to generalize this to the case when one has two or three space dimensions. Figure 8 shows an example of a spacetime diagram.

The space dimension $x$ is on the horizontal axis and the time dimension $t$
Figure 8: An example of a spacetime diagram.

on the vertical axis. Each of the lines in the spacetime diagram represents the motion of an object, such as a particle, in space with respect to time. The lines describe where each object in space are at every point in time. The slope of the curve gives the object’s speed. If a curve is not straight, this means that the speed is not constant, but the object instead describes an accelerated motion. In this case, the instantaneous velocity of the object is given by the slope of the tangent to the curve.

The red lines show the motion of two light beams in space, which occur at the highest possible speed, i.e, the speed of light, approximately 300 000 000 m/s. For simplicity we have in figure 8 chosen to use a second as time unit, and as
length unit a light second (ls), which is 300 000 000 m. Light speed expressed in light seconds is then 1 ls/s. All other speeds have a value between 0 and 1 ls/s, where the speed 0 means that the body is at rest. Light beams then always move according to the special theory of relativity along straight lines making an angle of 45 degrees to the coordinate axes.

Note that spacetime is not an Euclidean space where distances $s$ are given by the Pythagorean theorem, i.e., $s^2 = t^2 + x^2$. In spacetime distances are instead mathematically defined by "$s^2 = t^2 - x^2$. (We could just as well have chosen to define distance as "$s^2 = x^2 - t^2", i.e., with opposite sign.) Since this distance also can become negative, it cannot in general be seen as the square of a distance $s$; hence the quotes around $s^2$ above. One can instead consider "$s^2" as a single symbol. But this in itself is nothing strange or mysterious. We can choose ourselves to define distance in spacetime as it pleases us, as long as we do it in a consistent manner so that no logical contradictions arise. That we have chosen to denote the distance measure as the square of something is just to show an analogy with the Pythagorean theorem. Since I do not want to go too much into the mathematics here, it is enough to explain in this rough or sketchy way.

Each point in the spacetime diagram represents a unique event in spacetime. The two-dimensional plane therefore consists of all events that take place in spacetime. The coordinates $x$ and $t$ correspond to the position and time coordinates, respectively, relative to a reference body or inertial reference system which we have chosen to regard as being at rest. Each point in space on this reference body has a position coordinate $x$ equal to the number of measuring rods away the point is from our chosen origin in space. At every point in space we can, in principle, imagine that there is a clock which is synchronized with all other clocks that are at rest relative to this reference body. Every point in spacetime
can therefore be indicated by a unique coordinate pair \((x, t)\), which gives the spacetime coordinates for this event relative to the reference body that we have chosen to regard as being at rest.

Since there are no reference bodies which are in absolute rest, we could just as well indicate each point in spacetime relative to another reference body with coordinates \((x', t')\). There are infinitely many inertial reference systems; more specifically, one for each velocity between -1 and 1, indicating the relative velocity of a reference body relative to a specific, but arbitrarily selected, reference body, e.g., the reference body with coordinates \(x\) and \(t\). (Inertial reference systems which differ only by a normal rotation in the spatial space, I here regard as equivalent, and not as different inertial reference systems.) A negative velocity indicates that a body is moving in the negative \(x\)-direction in space. Figure 9 shows where the coordinate axes, belonging to the reference body with coordinates \(x'\) and \(t'\), will be in relation to the reference body with coordinates \(x\) and \(t\).

Let us refer to the coordinate system \((x, t)\) as \(K\), and the corresponding reference body as \(R\); and similarly for the other coordinate systems and reference bodies. We have here chosen to consider \(R\) as being at rest. Therefore the \(t\)-coordinate axis points only in the time direction of \(K\). Since \(R'\) moves relative to \(R\), the clock in the origin of \(K'\) moves relative to \(R\) along the line that constitutes the \(t'\)-axis in the coordinate system \(K\).

