EINSTEIN, THE THEORY OF RELATIVITY AND TIME

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Summary

With Einstein, a little over a hundred years ago, the era of the theory of relativity began – one of the most celebrated, but also one of the most frequently debated ideas in physics. Many are enthusiastic about the theory; others see open questions and weak points in it; still others oppose it resolutely. In any case, it is hard to pretend that relativity does not exist – sooner or later we encounter it in school, in books or on the internet.

Let us look at where things "go wrong". Einstein understood time differently from how it is described by the definition of the second. Today, the second in physics is precisely defined (via an atomic clock) and is supposed to be the same everywhere and at all times: two identical clocks that are synchronised at the beginning must, according to this definition, again show the same time when they meet, as long as they both follow the same definition of the second.

Einstein, however, says something else. Let us imagine two pilots with identical watches who fly different routes. When they meet again, according to the theory of relativity one watch will lag behind the other, even though they were perfectly synchronised at the start. This contradicts the expectation that the definition of the second guarantees the same flow of time for both watches.

This text shows where relativity becomes tangled or leaves the reader without a clear answer, and it offers suggestions on how to understand these questions. It brings to the foreground a simple question: whom should we believe – the definition of the second or Einstein's prediction of differing times? If you are among those who are curious about why things work the way they do and where the source of the tensions lies, you are in the right place.

The aim? Less dogma, more clarity – and an opportunity for everyone to form their own opinion on the basis of understandable arguments.

1) The Theory of Relativity and the Speed of Light

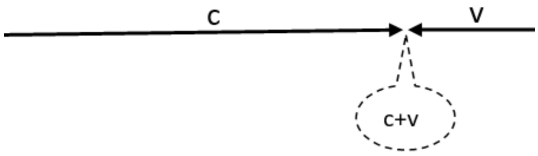
Einstein imagined that light in vacuum always has the same speed, regardless of who observes it or how the source moves. We denote this speed by the letter c. Together with his wife Mileva, he translated this idea into mathematical language, and the theory of relativity was born. Mathematically, the theory is elegant. The foundation of the theory is the postulate that in vacuum light propagates with a constant speed c.

If this assumption holds, the theory of relativity describes phenomena at very high speeds and in strong gravitational fields.

To make it easier to picture what we are talking about, let us use an anecdote about two observers. The first observer stands at the source of light, and the second is at the sink – at the point where the light is intercepted.

Light leaves the source with speed c. The observer at the source (from the perspective of Maxwell's theory) knows that light travels with speed c along its entire path to the sink.

Now imagine that the sink is moving towards the source with speed *v*. In the frame in which the source is at rest, the observer sees the following: the light beam travels toward the sink with speed *c*; the sink moves toward the beam with speed *v*; the distance between the beam and the sink therefore shrinks at the rate *c + v*.



This is also how we learn it in elementary physics: if something moves towards us, the speeds are simply added. Such a closing speed (*c + v*) can also be accepted by the theory of relativity – as the speed at which the distance shrinks, not as a "new speed of light".

Now let us also look at the observer at the sink. The theory of relativity says that this observer will always measure the light as striking him with speed *c*, not *c + v*. It also says that the light is moving away from the source with a speed that is not equal to *c*. As a result, in his frame of reference the description of the motion of light between the source, the sink and the beam is much less intuitive than in Newtonian (classical) physics, where we simply imagine that light leaves the source with speed *c* and arrives at the sink with speed *c + v*.

The influence of the observer's speed on the description of the speed of light is mentioned in relativity. One must always know who is observing what, which is more demanding than the Newtonian viewpoint. In addition to conceptual ambiguities, there are also terminological ones: one should distinguish between the "closing speed" and the "incident speed". In relativity these terms are not always explained in a pedagogically clear way.

The purpose of this introductory chapter is not to resolve all these ambiguities. There are many of them, and many are difficult to understand. The goal here is to draw attention to the style of writing and understanding in the theory of relativity. In what follows we will not attempt to clarify these issues. Instead, we will focus on another, somewhat simpler question in the theory of relativity: how this theory understands time.

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2) What Does a Second Measure?

