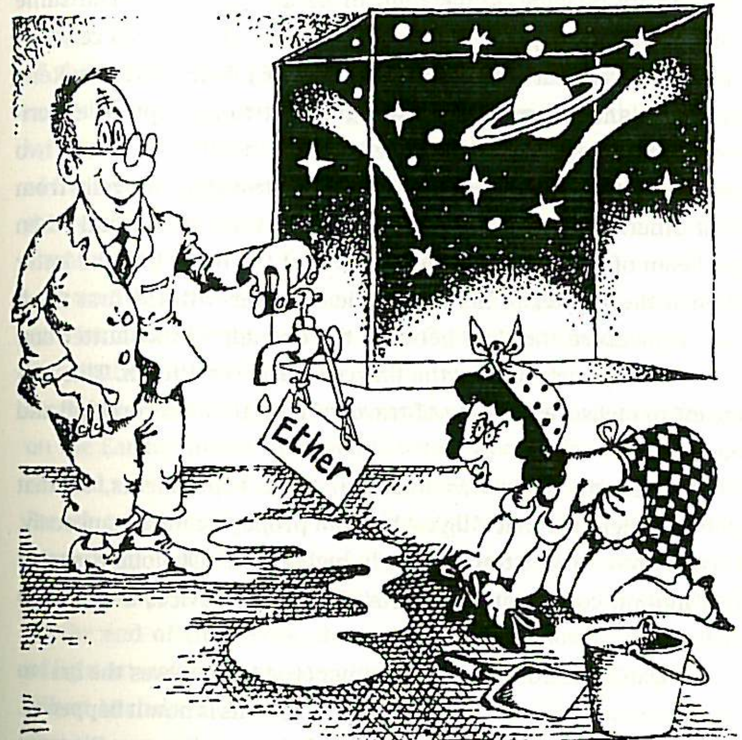
3

Light



I was not quite correct when saying that only motion at relatively modest velocities was known in Isaac Newton's time. Of course, this would be true if only the motion of physical bodies was meant. However, from time immemorial mankind knew a process which propagates at a truly fantastic speed. I mean light. What is it?

Suggestions that light consists of particles which are emitted by a glowing body were made in ancient Greece. Aristotle held this opinion and Newton also shared this point of view. Aristotle assumed the velocity of light propagation to be infinitely high. The same point of view was prevalent until the middle of the 17th century. This belief was shared by the great scientists Johannes Kepler, René Déscartes and others. Galileo was the first to attempt an experimental determination of the speed of light in 1688. He placed two torches on top of two hills at a distance of less than one mile from each other. First the shutter of one torch was opened and when the beam of light reached the observer at the other hill, the latter opened the shutter of his torch. The observer with the first torch was to measure the time between the opening of its shutter and the moment when he saw the flash of the second torch. This was meant to measure the time of travel of light to the second hill and back again.

However, no delay was found in these experiments, so that Galileo concluded that if light 'does not propagate instantaneously, then it does so at a tremendously high speed'. Obviously, such a fast motion could not be measured with the devices available to Galileo.

The Danish astronomer Ole Roemer (1644–1710) was the first to really measure the velocity of light in 1676. This is how it happened. In the middle of the 17th century, the Italian astronomer Giovanni Cassini, who became famous for his high-precision observations of planets through large telescopes, compiled tables of the motion of the Jovian satellites discovered earlier by Galileo. Further studies

demonstrated that the calculated moments at which the innermost satellite of Jupiter, Io, entered the shadow of the huge planet did not always coincide with observational data. In the month when the Earth, moving around the Sun, was at its maximum distance from Jupiter, the moments of eclipses were delayed in comparison with the calculated values by almost 22 minutes. When the observations were conducted at the minimum distance between the Earth and Jupiter, there was no delay.

When Roemer heard about this, he explained the delay in 1676 by suggesting that light needs 22 minutes to travel along the diameter of the Earth's orbit. By that time this diameter was known with considerable accuracy. Having divided the length of this diameter by 22 minutes, Roemer came up with the first numerical estimate of the velocity of light: about 214 000 km/s. It was found later that the velocity that Roemer reported was less than the true value by about one third.

It was thus shown for the first time that light does not propagate instantaneously: its velocity is finite, even though very high. Only in the middle of the 19th century was the velocity of light measured not by astronomical observations but directly in experiments on the Earth. These experiments, which were in fact greatly modernized versions of Galileo's experiments, were carried out by the French scientists Fizeau, Foucault and Carnot. Their experiments, carried out at different periods and with gradually better and better accuracy, yielded the velocity of light close to 300 000 km/s. At the end of the 1870s, the problem of measuring the velocity of light attracted the outstanding American experimental physicist Albert Michelson (1852–1931). The experiments he carried out at that time gave the value of 299 910 km/s.

This problem attracted Michelson until the end of his life. It was gradually becoming clearer that the velocity of light plays a fundamental role in the structure of the laws that reign in our world.

The final series of experiments to measure the velocity of light in Michelson's laboratory started in 1929. His daughter recalled that in May 1931, in the last days of his life, Michelson, world-renowned physicist and Nobel prize winner, waited impatiently for the final results of his experiments:

> On the seventh of May, Pease (Michelson's assistant) came to Michelson with the latest figures for the new determination of the speed of light: 299,774 kilometers per second. Michelson's face lighted up with an almost child-like pleasure. Knowing that he did not have long to live, he told Pease to pull up a chair and open a notebook at once so that he might start dictation. "Measurement of the Velocity of Light in a Partial Vacuum." The effort exhausted him, and after dictating the first paragraph, he fell into a peaceful sleep...
>
> On the morning of May 9, 1931, Michelson died.
>
> Dorothy Michelson Livingston, *The Master of Light*, 1973 (Charles Scribner's Sons)

These lines are evidence of what sort of people belong to the cohort for whom to gather knowledge about the Universe is the meaning of their lives; due to these scientists, we have penetrated profoundly into nature's mysteries. The current value of the velocity of light, determined by using an atomic clock, is 299 792.458 km/s. The possible error of this value does not exceed 0.2 m/s.