A line which is parallel with the space axis of a coordinate system, corresponds to events that are simultaneous relative to one another in this coordinate system. E.g., are all the clocks that are at rest relative to \(R'\) and are located along the \(x'\)-axis, synchronized to one another relative to the coordinate system \(K'\), and all show the time \(t' = 0\) (see figure 9).
Consider different reference bodies which are in constant uniform motion relative to one another, i.e., different inertial reference systems. A coordinate system is thus a set of coordinate pairs $(x, t)$, which in a systematic way indicate all the events in spacetime relative to a certain inertial reference system. For each coordinate system, there is to each event a corresponding coordinate pair, i.e., each event corresponds to an infinite number of different coordinate pairs.

Inversely, assume that one has labeled each event in spacetime with a coordinate pair $(x, t)$. All these coordinate pairs together constitute a coordinate system. Further assume that one has labeled the events in spacetime in such a way, that one has an infinite number of different such coordinate systems. This means that each event is labeled by an infinite number of coordinate pairs. In addition to this, also assume that one has labeled the events in such a way, that these coordinate
systems are related to one another in the way that the special theory of relativity (Lorentz equations) prescribes that they should.

This gives us a set of an infinite number of different coordinate systems, which in a systematic way label and structure all the events in spacetime. One can now choose to view each coordinate system as corresponding to an inertial reference system. The space and time coordinates in every coordinate system, then correspond to the position and time of events relative to the corresponding inertial reference system. Hence can, for instance, the set of events in spacetime corresponding to straight lines parallel with the space axis of any coordinate system, be viewed as simultaneous events in the inertial reference system corresponding to this coordinate system. And the set of events corresponding to straight lines parallel with the time axis of any coordinate system, will be the paths in spacetime that objects, which are at rest relative to some reference body, will follow (see figure 10).

One can think of a spacetime diagram as a graphical representation of the Lorentz equations. By studying a spacetime diagram, one sees how space, time, and simultaneity change for reference bodies in motion relative to a reference body at rest. Thanks to the spacetime diagram representation of spacetime, one can demonstrate both the Lorentzian and the spacetime interpretation of the special theory of relativity only by interpreting the diagram in two different ways.

The Lorentzian interpretation, which is of absolute character, means that one and only one of the coordinate systems in the spacetime diagram corresponds to a reference body which is in absolute rest relative to the absolute Newtonian space. Assume that the reference body corresponding to the \((x, t)\) coordinate system, is in absolute rest. In the Lorentzian interpretation, time is also absolute. Assume that in the present moment in time, the absolute time has a certain value, say \(t = 0\). This means that only those events that are on the \(x\)-axis in figure 10
Figure 10: Coordinate systems of different inertial reference systems shown relative to one another.

exist. All other events in the spacetime diagram do not exist in this moment in time. All other reference bodies are only seemingly (i.e., seen from an observer’s point of view) equivalent to this absolute reference body. Thus, for all other reference bodies, time objectively seen goes slower and distances objectively seen are shorter, relative to the reference body which is in absolute rest. By studying the spacetime diagram with this in mind, it is easier to understand how, accord-
ing to the Lorentzian interpretation, all reference bodies can seem to be equivalent.

With a spacetime interpretation, there is no inertial reference system which is in absolute rest. All events in spacetime have the same degree of existence. One could compare the spacetime with a tabletop (which we can imagine to be so large that we do not see the edges of the tabletop). Imagine that one has drawn up straight lines across the whole tabletop, all parallel with one another. Now it is not the case that the tabletop only exists along one of these lines, or that the tabletop only exists along one of these lines at a time. For what would it even mean to say such a thing!? The tabletop is, of course, something we imagine exists as a whole.