In physics we measure time in seconds, as defined by the official definition of the second. In 1968 the General Conference on Weights and Measures (CGPM) unanimously adopted the standard for the length of the second and the method of measuring time. The second is defined as 9,192,631,770 oscillations of a specific transition of the cesium-133 atom in an ideal clock [1]. In practice this means that every good clock ticks locally at the same rate; one second is equally long everywhere. We measure the time between two events by counting the number of seconds between them.

From this follows a uniform and unambiguous way of measuring time. At this point, however, we encounter the concept of time measurement in the theory of relativity. The theory of relativity agrees with the definition of the second, but differs in the way time is understood: in relativity the passage of time is influenced by gravity and by the observer's speed, which do not appear in the standard definition of the second or in the procedure for measuring time.

We thus have two mutually incompatible views: (1) the definition of the second, which is supposed to hold always and everywhere, and (2) the theory of relativity, in which time can flow differently. This confuses us. Because differences in time measurement reach all the way to the foundations of physics, it is important to explain them and present these discrepancies using understandable examples. The first such example is presented in the next chapter.

3) The Story with the "Athletic Coaches": Motion and Time

The definition of the second does not allow any extension with respect to the motion of the clock or with respect to the gravity in which the clock is located. The definition of the second is independent of motion and gravity, and whatever we might want to add on top of it is an act of violence against that definition. Let us illustrate what this "violence" leads to with the following story.

Imagine an athletics club on a distant planet that moves relative to Earth at half the speed of light. On both Earth and this planet we measure time with the same cesium (Cs) clocks. At both locations we organise a 1000-metre race and then compare the race times of the athletes from both clubs. It is agreed, also in relativity, that the clocks at both venues run at the same rate. There is no ambiguity in evaluating the recorded times. So where does the problem arise?

According to the theory of relativity, time flows at the same rate only when it is measured locally. However, when we compare two clocks in different worlds, it turns out that the times on the clocks can differ. On the planet that moves relative to Earth with speed 0.5*c*, they conclude that time here on Earth runs about 13% slower than the definition of the second would suggest, because of our motion relative to them. Our clock does not show this slower passage of time that they would expect; it always shows us standard seconds, regardless of our motion relative to them.

According to the theory of relativity, even they themselves have two mutually contradictory views regarding our clock. On the one hand they know that locally our clock runs in accordance with the definition of the second; on the other hand they claim that our clock runs 13% slower. We do not even know for whom and for what this slower time is supposed to be meaningful. They thus have two conflicting views of the passage of time on Earth. Here we must ask: how, and why, is this so?

The theory of relativity says that the observer on the distant planet should not understand this slower passage of our time as an illusion caused by the great distance and high speeds. He claims that time on Earth really runs slower, even though we ourselves do not notice this on our own clock. For us, this slower flow of time has no use, because we do not experience it, even though we move at half the speed of light relative to the observer on the distant planet. Our clock shows us the same time regardless of the speeds of the various observers who may be watching us.

This slower flow of time is therefore something that I do not notice and cannot measure. For me it is not measurable, because my clock always shows the standard time; for the distant observer it is only something that can be calculated, not directly measured. It is difficult to regard something that is neither observable nor measurable as a scientific concept.

The theory of relativity may be mathematically impeccable. The difficulty lies not in the mathematics, but in the fact that this mathematics may not describe reality. From this perspective it does not describe reality because it is based on the assumption of an always constant speed of light, rather than on a firm empirical confirmation of the speed of light in all circumstances.

4) Clocks at Different Heights: Does Altitude “Speed Up” the Flow of Time?

The example of the running competition over large distances and at high speeds cannot be observed simultaneously at both locations. However, we can search for measurable examples of the theory of relativity in our immediate surroundings. Let us imagine two athletics clubs at different altitudes: one in the valley and one on a hill. At both clubs, the clocks locally run at the same rate according to the definition of the second. In this case as well, we can measure the results of a 1000-metre race locally and objectively compare the performances of the runners. Such a measurement of time is in agreement with the theory of relativity.