Michelson's name is also inseparable from the experiments which lead to the development of relativity theory. This theory, created by Albert Einstein at the beginning of our century, made it possible to look at the properties of space and time from a completely new standpoint.

Before describing Michelson's experiments, let us step back a century, to the time when physicists tried to figure out the nature of light.

The idea that light is of wave nature was first suggested by the Czech scientist Jan Marzi in 1648. However, a consistent theory of light was only created thirty years later by the Dutch physicist Christian Huygens. This theory explained elegantly a large number of effects in the reflection of light by plates, the formation of moiré films and other interference, diffraction and polarization phenomena, that the corpuscular theory of light was able to interpret only under very artificial assumptions or failed to explain at all.

Physicists had to argue, however, that if light is a wave phenomenon, the waves must propagate through some medium. The reigning hypothesis was that the propagation medium for light waves was the ether: the finest, all-permeating medium filling the entire Universe.

By the end of the 19th century, the theory of light waves propagating through the world ether was gaining ever increasing recognition.

Unfortunately, mind-boggling properties had to be ascribed to the ether. This medium had to possess hugely greater elasticity than ordinary matter, because only then could light vibrations propagate through it at the enormous velocity that we observe. It had to possess perfect zero viscosity, to allow heavenly bodies to move through it without any resistance, which was another feature observed experimentally.

However, difficulties of this sort were easily waved away: indeed, the ether was not 'ordinary matter'. Thus the well known British scientist Thomas Young wrote at the beginning of the 19th century, that in addition to the so-called solid, liquid and gaseous forms of matter, we also know semi-material forms that produce the phenomena of electricity and magnetism, and also ether.

Today's reader may be interested to know that Thomas Young, one of the creators of the wave theory of light, was a uniquely gifted person. He learned to read fluently when two years old and two years later was reciting numerous memorized verses; when eight years old, he had already constructed physical instruments, then rapidly mastered differential calculus and a large number of languages, among which were Greek, Arabic and Latin. He worked as a doctor, a physicist and an astronomer, but by the end of his life he was compiling an Egyptian dictionary.

Young carried out numerous experiments which proved the wave nature of light; he also provided exhaustive interpretations of these experiments. Young demonstrated that the oscillations in light waves are not longitudinal as in acoustic waves but transverse, as in vibrations of liquid particles in waves on the surface of water.

After the work of Young and other scientists, the wave nature of light was assumed to be proved beyond doubt. The theory of the world ether was treated as one of the most important achievements of 19th century science, and the existence of the ether itself was regarded as firmly established.

The entry for the ether, written at the very beginning of our century for the excellent and extremely popular Russian encyclopedia by Brokhaus and Ephron, says with complete assurance that once the experiments proved the validity of the wave theory of light, '... The existence of ether as an energy carrier where there is no matter in forms that are familiar to us, became proved and the ether ceased to be a hypothesis.' Several sentences later the author regretfully remarked that 'Nevertheless, arguments against the existence of ether are still encountered even in our time.'

We thus see that the majority of physicists firmly believed that there was a medium which permeated entire space. However, this meant that Isaac Newton's 'absolute space' was not empty but filled with ether. It was then natural to try and measure the velocity of motion of the Earth relative to the ether, and hence relative to the absolute space. If this were possible, Newton's absolute space

would cease to be a pure abstraction that does not manifest itself in anything, but would become a specific object of study.

Albert Michelson, whom I have already mentioned, became interested in this problem in the 1880s. He designed an excellent high-precision instrument now known as the Michelson interferometer, which was expected, according to calculation, to solve the problem.

However, how would one measure the velocity of the Earth with respect to the ether? Indeed, since by definition the ether wind blowing against the Earth flows freely through all bodies, producing no pressure at all, unlike the ordinary wind in the air, the expected displacement of the Earth relative to the ether could be determined in the following way.

Let us send light signals in a laboratory moving together with the Earth through the ether, along the direction of the motion, so that these light pulses return to the light source after being reflected by a mirror. Let us refer to them as signals A. Another set of signals B will be sent at right angles to the motion of the Earth. Signals B, reflected by another mirror at the same distance from the source as the first one, also return to the source. If the Earth is at rest relative to the ether, the signals A and B will obviously spend the same time traveling from the source to the mirror and back. If, however, the Earth is moving, then it is easy to calculate that these times will be slightly different. Signals B will need slightly less time to travel. Knowing the dimensions of the instrument and the delay time, it will be a straightforward matter to calculate the velocity of the ether wind blowing against the Earth because of its motion.

In Michelson's instrument, the path covered by the light signals was about 22 meters. If we assume that the velocity of the ether wind is the same as the velocity of the Earth on its orbit around the Sun, then the delay time of signals A was calculated to be only about three ten-thousandths of a millionth of a millionth of one second (three divided by one followed by sixteen naughts).

The instrument was so perfect and precise that it was capable of measuring a delay even a hundred times smaller!

Of course, the Earth moves in the ether not only along its orbit around the Sun but also moves with the Sun, together with the Solar System as a whole. Hence, the direction of the ether wind is not known beforehand. The experimenters were able to take that into account too. They made their instrument, which was floating in a pool of mercury, rotate slowly, changing its orientation. Finally, it could not be excluded beforehand that the orbital motion of the Earth at the moment of measurement was accidentally compensated for by the displacement of the Sun in the opposite direction. To exclude such a coincidence, experiments were repeated every three months, when the direction of the orbital motion of the Sun had changed considerably.

In 1887 Michelson and Morley published the results of a series of their most accurate measurements carried out with this instrument. They failed to detect any ether wind. At this time, Michelson wrote to the famous British physicist John Rayleigh that he had completed an experiment aimed at measuring the relative motion of the Earth to the ether, and that the result was decidedly negative. This result was baffling for everybody. Michelson was openly disappointed. Many people tried to find imperfections in his experiments or to reformulate the theories of the world ether; other experiments were conducted, including experiments on detecting the ether wind in the mountains where, according to the same hypothesis, the effect of the ether wind would be more pronounced. But it was to no avail. This great disappointment for Michelson turned out to be the greatest triumph of his life. The negative result meant that the ether not only leaves the motion of heavenly bodies unaffected (this was clear even before these experiments) but that it does not affect experiments with light either. Hence, it was an invention, a fiction!