It is the same way with space and time in the spacetime interpretation. Space is there not something which exists along one parallel line at a time in spacetime, as the hand of the absolute time moves around its clock face. ["One parallel line at a time" would instead have become "one parallel plane at a time", if we would have considered two space dimensions instead of one space dimension, and "one (parallel) three-dimensional space at a time" if we instead would have considered three space dimensions.] Spacetime is not a (infinite) three-dimensional space that, together with its contents (such as particles, magnetic fields, stars, planets, etc), change appearance "as the hand of the absolute time moves around its clock face". For the first, there is no absolute time according to the spacetime interpretation. Secondly, spacetime is not something that changes with time, since time is already included in spacetime. Spacetime only is. Spacetime exists as a whole. Different inertial reference systems or coordinate systems, are just different ways to arrange ("to network", draw up, or structure) spacetime. All inertial reference systems are equivalent. No inertial reference system can claim to be "absolute" or "more correct" than any other inertial reference system; in the same way as no coordinate system (with orthogonal axes) on a plane, can be
Figure 11: Two different space coordinate systems of the same plane.

considered to be "absolute" or "more correct" than any other coordinate system (with orthogonal axes) [see figure 11].

According to what has been said above, a coordinate system $K$ in spacetime allows the concept of inertial reference system, reference body $R$, and the concept of an observer who is at rest relative to $R$. Each and every one of all the lines that are parallel to the $x$-axis of $K$, corresponds to $R$ at different points in time $t$. All events that are on such a line, occur simultaneously relative to $R$ at a time $t$ (given by the intersection of this line and $t$-axis of $K$).

The time order between two events $A$ and $B$ in spacetime, i.e., which one that occurs before or after the other one, is coordinate system dependent. If $A$ and $B$ are simultaneous relative to a reference body $R$, then it is always possible to find
a reference body $R'$ where $A$ occurs before $B$, and a reference body $R''$ where $B$ occurs before $A$. Hence the time order is not absolute. To ask which of the events $A$ and $B$ that really occurs first, makes as little sense as to ask which of two points in a plane that lies ”highest up” in the plane. Which point that lies ”highest up” depends on which coordinate system one refers to.

Consider two different coordinate systems $K$ and $K'$, with orthogonal coordinate axes, in a two-dimensional spatial space (see figure 12). Which of the points $A$ and $B$ that lies ”highest up” in the plane, is coordinate system dependent. In $K$ point $B$ lies higher up than $A$, because it has a larger $y$-value. But in $K'$ point $A$ lies instead higher up than $B$, because it has a larger $y'$-value. It is therefore not meaningful to ask which of two points that lies ”highest up” in a plane in any absolute sense, but it only makes sense if one also specify the coordinate system that one refers them to. Analogous to this, the time order
between events $A$ and $B$ (see figure 13) depends on which coordinate system one compares them in. Relative to $K$ the event $A$ occurs before $B$, while relative to $K'$ the event $B$ occurs before $A$ (since $B$ lies below and $A$ above the $x'$-axis).

However, in spacetime there exist (infinitely many) combinations of pair of events $A$ and $B$, with the same time order relative to one another in all inertial reference systems. This is the case for all events which are in each other's future or past light cones. An event’s light cone is defined as, all the events which can reach, or be reached from, this event with a signal whose maximum speed is the speed of light. To every event in spacetime there is a unique light cone (see figure 14). All events that are within the light gray area of spacetime, belong to event $O$'s future light cone, while all events in the dark gray area belong to $O$'s past light cone. All events that belong neither to the past, or future light...
cone to an event, are said to lie *elsewhere*. Each event which is located elsewhere relative to $O$, is in some inertial reference system simultaneous with $O$. These different areas are bounded by lines (or cones in a three-dimensional spacetime) corresponding to the paths of light beams through spacetime.

On the other hand, for such pairs of events $A$ and $B$, one can also always find an event $C$ which both $A$ and $B$ are simultaneous with in the following sense: Suppose that the event $B$ lies in the event $A$'s future light cone. Then there is always some event $C$, which in some coordinate system $K'$ is simultaneous with the event $A$, and in another coordinate system $K''$ is simultaneous with $B$ (see figure 14). An event $C$ can thus be simultaneous with two events $A$ and $B$ having the same time order in all inertial reference systems.

It is therefore perhaps tempting to regard events as more or less simultaneous, depending on whether they lie in, or outside one another's light cones. So perhaps it is, in some sense, meaningful to speak about an absolute, objective or ontological time order between certain events in spacetime after all?