Up to this point there are no differences. The difference arises when we compare the two clocks with each other. Supporters of the theory of relativity believe that the clocks on the hill and in the valley run at the same rate only when they are observed separately and locally. Then both clocks run in accordance with the definition of the second: the clock on the hill is observed by those on the hill, the clock in the valley by those in the valley.

In the theory of relativity there is also a cross-comparison of clocks: according to its supporters, higher-lying clocks, when the clocks are compared with one another, run faster than those at lower altitudes, while the lower-lying clocks run slower than the higher ones.

This explanation is hard to imagine. A clock that runs synchronously and in accordance with the definition of the second when viewed separately is supposed to show a different time than the standard time when the two clocks are compared. Such a view is “magical” in nature, and thus merits a closer look.

In such a case, the clocks are not so far apart that they could not be compared in practice. To remove any doubts that the difference between the two clocks might be due to inaccuracy, let us posit an ideal clock. Even very accurate clocks may deviate by a few nanoseconds per year. By an “ideal clock” we mean one that does not have even this deviation.

5) The Ideal Clock and the Definition of the Second

In a room I hang two clocks on the wall, one near the floor and one under the ceiling. In the theory of relativity it is agreed that the two clocks run at the same rate and show the same time if we observe either one or the other separately and do not compare their times. However, when the two clocks are compared with each other, according to the theory of relativity we should observe that after some time they show different times.

This way of looking at time is self-contradictory. Each clock has its dial and runs at the rate that we read directly from that dial. The hands on the clock cannot show one time when the clock is observed “locally” and another time when the two clocks are compared. A clock can show only one time on its dial, regardless of who is looking at it.

Here we allow the possibility that the clocks are some distance apart and that light from the clock takes some time to reach the observer. We know how to take this into account: we calculate how long the light needs to travel to the observer, and from this we infer whether the two clocks are showing the same time or not.

Supporters of the theory of relativity try to support the idea of different rates of clocks at different altitudes with experiments. A laboratory experiment is often mentioned in which time was measured at different altitudes with two clocks whose mechanisms were only 33 centimetres apart vertically (NIST, 2010) [2]. The measurement is said to have shown that the two clocks run at different rates.

Over the course of one year, the relativistic calculation predicts a time difference between the clocks of about 1 ns. This time difference is much smaller than the typical annual uncertainty of the clocks (around 10 ns). We must therefore ask whether we can really measure such a tiny relativistic effect with a clock that is less accurate than the effect itself. The publication of such a measurement casts a poor light both on the methodology and on the reported results. A measurement of this kind raises the question of whether science truly has an appropriate methodological tool for such tests.

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6) The Definition of the Second

These considerations are confusing, so let us look more closely at the definition of the second. Let us observe two time-synchronised ideal clocks. We call them ideal in order not to have to think about possible random inaccuracies. Two clocks are ideal if at all times they show exactly the same time. Ideal clocks show the same time regardless of gravity, regardless of the speed of their motion, and regardless of who is observing them and how. In the definition of the second there are no additional conditions that would have to be satisfied for a clock to show ideal time. According to the definition of the second, the two clocks run at the same rate – full stop.

In relativity, the two clocks are not supposed to show the same time if they travel with different speeds through different gravitational fields and later return to their starting point. This claim disagrees with the concept of an ideal clock. We thus have two conflicting basic definitions, and this conflict should not be ignored. The ideal clock measures time differently from how time is supposed to pass in a gravitational field according to the theory of relativity.

In the theory of relativity this conflict is either overlooked or perhaps even deliberately left unmentioned. Instead, emphasis is placed on measurements that are said to confirm the laws of the theory of relativity and thus refute the definition of the second. For example, the measurement from 1971 is often cited, when Hafele and Keating carried out an experiment with an aeroplane and an atomic clock. They supposedly measured the influence of the aeroplane’s speed and altitude on the rate of the clock. They reported a time difference of several tens to several hundreds of nanoseconds, which is measurable.

Such measurements force us to decide either for the definition of the second or for the theory of relativity. The definition of the second and the “measured” passage of time on the aeroplane are in contradiction. The definition of the second does not include conditions such as the clock’s speed of motion or the gravity in which it is located. According to the definition of the second, a clock runs the same way regardless of the circumstances.