However, the Michelson–Morley experiments were not only a death blow to the theory of ether. Their significance was much larger. In fact, these experiments proved that the motion of the Earth does not affect the velocity of light: it remains constant in all cases. Note that this conclusion was independent of the nature of light.

Nevertheless, what is light if it is not a vibration of an as yet unknown world-permeating medium, of a putative ether?

By the end of the last century, physicists were quite ready to answer these questions. The work of Michael Faraday, James Clerk Maxwell and Heinrich Rudolph Hertz proved that light comprises oscillations of the electromagnetic field, which can propagate through space as electromagnetic waves and needs no medium, no ether; it became clear, therefore, that nothing in nature can be put in correspondence with this 'ether'.

It was thus concluded that light in the form of electromagnetic waves propagates through space without the mediation of any ether.

The Michelson–Morley experiments and numerous other experiments demonstrated really surprising properties of light. It was found that regardless of whether the observer moves towards a light beam or recedes in the opposite direction, the velocity of the beam relative to this observer remains unchanged! (Note that with the advent of lasers, it was possible to confirm experimentally that the velocity of light is independent of the velocity of light sources to within 0.03 mm/s.) In Michelson's time this was quite incomprehensible. Indeed, it was quite clear that if a car is moving along the road at a speed of 60 km/h and the observer drives in another car towards the former car, then the relative velocity of approach towards the observer is 120 km/h. This is indeed so. In this example velocities simply add up. However, if one of the cars is replaced with a light beam, the answer is dramatically different. The velocity of approach to a light signal is unchanged by the observer's motion.

A well-known Polish physicist Leopold Infeld wrote that the famous Michelson–Morley experiment '...has ultimately proved that there cannot be different velocities of propagation for light... that these velocities are identical in all directions and their value is c, which is the velocity of light and which, in the most strange manner, remains itself, ever constant, ever unalterable.

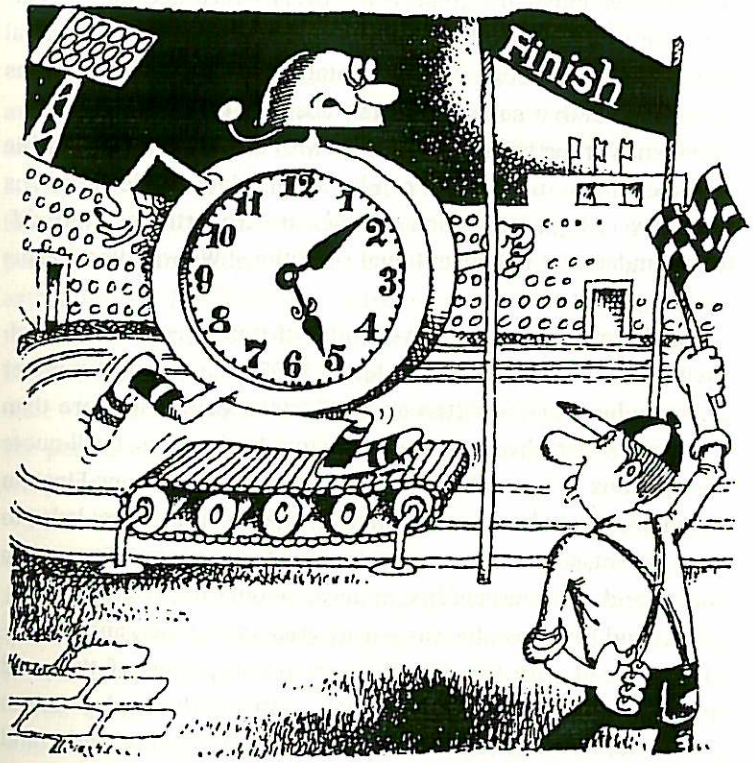
This result was catastrophic for the mechanistic view.'

Indeed, this was a really crushing blow to familiar notions. It was later understood (we are going to talk about it in subsequent chapters) that Michelson's experiments in fact demonstrated an inevitable conclusion: the properties of space and time undergo changes as the velocity of motion becomes very high.

This discovery, which signified a revolution in natural sciences, was made in 1905 by Albert Einstein.

4

The pace of time can be slowed down!



Here unfolds the story of the momentous achievements of science in the 20th century. I would say that the most impressive discovery was made at the very beginning of the century by Albert Einstein when he created relativity theory. He showed that there does not exist any 'absolute time', no unified unchangeable river of time which impartially carries all events occurring in the Universe.

Academician A. Alexandrov of the Academy of Sciences of the USSR wrote: 'Einstein's greatest discovery which became the cornerstone of relativity theory and a turning point in the general physical and philosophical interpretation of space and time was the revelation that nature knows no absolute time.'

Evidently, time behaves as a river with constant, unchangeable flowrate only in the habitual conditions of relatively slow motions and not very high interaction energies. Its properties are very different under very unconventional conditions! We will discuss this later in great detail.

The discovery of the relative nature of time is contained in relativity theory that Einstein created in 1905. An enormous number of books have been written about Einstein, definitely more than about any other physicist. Several factors explain this. I will quote the opinions of several well-known scientists who knew Einstein personally, and also Einstein himself; these sources may help, to some extent, to reconstruct the image of this personality and to understand the causes of his immense popularity.

First and foremost, he was a truly great researcher, and his discoveries dealt with the most mysterious properties of time and space. The scent of mystery invariably attracts those who wish to ponder the meaning of the world and our being in the world (and who are sufficiently strong to find time for this in the perpetual bustle of life). The USSR theoretical physicist academician Igor Tamm wrote:

> Einstein, whom Lenin regarded as one of the greatest revolutionaries in natural sciences, is rightly compared with Newton. I am of the opinion that this comparison is correct not only in the sense that Newton's and Einstein's discoveries signify pinnacles in human striving to comprehend nature, and that these pinnacles tower over 300 years of history of development in sciences and directly talk to each other. I think that Newton and Einstein can also be compared in the sense that Newton laid the foundation of modern natural sciences while Einstein's creation, his relativity theory, completed the edifice of classical physics.