However, the fact of the matter is that, in and with the special theory of relativity, Einstein replaced the notion of absolute simultaneity with a *definition* of the concept of simultaneity. Although a natural definition, it is strictly seen still an arbitrary definition of what is to be meant by the concept of simultaneity. A definition used by observers in the operational special theory of relativity as well as in the Lorentzian and spacetime interpretation. However, the Lorentzian interpretation assumes in addition to this that absolute simultaneity objectively seen exists. In the spacetime interpretation, spacetime is instead something which objectively seen exists as a whole. Those parts of spacetime which are "more towards the upper future part" of the spacetime plane, therefore cannot be

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considered to be more real than those parts of spacetime which are "more towards the lower past part" of the spacetime plane.

So concepts such as *simultaneity, past and future light cone, elsewhere*, etc, are created by and exist in relation to observers. What objective or ontological counterparts and significance these concepts have, depend on the interpretation one makes of the special theory of relativity. Because operationally or strictly seen these concepts only show different conditions, relationships or correlations that exist between events. E.g., that an event $B$ lies in another event $A$'s future light
cone, shows that event $B$ can be reached from event $A$ with a signal travelling at a speed that is lower than the speed of light. Or if the events $A$ and $B$ instead would be simultaneous in some inertial reference system, this shows, e.g., that it is not possible to send a signal between the events with a speed that is lower than the speed of light.

But what about the experience we all have that time has a direction? Because we experience that time goes from the past towards the future, and that we can influence what will happen in the future, but not what have happened in the past. It is true that time and simultaneity are inertial reference system dependent concepts in the special theory of relativity, but the direction of time is the same for all inertial reference systems, since time in all inertial reference systems points from a "common past" towards a "common future". Or to put it differently, the time axis in all inertial reference systems points "upwards" in a spacetime diagram. So in what way would then a time direction in spacetime really have an absolute meaning, if now spacetime and all its events exist as a whole?

With a spacetime interpretation, the time direction only has an objective or ontological counterpart and significance in that it shows certain conditions, relationships or correlations that exist between events in spacetime. The subjective experience of a time in motion and that time has a direction, is something that only exists in relation to a human brain or a (biological) machine of some other kind.

XIV. THE TWIN PARADOX

We will now see how one can explain the so-called "twin paradox" according to a spacetime interpretation of the special theory of relativity. The reason that I
choose the twin paradox as an example, is that I think it involves much of that which is central, interesting and puzzling with the special theory of relativity.

The scenario of the twin paradox is the following: Imagine two identical twins that are on Earth. One of the twins travels into space on a spaceship at a speed close to the speed of light, while the other twin remains on Earth. After a number of years have passed on Earth, the twin travelling in space returns from his (or her) trip. But when the twins are reunited, they are not of the same age anymore. The twin who stayed on Earth turns out to be older than the twin who traveled in space. It could, e.g., have been the case that the space travelling twin aged 5 years, while the twin who stayed on Earth aged 9 years, i.e., the space travelling twin after his journey is 4 years younger than his twin brother(!).

But if motion is something relative, should not the situation be symmetrical for the two twins? Relative to the space ship, was it not Earth which instead moved and the spaceship which was at rest? Should not the time then have gone slower on Earth than on the space ship? And if so, should not the twin on Earth have been the younger of the two when they reunited? This seemingly paradoxical scenario is called the "twin paradox".

Let us first point out that it is an experimental fact that reality behaves as described above in the twin paradox scenario. Admittedly one has not managed to build any spaceship that can travel at a speed close to the speed of light, so the twin paradox has not been experimentally verified exactly in the way that the scenario above describes. But one has shown that the twin paradox is in agreement with what experiments show when it comes to the microscopic world, i.e., for microscopic particles such as elementary particles and atoms. And there is no reason to expect that it would be different on a macroscopic scale, e.g., for
space travelling twins.

To be somewhat poetic, if one wants to see more of the world, i.e., travel far and wide in space, one gets to see a lot in a short amount of time. But if one wants more time for reflection, one would be wiser to stay at home. However, this is a truth with modifications, because one’s personal or subjective time always goes at the same rate regardless of how one moves. I.e., personally one does not experience that life becomes longer or shorter, no matter how fast one moves. However, different people’s lives may seem shorter or longer in relation to each other, depending on how they move relative to one another.