The authors of the measurement did not object to the definition of the second. They behave as if they do not notice the contradiction. They leave it to us to decide which of the two we should believe. Our personal, perhaps even emotional judgment of this conflict is not a scientific approach. Science should offer a clear, unambiguous and well-argued definition of the second.

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7) The Theory of Relativity Is Not Consistent with the Definition of the Second and with Time Measurement

The relativistic view thus more or less “threatens” the definition of the second, and vice versa. On the one hand, we recognise the definition of the second and time measurement as something unconditional; on the other, we carry out measurements and even accept their results when they contradict this definition.

The measurement of clocks on aeroplanes would make sense if we were evaluating two opposing viewpoints and, on the basis of the measurement, tried to refute either the definition of the second or the theory of relativity. But we cannot at the same time accept the relativistic view of time and accept the definition of the second in its original sense.

Among the supporters of the theory of relativity a well-known hypothetical example is the so-called twin paradox. The twins supposedly age differently if one of them travels differently from the other. In the light of the definition of the second, this story is completely superfluous, because the twins age in the same way – that is, in the way measured locally by an ideal clock – regardless of where and how they travel. Here the tension between the definition of the second and the relativistic view of time is particularly evident.

We can expect answers to the question of the influence of gravity or the clock’s speed on its rate from the European ACES (Atomic Clock Ensemble in Space) system for time measurement on the International Space Station (ISS). The cesium clock PHARAO on the ISS makes it possible to carry out precise comparisons between clocks in space and on the ground. ACES was launched on 21 April 2025; installation on the Columbus module followed on 25 April, and the first switch-on took place on 28 April 2025.

We are still waiting for the results of these measurements. We can reasonably expect only one result: that the clock on the ISS runs at the same rate as the clock on Earth, regardless of how we compare them. A delay in publishing the results may also occur if the authors of the experiment had certain expectations that the measurements did not support.

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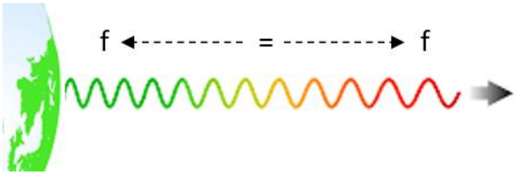
8) Gravitational Shift: Frequency, Wavelength and the Colour of Light

Supporters of the theory of relativity cite measurable phenomena in support of their arguments. When light passes from a stronger gravitational field in a valley into a weaker field on a hill, we observe (measure) a shift of spectral lines (roughly speaking: the colour of the light changes).

Let us send, between the hill and the valley, an electromagnetic wave with the frequency of a cesium clock, f = 9,192,631,770 Hz. Locally we measure that the frequency of this electromagnetic wave is the same in the valley and on the hill.

The wavelength of this wave is also the same in the valley and on the hill when we measure it locally. Things change, however, when we measure on the hill the wavelength of a wave whose source is in the valley. In this case we observe a redshift – the wavelength of the light becomes longer. A change in wavelength along the path, with an unchanged locally measured frequency, is evidence that the wavelength of light changes as it moves through the gravitational field. With an unchanged frequency this means that its speed also changes.

The relativistic explanation does not accept a change in wavelength and thus in the speed of light, because the entire theory of relativity is built on the assumption of a constant speed of light. According to the relativistic explanation, the clock in the gravitational field runs more slowly, so the frequency of the light at the source changes. Such an explanation is not acceptable, because the frequency of the wave (of the Cs clock) can be measured.



The change in the “colour of the light” that we observe is therefore not the result of a change in the light’s frequency at the source, but of a change in wavelength along the path. Gravity affects the wavelength and thereby also the speed of light. The frequency of the light remains the same.

Here the viewpoints diverge sharply: supporters of relativity consistently defend a constant speed of light and explain the redshift/blueshift through a changed rate of time at the light source. The definition of the second, however, demands that the second remain independent, and therefore the frequency of the light should also be independent of gravity at the source.

We thus have two explanations of the redshift/blueshift of light from a gravitational field: the first is based on a change of frequency at the source (which undermines the definition of the second), the second on the influence of gravity on the speed of light (which undermines the postulate of the constant speed of light on which the theory of relativity rests). This is a key question; an answer to it can offer a way to understand the issues and dilemmas presented here.