In Soviet times, a reference to Lenin's authority was regarded as the highest commendation. Furthermore, I am aware that some Soviet physicists quoted Lenin in order to shield the progress of relativity theory in our country from very vigorous attempts to declare Einstein's creation a 'bourgeois, idealistic anti-science'; during one period, this onslaught looked very realistic. Well-known Moscow astrophysicist J. S. Shklovsky wrote that the '"bureaucratic warriors for the purity of Marxism" were admonished "from above": bosses realized that the military potential of the country is impossible without true physics'. I should remind the reader that this was the period when the USSR was developing its rocket and nuclear weapons.

I will return to Einstein's discoveries later. However, the greatness of these discoveries cannot fully explain the scale of his global fame, a fame that has not ebbed throughout the 20th century. This last observation is especially surprising since the ever-changing fashion of our time never ceases to generate new idols.

The decisive point was Einstein's personality. Soviet writer V. Kaverin once remarked: 'Above all others, I value in people kindness and courage. We may agree that a combination of these features makes a man a decent human being. These two qualities must inform his moral stance.'

I believe that these words give a pithy formulation of the concept of a 'fine man'. It is fairly difficult to withstand the test for these seemingly simple and clear criteria over the whole length of one's life. Not everybody succeeds in it, but so many do not even try.

Albert Einstein was kind and courageous. People who knew him well say that his kindness stemmed from his extraordinarily clear mind and was not subject to surges of feelings and emotions. Einstein helped numerous people. The fates of scientists who suffered persecution in Germany after Hitler came to power were especially close to his heart. The Polish physicist L. Infeld wrote in a magazine *Tworczosc*: 'Never in my life could I witness so much kindness completely devoid of emotion. Although only physics and the laws of nature lifted Einstein to true emotions, he never refused calls for help if he thought that help was really needed and concluded that this help could be efficient. He wrote thousands of recommendations, gave advice to hundreds of people, spent hours talking to a lunatic whose family wrote Einstein that he alone could help the afflicted man.'†

Is not this an outstanding example of kindness and mercy which are often in very short supply in our frequently cruel life? This purity of goals is all the more valuable because it emanated from a man who seemed to exist in the world of abstract formulas and far removed from real life. In fact, he *was* far from the little daily worries – in that area which did not touch the primary human values. He tried to spend an absolute minimum of time on the trivia of life, thus saving time for the really important. He wore his hair long to minimize visits to the barber, preferred a leather jacket to avoid shopping for a new suit as long as possible, decided to forgo socks, suspenders and pajamas. Immersed in his thoughts, he often ate

† Translator's comment: We follow the Russian translation of the original text in Polish in: *Einstein and Today's Physics* ed. E.B. Kuznetsova (Moscow: GTTL) 1956 (in Russian).

automatically, paying no attention to what he swallowed. And he *was* courageous! He never flinched from defending the just cause, never bothered whether his actions may have led to personal troubles. He took part in anti-war demonstrations even during World War I. All his life he agitated for peace and unity of people.

Being worried that Hitler's Germany could develop the atomic bomb, Einstein was one of those who helped initiate the work on this weapon in the USA.

He realized, even before the first atom bomb was exploded, the scale of the threat brought by nuclear weapons to mankind, and thus advocated international control of nuclear arsenals.

I will give here an excerpt from his letter to Infeld, written in 1950 but sounding topical and wise almost fifty years later.

> You know well that I hold the striving to true peace in the highest esteem. I believe that in the terrible situation we are now facing the direct measures that became increasingly popular have no chance of success because confidence in honest intentions of the opposing side declined everywhere. I have no immediate suggestions. Only some individual steps by the sides can be considered at present, which promise to revive the confidence without which there may be no approaches to sustaining international security.

Is it surprising, therefore, that this man excited hatred in people who were his antitheses. Such people went as far as founding an anti-Einstein organization, and called for having him murdered.

Here is how Einstein defined his moral position in a letter to his friend, the German physicist Max Born.

> What is required of a man is to show an example of purity of ethical principles and have courage for retaining these principles in a cynical society. I kept trying to live in this way for a long while – with various degrees of success.
>
> *Naturwissenschaften* **42** 425 (1955)

Max Born concluded: 'This is about ... the purity and honesty in thought and feeling. We bow our heads to Einstein as example and teacher in both respects.'

I will also mention Einstein's attitude to his unusual fame: he seemed to be absolutely indifferent to it. I will again quote L. Infeld:

> Einstein was utterly indifferent to his fame: he may be a unique person who was not affected in the least by the greatest imaginable glory. The Nobel Prize medal, together with other medals and dozens of honorary diplomas were kept in a box in his secretary's room, and I am quite sure that Einstein had no idea of what the Nobel Prize medal looked like.

Einstein's long-lived fame which was his fate when he lived and has kept growing since he died, finds its explanation in the complete harmony of his greatness as a scientist and his striving to defend the oppressed and help the progress of humankind. The combination of these impeccable moral standards with amazing discoveries of mysterious properties of nature produced a firm foundation for his fame. Lev Landau, Soviet theoretical physicist, winner of a Nobel prize for physics, was of the highest opinion of Einstein. This is how Vitaly L. Ginzburg remembers his words:

> Landau had a scale of merit in physics. The scale was logarithmic (class 2 meant achievement smaller by a factor of 10 than that of class 1). Among physicists of our century, only Einstein had class 0.5, Bohr, Dirac, Heisenberg and some others were class 1... As you see... Landau placed Einstein above all physicists of our century, and this opinion is simply unassailable.

The reminiscences of people who knew Einstein well and the words of outstanding physicists quoted above are all laudatory to the highest possible degree. They may be leading the reader to a

picture of a perfectly ideal person, devoid of any drawbacks. Was Einstein such an ideal human being?

This is very unlikely. Being ideal is not for a real, non-fictional, living person. Such is the 'logic of real life'.