The so-called "twin paradox" is however not a real paradox. The special theory of relativity gives a completely logical and consistent explanation of why it must be the twin who went off on the spaceship that will be the younger of the two. The explanation in short has to do with the fact that the situation was not symmetric for the two twins. The difference between their situations is that the twin on Earth the whole time remained at rest relative to one and the same inertial reference system, while the twin who was on board the space ship did not. The twin on board the space ship in fact changed inertial reference system (at least once) during his trip. Because the spaceship must at some stage have turned around, in order to be able to return to Earth. And this means that the twin on board the space ship was not at rest relative to one and the same inertial reference system during the whole trip.

It does not really matter for the "twin paradox" exactly how the space ship moved during the trip. The only important thing is that the twin at some stage returns to Earth, so that the twins’ (biological) clocks, or in other words their ages, can be compared with one another when both are in the same place in space again.
Note that we in the train example above have already seen that the situation is completely symmetrical for both inertial reference systems when clocks instead are compared with one another at different places in space. But in the train example, the observers never changed their state of motion. Separately both of them remained the whole time at rest relative to one and the same inertial reference system. The embankment and the train never returned to a position that they at an earlier stage had already been in relative to one another. So in that case one was forced to make use of two different clocks along the embankment to compare times on the two reference bodies. This meant that one had to make use of synchronized clocks. The relativity of simultaneity thus enabled both reference bodies to maintain their opinions that the clocks of the other reference body go more slowly.

Assume that the twin who went off on the space ship, did it first with a constant speed away from Earth, and then returned with another constant speed (of course in the opposite direction since the space ship intends to return to Earth). How much time the space ship takes to accelerate up to the constant speed it then maintains, does not matter for the demonstration of the twin paradox. Nor does it matter how much time the space ship takes to reverse its motion, which also must involve an acceleration. One could even imagine that the change in velocity was instantaneous, i.e., a discontinuous velocity change, or an infinite acceleration if you like. In fact, the twin paradox has nothing to do with acceleration. Nor has the twin paradox in principle anything to do with twins for that matter. Instead to let a twin go off into space, one could instead replace the two twins with clocks. Neither do we need to accelerate the spaceship to a certain velocity. Instead we assume that the space ship going off, instead just passes Earth with uniform constant speed. On board the space ship is a clock $B$. 
When the space ship passes a clock $A$ on Earth, both clocks are set to show the time 0. The space ship then continues its journey into space with a constant speed.

At some point in time on the clock $B$ on board the spaceship, we assume that spaceship meets another spaceship which is moving towards Earth, also with a constant speed. On board this second spaceship is a clock $C$. We assume that the clocks $A$, $B$ and $C$ are all of identical construction, i.e., at rest they are all ”ticking at the same rate”. When the space ships pass one another, the clock $C$ is set to show the time that clock $B$ shows in this moment. Clock $C$ thereby ”takes over the time” from clock $B$, without clock $B$ itself needs to change its state of motion (inertial reference system). Clock $C$ then continues with constant speed back to Earth. When it passes clock $A$, one compares the times on the two clocks. One will then discover that clock $C$ shows a time which is before the time on clock $A$. In other words, clocks $B$ and $C$ in total appear to have been ticking at slower rate than clock $A$.

Note that we have not involved acceleration in the picture, which means that the twin paradox is independent of acceleration. That clock $C$ has ”lagged behind” clock $A$ has nothing to do with how the space ships are moving. However, how much clock $C$ has ”lagged behind” clock $A$, depends on how the space ships have been moving; because the faster something is moving, the slower time goes.

Thus, the difference between the Earth clock’s path and the spaceship clocks’ path through spacetime, is that the path of the Earth clock involves only one inertial reference system, while the path of the spaceship clocks involves two different inertial reference systems. Figure 15 shows how the twin paradox can be illustrated in a spacetime diagram. One can clearly see how the ”spaceship path” through spacetime involves two different inertial reference systems, while
Figure 15: A twin paradox scenario shown in a spacetime diagram.

the "Earth based path" through spacetime involves only one inertial reference system.