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9) The Life Cycle and Maturity of the Theory of Relativity

The theory of relativity has been a popular scientific topic for more than a hundred years. In this time the inconsistencies mentioned here have often been criticised, but this has not diminished its popularity.

The theory of relativity often has a sensational flavour, for example in the so-called twin paradox. People generally crave sensations, which constantly encourages a broader circle of admirers to delve deeper into the theory of relativity. For many of them it is not even necessary to understand the paradox of the twins; it is enough to have the feeling that “miracles” also happen in “science”.

The theory is also interesting for those who know physics. The mathematical models of the theory of relativity are presented in various graphical forms, where physicists can construct their own “sensations” in relation to the light cone – something like solving crossword puzzles that we never get tired of.

The popularity of the theory is supported by a significant number of physicists who are willing to overlook the obvious contradictions between relativity and the definition of the second and who look for evidence in the form of measurements that supposedly confirm the theory. Among these measurements, however, we do not find any that would confirm the theory of relativity unambiguously in a way suitable for pedagogical use. The measurements mainly inspire those who already believe in the results in advance.

There is also a large number of physicists who do not deal with the theory of relativity. They know its weaknesses and contradictions, but see no reason to draw attention to them. The theory itself has no noteworthy impact on our everyday lives; in our surroundings it neither supports us nor hinders us, so there is no reason to invest effort in giving the theory a "final epilogue".

Because, in this view, the theory of relativity has no influence on everyday life, the theory is given a second-rate role. Its supporters therefore try to find reasons to place it more in the foreground. They often point out, for example, that the clock on a navigation satellite (GPS) runs faster by 38 microseconds per day than a clock on Earth. This faster passage of time on the GPS satellite is questionable for two reasons: (1) data on GPS are said to be a closely guarded military secret of the U.S. armed forces; (2) the clocks on GPS satellites can be adjusted remotely from Earth, and over a range that exceeds 38 microseconds per day by several times. The clocks on GPS satellites are therefore supposedly synchronised remotely with clocks on Earth, without any prior consideration of relativistic time effects.

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10) The Universality of the Theory of Relativity

The theory of relativity describes phenomena at high speeds and in strong gravitational fields. One would expect that the higher the observed speeds are, the more sensible it becomes to use the theory of relativity to describe such phenomena.

Consider, for example, two photons that travel from the Sun toward the Earth side by side, at a fixed distance from each other (say a few metres); their journey lasts just over eight minutes. We can say that the two photons remain at the same distance from each other all the time, but the theory of relativity does not allow us to say that they are at rest with respect to each other. Why not? Because for light it is supposed to be true that it always has the speed of light, everywhere and always, relative to anything. According to the mathematical rules of the theory of relativity, the two photons therefore have only two possibilities: either they move relative to each other at the speed of light (even if they remain at the same distance), or their relative speed cannot be determined at all. In the theory of relativity the photon has no rest frame of its own; the "relative speed of two photons" is therefore not a defined concept. In this respect the theory of relativity loses transparency and comprehensibility.

Mathematics ought to describe our observations in an understandable way, and the observations ought to be reflected unambiguously in the mathematics. In the case of two photons, the mathematics of the theory of relativity is far from our expectations and intuitions. This raises the question of whether the relativistic description of the motion of photons is really the best that physics can offer as a comprehensible picture of rapidly moving particles.

We have several similar concerns about the universality of the theory of relativity. Let us mention one more. The electric and magnetic fields within an electromagnetic wave change and propagate at speeds that may even exceed the speed of light. Here we encounter a difficulty: at very high speeds, time slows down dramatically, seconds become very long, and spatial dimensions contract to a point.

We do not see these effects of field speeds on the passage of time in the form in which Maxwell's equations are written. Those equations mathematically describe the electromagnetic wave without any slowing of the flow of time. Maxwell's equations are based on an understanding of electromagnetic waves in the way that Newton's physics describes phenomena and time.