For some years now, I have begun to hear muted statements by my German colleagues that in his private life Einstein was anything but ideal. Even books based on documents have begun to appear recently, which state that Einstein did have many drawbacks typical of ordinary people. It is not easy to sort out nowadays what is true, what is rumor and gossip and what is pure invention. Myth is always created about great historical figures.

In this connection, it will be of interest to recall what Einstein himself wrote in his letter to Morice Slavin on March 28, 1949: 'Very often we can only see an outstanding personality through a haze of sheer fog'.

My own experience has taught me that reconstruction of the personal life of a famous figure person is especially difficult. It happened when together with my colleague Aleksander Sharov, I worked on a biography of Edwin Hubble (*Edwin Hubble, the Discoverer of the Big Bang Universe*, Aleksander Sharov and Igor Novikov, Cambridge University Press, 1993). I quite agree with a remark by the well-known American astronomer Alan Sandage quoted in that book: 'It seems to me that from the scientific standpoint, we know a great deal of what he did, and that was all documented in the records and his publications. There is no question about the great things he did, but his personal life will be quite a bit more difficult to reconstruct.'

I would like to end the short digression on Einstein's personality with two of his comments that he made in a letter to the Polish physicist L. Infeld, written in 1950 (see footnote to p. 50).

The first of them sounds very fresh today. 'Before our time, man was essentially a plaything in the hands of blind forces of nature;

nowadays we are a plaything in the hands of bureaucracy. Nevertheless, man accepts this role. You know Lichtenberg's aphorism: "Man learns little from experience since each new blunder appears to him in new light".'

The second passage characterizes Einstein's attitude towards life in general and brings out clearly the inherent harmony of his inner world, which was always at one with the natural run of processes dictated by the laws that rule the world. 'Life is an exciting and splendid spectacle. I love it. However, I wouldn't be greatly impressed if I found out that I was to die in three hours. I would think how to use best these three hours left for me. I would then put my papers in order and lie down to die.'

Such was the creator of relativity theory. Now, what does this theory tell us?

The theory is based on two postulates which generalize the observational data. The first of them states that uniform translational motion cannot in any way affect physical phenomena.

We have already met this statement when discussing the Galilean principle of the relativity of motion. However, Einstein's postulate brings an important generalization to it. The reader will recall that Galileo was speaking only of mechanical phenomena: the motion of objects thrown by hand, the flight of flies etc. These were not affected by the motion of the ship. However, Einstein emphasized that not only mechanical phenomena but all the others, such as electromagnetic phenomena, will proceed in the stateroom of a moving ship exactly as they do in a ship at rest.

The second postulate of relativity theory states that the speed of light in vacuum is always the same, regardless of the motion of the light source or light detector, and equals (by today's data) $c = 299\,792.458$ km/s.

We accept the first postulate as something very natural; the second one, however, meets with serious doubts.

Indeed, imagine a spotlight and an observer to be at rest relative to each other, the observer measuring the speed of light c arriving from the spotlight. It seems logical that if the observer moves towards the light beam, the speed of light relative to him must increase and be higher than c. We know, nevertheless, that numerous experiments have proved that this expectation is wrong and the speed of light remains unchanged. All the same, it will be useful to discuss the situation further.

Let an observer in a rocket moving at high speed send a light signal from ceiling to floor; after reflection from a mirror placed on the floor, light returns to the ceiling (see figure 4.1). The observer in the rocket sees that the light beam travels in both directions along the same trajectory. As for the non-moving observer outside the rocket, he records that the light beam moving with the rocket follows a V-shaped trajectory which is longer than the simple 'up and down' path for the observer in the rocket. Hence, the velocity of the light signal must seem higher for the outside observer than for the observer in the rocket.

Stop! Recall that the velocity of a signal is the ratio of the path length to the time of travel. The path is longer for the outside observer, that is true. Doesn't this mean that the velocity is also higher? This would be so if the time of passage were identical for both observers; doesn't this equality appear obvious? Indeed, in both cases this is the time of signal propagation 'there and back again'. True, of course, but only if we assume that time flows identically for both the moving observer and the one at rest. Is there any basis for doubt here? Isn't time the duration that is common for everyone and everything?

Here lies the snag. We tacitly assume that time does flow indistinguishably for all observers. What is it, however, which makes us accept this assumption?

It is our accumulated experience that does it. In all the situations

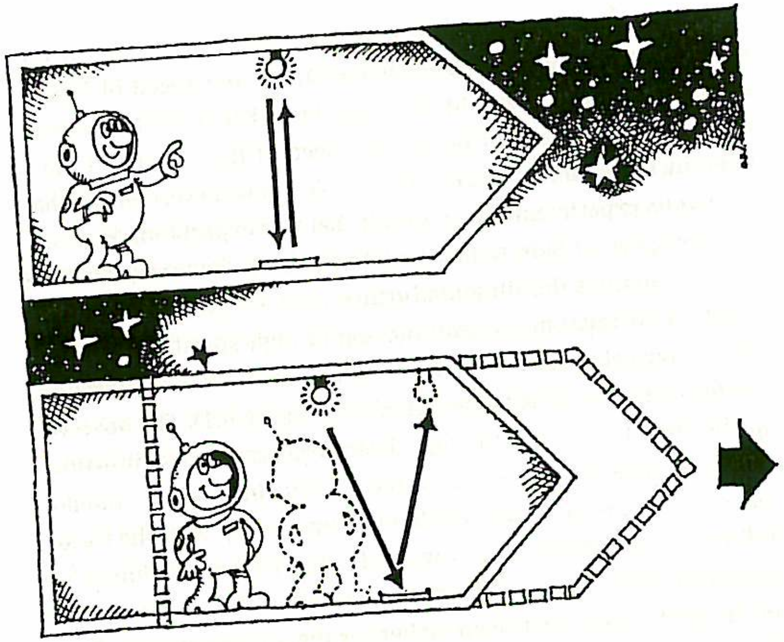


Fig. 4.1.

we have ever experienced, clocks ticked at the same pace (provided they were in good working order) regardless of motion; in other words, time flows identically. When the journey is over, both the stationary clock and the clock that moved show the same time. However, this only happens because we deal with slow motions! The Michelson–Morley experiments and other later experiments gave the first indication that it is wrong to assume that time flows at the same rate in fast motions.