In the spacetime diagram shown in figure 15 one sees that the different paths
Figure 16: The shortest path between two points in space is along a straight line.

form a triangle in spacetime. (Depending on how the involved spaceships move, the paths through spacetime could, of course, form a more complex geometrical figure than a triangle.) An interesting observation one can make, is that there is an analogy here with the *triangle inequality* in the ordinary spatial space. The triangle inequality basically means that the *shortest* path through space, from a point \( Q \) to another point \( S \), is along a straight line. This means that, if one instead goes via a third point \( R \), then one goes a *longer way* (see figure 16). Analogous with this (though the other way around), in spacetime a straight line represents the *longest way in time* between two points, whereas all other paths are *shorter in time.*
All inertial reference systems will agree on that it was the twin who traveled in space, and then came back again, who aged the least. All in accordance with the predictions of the special theory of relativity. The special theory of relativity does not contain any logical contradictions in the case of the twin paradox; or in any other cases for that matter. Consequently there is no real paradox, i.e., no twin paradox.

But how does then reality manage the feat to get all inertial reference systems to observe that time moves slower for all other inertial reference systems in motion relative to them? And, despite this, how does reality manage the feat to get all inertial reference systems to agree on for whom time really has gone the slowest, when they decide to meet to examine the matter more closely?

The answers to these questions depends on which interpretation one makes of the special theory of relativity. Strictly seen, the special theory of relativity is an operational theory and it does not explain why or how reality manages this feat. It only says that it logically must be in this way, if reality is such that the speed of light is the same and that reality appears the same for all inertial reference systems. The predictions of the special theory of relativity are logical consequences of these two postulates. And both postulates and the predictions of the special theory of relativity, have been confirmed by countless number of observations and experiments. The special theory of relativity is a logically consistent theory, that describes how space and time change for bodies in motion.

However, the "Lorentzian interpretation" and the "spacetime interpretation" of the special theory of relativity, both offer an explanation of how reality manages this feat. According to the "Lorentzian interpretation", reality manages this feat by making time objectively seen go slower for clocks which move relative to the
absolute space.

In the "spacetime interpretation", it is not in the same way meaningful to talk about who is objectively seen the youngest or oldest, or for whom time objectively seen goes slower. In general one needs to meet at an event in spacetime to settle the matter. To be able to answer questions such as "who is the oldest or youngest" and "for whom the time goes the slowest", when the observers are at different events in spacetime, then one also has to specify relative to which inertial reference system one compares their ages or times to. And as we previously have established, are time and simultaneity coordinate dependent concepts. Therefore, it is not meaningful to ask which of two events that really or objectively seen occur before or after another event. All events in spacetime exist in the same way, and "all at once". Spacetime is.

The coordinate systems of the different inertial reference systems, just correspond to different ways to organize events in spacetime on, and they give the geometry and metric of spacetime. The grid of a coordinate system in spacetime thus shows how events are related to one another and gives the distances between events in spacetime. As we previously have pointed out, by distance is not meant an Euclidean distance, but distance in a spacetime sense, i.e., 

\[ s^2 = t^2 - x^2. \]

One can show that it follows from the Lorentz equations, that this distance measure is independent of the coordinate system it is measured in and thus works as an invariant distance measure in spacetime. All observers agree on what this spacetime distance measure between two events is.

From the spacetime diagram in figure 15, one sees that the spacetime distance between the event that the spaceship left Earth and the event that it passed clock C, is 2.3 years (\( s^2 = 2.3^2 - 0^2 \Rightarrow s = 2.3 \text{ years} \)). This spacetime distance involves only a change in time, because relative to clock B:s inertial reference
system, both events occur at the same place in space. There is only one inertial reference system for which this is the case. For all other inertial reference systems the events occur at different places in space, and then the space distance $x$ also enters the spacetime distance measure. The spacetime distance between the events, thus becomes the distance in time on clock $B$ between the events, also called the rest time or proper time, which in this case is 2.3 years. In the same way, the spacetime distance between the event that clock $B$ passes clock $C$ and the event that clock $C$ reaches Earth, is 2.7 years ($s^2 = 2.7^2 - 0^2 \Rightarrow s = 2.7$ years).