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11) The Speed of Light and Our View of the Universe

Even if the theory of relativity has no effect on everyday life, it can, on the other hand, hinder and distort our view of the universe.

Let me illustrate this with an example. The explosion of a supernova can be instantaneous or very short-lived, but on Earth we see it as an event that can last for months. The apparent duration does not reflect the true length of the explosion itself, but the fact that light from different glowing parts of the supernova, which move at different speeds, reaches us at different times and thus apparently stretches out the event.

Another example is pulsars. On the way from a pulsar, light beams that move at different speeds catch up with one another and, upon merging, create interference, which gives us the impression of very rapid rotation of the pulsar. The pulsar may in reality rotate slowly; the rapid pulsation is just an apparent effect, a consequence of the interference of the light when beams with different arrival times catch up and merge.

An understanding of the speed of light that is too shallow – and possibly even mistaken – also affects our understanding of other phenomena, such as dark matter. We may not understand dark matter until we deepen our understanding of light.

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12) How to Recognise When a Belief Is “on Thin Ice”

From social developments in the past, certain criteria have emerged that warn us when a belief or theory does not rest on solid foundations. Let us look at some key, long-known warning signs and see what they mean for the belief in an always constant speed of light and for the theory of relativity.

It offers a very simple explanation of a complex problem.

The view of the speed of light rests on the claim that the speed of light is always the same. A scientific approach should be different: we should measure the speed of light under different conditions, clearly publish in which circumstances it has been measured and what the results are, and clearly state in which conditions no measurement has yet been made and the speed is therefore unknown.

The belief is strongly tied to identity or emotions.

In the case of the belief about the speed of light and in the case of the theory of relativity, we often see very personal and emotional defence of these notions. Many people identify with them, which could be summarised with the thought: “If this is not true, then who am I?”

The evidence consists mainly of anecdotes.

This warning criterion comes from other fields, but it is useful here as well. In the case of the theory of relativity these are not anecdotes in the usual sense, but rather questionable measurements that do not have broad scientific acceptance. Too often such measurements are intended for self-confirmation. When debates about such measurements flare up, supporters of the theory of relativity often conclude: “These results are good enough for me.”

It is hard to say what would convince us that we are wrong.

The theory of relativity is so deeply anchored in our thinking that we often see no reason for doubt and find it hard to imagine what could turn us away from this belief.

Every counter-argument is interpreted as an attack or a conspiracy, not as potentially useful information.

We usually accept most other sciences without much emotional involvement: if there are changes and progress, we are pleased and gladly extend our understanding of natural phenomena. In the case of the theory of relativity, however, things are often different because of emotional attachment, and any expressed doubt can easily make us angry.

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13) The Future of the Theory of Relativity

To resolve the inconsistencies mentioned, either the theory of relativity or the definition of the second will have to undergo a thorough revision. It is important that such a revision be supported both empirically and theoretically, and that its foundations be broadly understandable also in teaching. Many paths are open for such a revision; our task is to consider and evaluate them.

The redshift/blueshift in light from gravitational fields is not a self-evident proof that the frequency of light – and thus the duration of the second – changes, especially since a change in the rate of time would contradict the definition of the second. We must allow the possibility that gravity acts on light in such a way that its wavelength and speed change along the path, while its frequency (and consequently the rate of the clock) do not.

We thus have two views of the redshift/blueshift in light from a gravitational field, of which only one can be real and consistent with the rest of physics.

Fortunately, conditions for understanding physics are changing rapidly today. Let us mention artificial intelligence, which has also inspired this text. On the other hand, science has long planned the above-mentioned comparison of clocks (Earth–ISS) within the ACES project, which is crucial for assessing the inconsistencies discussed here [5][6]. Based on the earlier reasoning, we can expect ACES to show that the two clocks run synchronously and do not show different times because of gravity and the satellite's speed.

Of course, neither technological progress nor unambiguous results from ACES guarantee that science will quickly take a position on these open questions and soon make one of the key steps in the development of physics. Further progress can be significantly hindered not by physical, but above all by emotional obstacles.

Finally, let us remember that throughout human history various theories have arisen, matured, grown old and disappeared. We can expect the same life cycle in the case of the theory of relativity.

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