Albert Einstein was the first to clearly recognize this fact. To do so was far from easy. Not only was it necessary to analyze all the results of numerous experiments; one had to achieve the most important thing: to disengage oneself from habitual stereotypes

of thinking, which had been building in science for so long and seemed so unshakable.

The conclusion made by Einstein's theory was as follows. If the observer studies processes in a 'laboratory' that moves at high speed relative to him, these processes unfold at a lower rate than the same processes in his stationary 'laboratory'. For example, a clock on a fast-moving rocket ticks more slowly, the astronaut's heart beats more slowly, all biochemical processes in his body are slower, electrons in atoms oscillate more slowly, etc. Absolutely all processes go at a lower rate, hence time itself has slowed down. The higher the velocity of the spaceship, the greater the time slowdown. As the rocket velocity approaches that of light, the rate at which time flows tends to zero (time stands still) and all processes become infinitely long. If the velocity is low compared to the speed of light (say, as low as our ordinary terrestrial velocities), the time slowdown is so minute that it goes absolutely unnoticed.

The reader may have a suspicion that this slowdown of processes is only apparent when an observer regards the rocket hurtling by at a high speed. At different moments of time the rocket is at different distances from the observer, and the light that carries the image of processes on the spaceship to the observer, leaves the rocket at different moments of time and covers different pathlengths to the observer, thus taking different times to travel. Could it be that light signals have different delays when they reach the observer and this warps the true picture of what happens in the spaceship?

No, all that was said about time slowdown holds true for the actual rate of processes and does take into account unequal retardation of light signals arriving at the observer. In other words, this is the true slowdown of everything happening on the rocket as recorded by the external observer.

This effect of time slowdown may be very difficult to be at ease with for anyone who hears of it for the first time. I tried to sort it out for myself when still in the fifth form, and it took years before I was able to understand it all to my satisfaction. I will return to difficulties encountered in comprehending relativity theory.

The next question is: are there any observable facts which prove that time does flow less fast on a rapidly moving body? Yes, such facts are known, and they are the weightiest arguments in favor of this conclusion of relativity theory.

I have emphasized already that time slowdown becomes appreciable only when the body moves at a velocity close to the speed of light. Enormous energies would have to be expended to accelerate large bodies to such speeds, so this is unfeasible in terrestrial conditions. Elementary particles are a different proposition. Physicists learnt to accelerate them a long time ago to nearly the speed of light in special devices called *accelerators*. The study of processes involving fast particles completely confirmed the results of relativity theory.

Here is what happens in one of the experiments with particles known as charged pi mesons. These particles are unstable and, being created in certain processes, live only a very short time and spontaneously decay. If very many such particles are born and all are moving at low velocities, one half of them decay in just seventeen billionths of a second. This is the so-called decay half-time. Seventeen billionths of a second later one half of the survivors decay, and so on.

However, if pi mesons are accelerated to a velocity of about nine-tenths of the speed of light, then time for them begins to flow more slowly and by our clocks their lifetimes increase. This is indeed observed in real experiments. The decay half-life of these fast-moving particles is found to equal thirty-nine billionths of a second, which is more than twice the decay half-life of pi mesons at rest. The result is in complete agreement with the conclusions of the theory.

Another example. Particles with very high kinetic energy are constantly arriving in our atmosphere from cosmic space. These particles are called *cosmic rays*. The interaction of cosmic rays with particles of the upper layers of the atmosphere creates a host of new elementary particles. Among them we find the so-called muons. These are also very short-lived particles. They decay after only two millionths of a second. This is their lifetime when these particles are at rest with respect to the observer. Having been created in the upper atmosphere, muons may have velocities of about 99% of the speed of light. If time for them did not slow down, they would cover only about six hundred meters during their allowed two millionths of a second. In fact, measurements show that they traverse many thousands of meters before decaying. This happens because time on such fast-moving particles flows approximately seven times more slowly and 'for us' they live so much longer, having time to cover such a long distance.

I can give an even more impressive example. Among particles in cosmic rays we find protons (nuclei of hydrogen atoms) that move so fast that their velocities differ infinitesimally from the speed of light: the difference occurs only in the twentieth (sic!) non-zero decimal after the decimal point. Time for them flows more slowly than for us by a factor of ten billion. If, by our clock, such a proton takes a hundred thousand years to cross our stellar system – the Galaxy – then by 'its own clock' the proton needs only five minutes to cover the same distance.

The reader may counter that, well, this is true for the tiniest specks of matter. But is appreciable retardation of time flow ever observed in the motion of macroscopic bodies?

Yes, such phenomena are well known. They are observed by astronomers. At the end of the 1970s, a group of American astronomers headed by Bruce Margon discovered super-fast ejections of gas jets from a binary stellar system known as SS433. The stars of this system, tied together by mutual gravitational attraction, revolve around their common center of mass. The system lies at a distance of about ten thousand light years from the Earth. (One light year is the distance travelled by light during one year; roughly, it equals ten thousand billion kilometers.) Owing to complicated processes that I will not discuss here, two powerful gas jets are emitted from the system in opposite directions at a velocity of about eighty thousand kilometers per second each. This is almost a third of the speed of light! To give you some idea of the power of the gas flows in SS433, note this figure: each second the jets throw out a billion billion tons of gas.

With the velocity being so high, time must flow in the jets several percent slower than for us. This slowdown is not as dramatic, of course, as for fast elementary particles, but it is appreciable and can be easily measured. The jets of ejected gas consist mostly of hot hydrogen. Hot hydrogen under terrestrial laboratory conditions emits electromagnetic waves of strictly defined frequency. If this emission from hydrogen is analyzed by a spectrometer, one finds that hydrogen gas emits in certain lines of certain color, which correspond to well-defined frequencies of oscillating electrons that emit light waves.

As time is slowed down in the fast jets, the frequencies of spectral lines emitted by hydrogen must decrease, and the emitted light get redder. This is indeed observed.