The total proper time on the space ships, between the event that clock $B$ left Earth and the event that clock $C$ returned to Earth, is $2.3 + 2.7 = 5$ years. This should be compared with the spacetime distance between the event that the space ship leaves Earth and the event that it comes back again, which was measured by the clock $A$ to be 9 years ($s^2 = 9^2 - 0^2 \Rightarrow s = 9$ years). The proper time on Earth between the two events is thus 9 years. The proper time on Earth hence becomes longer than the total proper time on the space ships.

In the spacetime interpretation, the twin paradox thus arises as a geometric effect in spacetime. Spacetime is not an Euclidean space, but distances are instead given by $s^2 = t^2 - x^2$. This distance measure relates events in spacetime to one another, in an analogous way to how the distance measure given by the Pythagorean theorem relates points in the ordinary space to one another. A distance in spacetime does not only involve a distance in space, but is a mixture of a distance in space and a distance in time. The ”triangle inequality in spacetime” mentioned above, describes how ”proper time distances” between events in spacetime are related to one another. The spacetime distance between two events in spacetime is something that all observers or inertial reference systems agree on. In this case, there is no relativity. The spacetime distance measure dictates
how "far" it is between each pair of events in spacetime.

What can be difficult, is to imagine how spacetime looks and hangs together as a whole. Just because we know how far it is between all events in spacetime, does not mean that we have an intuitive or clear picture of how spacetime globally seen looks.

Imagine the time before humans knew that the Earth was round and we thought that we lived in a world flat as a pancake. Let us imagine that our ancestors discovered that the distance between two points in their (and our) flat world was not given by the Pythagorean theorem, but by a different distance measure. Suppose that our ancestors could mathematically describe this distance measure, and understood that they did not live in a flat world after all. Even if they themselves did not realize it, we know that it must be the distance measure for a spherical surface that our ancestors here had discovered. But as long as they do not understand this, the overall picture of the world they live in, will be hard for them to imagine and to get an intuitive feeling for.

A number of geometric effects could have arisen for these ancestors, that would have had to do with the fact that they, just like us, lived on a spherical surface and not a flat surface. E.g., two twins going in different directions from a point on the Earth’s surface (e.g., the north pole), will eventually meet again at the point on the opposite side of the Earth’s surface (the south pole); or that the sum of the angles of a triangle is not 180 degrees, but always a greater number.

There is however a flaw in this analogy, which has to do with the difference between their situation, which is being confronted by a spherical distance measure in a flat world, and our situation, which is being confronted by a non-Euclidean
distance measure in an Euclidean world. For even if they lived in a flat world on the surface of Earth, their world was after all three-dimensional. They therefore knew what a spherical-shaped surface was, e.g., by studying an orange, or a round stone. But neither we, nor our ancestors, have something in our everyday world, which has an equally directly obvious and intuitive non-Euclidean geometry like the one that spacetime has. Thus, we do not really have any equally direct or obvious everyday experiences, which can give us an intuitive feeling for what spacetime is and looks as a whole. Moreover, as we have discussed above, we humans are probably equipped with a Newtonian approach to and notion of the world. We are therefore not familiar with looking at space and time in the manner that the spacetime interpretation tells us that we should. We often have to be satisfied with using mathematical descriptions, analogies, abstract concepts and images, to imagine what spacetime is and what it looks like.

But by accepting a spacetime interpretation, Einstein could with the general theory of relativity also come up with the idea that the geometry of spacetime could be *curved*, analogous with how the geometry of our flat two-dimensional world on the surface of Earth is really curved as a two-dimensional spherical surface. By doing so, Einstein could explain acceleration and gravitation as two sides of the same coin, i.e., as effects of curvatures in spacetime. But this leads us into the general theory of relativity, which is not the subject of this paper.

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