Note that when the source moves with respect to the observer, the frequency of light, that is, its color, changes also for a reason not directly connected with relativity theory. This is the Doppler effect that we all know from school days: as the source moves towards us, the frequency of light waves received by us is increased and the light grows more violet. If the source moves away from us, the light is reddened. There is no doubt that these effects are not connected with the slowdown of time flow.

The Doppler effect is also observed in the stellar system SS433. However, this system is so structured that the direction of jet ejection is constantly changing in space, with a period of 164 days. Twice during this interval the jets are moving exactly at right angles with our line of sight. At these moments, the gas in the jets is neither approaching nor moving away from us, and the Doppler effect causes no frequency changes. (I ignore the relatively low velocity of motion of the entire SS433 system with respect to the Solar System.) It is at these moments that astronomers observe the reddening of hydrogen spectral lines that is caused solely by time retardation owing to the fast motion.

It should also be mentioned that the slowdown due to fast motion has been measured by a highly accurate atomic clock placed on an ordinary airline jet plane. True, some other subtle effects changing the 'ticking' of the clock also had to be taken into account.

We can summarize now. However paradoxical we may regard Einstein's conclusion – that from the standpoint of an external observer (relative to whom a body moves) time on this fast-moving body is slowed down – this has been conclusively verified and confirmed by direct experiments, and is now beyond any doubt.

Time is therefore relative. Absolute time is something non-existent.

We have seen already that the speed of light plays a special role in Einstein's theory. This is the velocity at which all electromagnetic oscillations propagate through the vacuum regardless of frequency – from low-frequency radio waves to visible light, to high-energy x-rays, to ultra-hard gamma radiation. This velocity remains unchanged relative to any observer.

The theory states that the speed of light is the largest of all velocities allowed in nature. The Soviet astrophysicist A. Chernin found an excellent image for this: 'This is the absolute record of velocity'.

What is the obstacle that prevents a body from being accelerated to a velocity above the speed of light?

Let us follow what happens to a body if it is subjected to a constant force which continuously accelerates it to a greater and greater velocity. Isaac Newton assumed that if the force acts for a sufficiently long time, the body can acquire an arbitrarily high velocity. However, Einstein's theory shows that as velocity grows, so grows the mass of the body, which is a measure of inertia, that is, of the 'resistance' of the body to the force applied. This growth of mass is a consequence of Einstein's famous discovery of the equivalence of mass and energy. As velocity goes up, and hence kinetic energy increases, mass increases too. But if mass increases, the acceleration produced by the force inevitably decreases. As the velocity approaches the speed of light, the mass goes to infinity and no force can make a body overcome the barrier of the speed of light. The speed of light sets the limit for the propagation of any field and, in general, for transmission of any information.

We should now look at another property of time discovered by Einstein. Imagine a train traveling at a very high speed. One physicist is standing at the midpoint of the train on an open flatcar. The other physicist stands on the ground and the train is rushing past. Signal lights that can be turned on when required are fixed to the front and rear points of the flatcar. Let us conduct an experiment by switching on the signal lights in such a way that light from both lamps reaches the 'train physicist' simultaneously and exactly as he is passing the 'ground physicist'. Both the 'train physicist' and the 'ground physicist' see both flashes at the same moment. What conclusions will the two make about the times when the lamps were fired?

The 'train physicist' says: 'I am standing in the middle of the flatcar at equal distances from the car ends. I saw the flashes simultaneously and, since the speed of light is always the same and equals *c*, the lamps have obviously flashed simultaneously.'

The 'ground physicist' comes to a different conclusion: 'I saw the flashes simultaneously, when being right against the midpoint of the flatcar, with the lamps at equal distances from me. Light needs some time to reach me, the train still moving during this interval. Hence the tail lamp of the flatcar was farther from me than the front one when light left it. Consequently, light emitted from the two lamps covered unequal lengths (that from the tail lamp traveled the longer path). The speed of light is always the same and equals *c*. I saw the flashes simultaneously, so the signal from the tail lamp must have been emitted earlier than from the front one. The flashes were not simultaneous.'

We see: what was simultaneous on the fast-moving body, was not simultaneous for the physicist on the ground.

The seemingly simple and clear concept of simultaneity of two events is found not to be so obvious after all. There is no absolute simultaneity. This concept is relative and depends on the motion of the 'laboratory' body with respect to which we consider the events; physicists say that it depends on the frame of reference.

If events are simultaneous and take place not far from one another in space, even comparatively fast motions make them non-simultaneous by only a tiny interval of time. In our day-to-day life, therefore, simultaneity is absolute, obvious and independent of any motion. For instance, the statement that a train left the platform simultaneously with the clock on the town square showing twelve o'clock sounds identical for all practical purposes and perfectly clear to an observer parked close to the railway station platform and for another who drives through the square. The situation is very different for events that are separated by great distances and regarded with respect to observers that move fast relative to one another. For example, a statement similar to the earlier example, made by a person on the Earth – 'A supernova exploded today at noon in the Triangulum constellation in the Galaxy' – may not be true for an astronaut traveling in a fast-moving rocket.

Relativity theory has established that the notions of 'now', 'before' and 'after' have simple meaning only for events occurring in the vicinity of one another. For events that are separated by huge distances the meaning of 'before' and 'after', 'earlier' and 'later' is unambiguous only when a signal propagating at the speed of light has had enough time to travel from the place of the first event to the place of the second one. If, however, the signal is still on its way, the 'before'–'after' relationship is ambiguous and depends on the state of motion of the observer. What is 'earlier' for one observer, may be 'later' for another, moving with respect to the former. Such events cannot be causally related, nor influence one another. Otherwise an event that was the cause of another (and thus had to precede the latter event) could be regarded by some other observer as having occurred after its consequence.

Such properties of time are related in the most direct manner to the fact that the speed of light in vacuum is always the same and independent of the motion of observers, and that this is the maximum possible velocity. Nothing in nature can move faster than light in vacuum.

Finally, I shall mention one more corollary of relativity theory. Fast-moving bodies contract in the direction of their motion, while their dimension at right angles to the motion remains unchanged. This contraction is absolutely unnoticeable at low velocities but is large at velocities near the speed of light.

These consequences of relativity theory dramatically change our notions of space and time.

A question is very likely to be prompted at this point: 'What are the feelings of an astronaut sitting in a rocket moving at such high

velocities? How will he (or she) perceive the changes in time and length that are apparent to an external observer?'

The answer is obvious: the astronaut will feel nothing at all! Indeed, as far as the external observer is concerned, both the pulse rate of the astronaut and the rate at which his clock is ticking, as well as all other processes, are slowed down to the same degree. Hence, pulse rate and clock ticking are synchronized relative to each other as before. Say, his heart still beats once each second. In his own time flow (known as 'proper' time) everything proceeds as in a rocket at rest. However, the flow of 'proper' time changed the flowrate with respect to the external observer. It is thus clear that the 'time river' does not flow at a permanent rate everywhere.

The astronaut cannot discover the contraction of the longitudinal dimension of his rocket either. Indeed, any meter-long stick or any other reference with which he might wish to measure a length will shrink equally and the number of such unit lengths along the contracted rocket will be the same as before it picked up high speed.

The astronaut has thus discovered nothing at all! He does not feel that his velocity is so high. Of course, this conclusion is in complete agreement with the first postulate of relativity theory which states that everything in a fast-moving rocket happens exactly as in the rocket at rest.

Since uniform motion is relative and there is no absolute motion, the astronaut has every right to regard himself as being at rest and the observer on the Earth as flying in the opposite direction. Furthermore, the astronaut assumes that time ticks more slowly on the Earth than in his rocket. The reader for whom this is the first encounter with relativity – and who has mostly forgotten what school teachers explained about it – may have a legitimate question here: 'How can that be? The terrestrial observer concludes that the astronaut's time ticks more slowly, while the astronaut believes the opposite is true. Where lies the truth? I can accept that time can slow down, although this is hard to digest, but has it slowed down for the astronaut or for the terrestrial observer? To quote A. A. Milne's Winnie-the-Pooh, "Either a tail is there, or it isn't there. You can't make a mistake about it." There must be an unambiguous answer to this question!'

Actually, there must not, however strange this may sound. In fact, this is not difficult to explain. For comparison, recall Galileo's argument concerning the fall of bodies in the cabin of a moving ship. For a passenger in the cabin, an object released from the hand falls straight down to the feet. For the external observer the falling object moves together with the ship and its trajectory is a parabola. One could ask: 'Is the body moving along a straight line or is it tracing a parabola?' Obviously, asking what is the 'true' shape of the trajectory is meaningless. The trajectory of a body depends on what one defines it relative to. It is 'truly' straight for a person in the cabin and 'truly' parabolic for the external observer. There is no contradiction here.

The same holds for time slowdown. Astronaut's time flows 'truly' slower for an observer on the Earth, while all events on the Earth are 'truly' slower for the astronaut. Again, there is no contradiction here. This all follows from relativity theory.

Of course, this is not very easy to digest. However, Einstein's theory is an inescapable corollary of experimental observations. In such situations it is useful to recall one of Sherlock Holmes' mottoes ' When you have eliminated the impossible, whatever remains, however improbable, must be the truth' (Conan Doyle *The Sign of Four*).

Those readers who have failed to achieve complete clarity immediately, in understanding all this, need not despair. After Einstein's discovery, even quite a few very prominent scientists took a long while to come to terms with his theory. As for 'average' scientists,

to say nothing of people not familiar with physics, they faced enormous difficulties in accepting the ideas that virtually overturned habitual notions. Many tried to uncover errors and contradictions in the theory.

Attempts of this sort had not ceased even decades later. For instance, in 1931, a quarter of a century after Einstein's theory was published, a book was published in Leipzig, entitled *100 Authors Against Einstein*. One hundred expert authors of the book completely rejected relativity theory and its corollaries. The legend has it that when Einstein was told about the book, he smiled and, as always phlegmatic in such situations, remarked that if his results were wrong, the arguments of one expert would be amply sufficient. (I retell this anecdote after the description in *Introduction to Relativity Theory and its Applications to New Technologies* by N. I. Goldenblat and S. V. Ulyanov (Nauka, Moscow, 1975).)

Of course, there are no contradictions in Einstein's conclusions. For serious scientists, arguments against relativity theory have long become pieces of past history. The theory lies at the foundation of all modern physics. It is used to design gigantic accelerators of elementary particles and atomic power stations; it was tested in such monstrous experiments as explosions of nuclear bombs.

It should be mentioned that school and college students of today usually have little difficulty in mastering Einstein's theory; they achieve this with greater ease than physicists of the beginning of the century and even people of my generation who were born closer to mid-century. The reason for this is quite clear: the very style of scientific reasoning has greatly changed as we have moved towards the 21st century.

I have mentioned already that in times when new seminal ideas are about to break through in science, it is typical for several scientists to come very close to formulating the emerging relationships and to interpret some of their properties. However, someone of real genius then comes up with the ultimate formulation of the new understanding. This was the fate of relativity theory as well. Some formulas of its mathematical equipment had already been written in the last century, by the end of the 1880s. The Dutch physicist Hendrik Lorentz and the French mathematician Henri Poincaré came very close to creating the theory. But the hardest step that demanded maximum courage, one that revolutionized the notion of time and space, was made by Albert Einstein. In 1912 Hendrik Lorentz was reminiscing about his attempts even before 1905 (that was the year in which Einstein's paper was published) to resolve contradictions that followed from experimental results. He wrote that in his paper written in 1904 he failed to derive in a complete and satisfactory manner the transformation formulas of Einstein's relativity and that this led to the weak and helpless arguments one finds in his paper. Lorentz added that Einstein's great achievement was that he produced the first formulation of the relativity principle as an all-encompassing, strict and accurately functioning law.

Another remark is in order here. Beginning in 1990, some authors have tried to find a foundation for the rumor that Einstein's first wife Mileva Marić played an essential part in the creation of special relativity. I do not think this story has any credibility at all. I will quote the opinion of an expert in the history of science, Harvard University professor Gerald Holton (*Physics Today*, August and September, 1994):

> Careful analysis by established historians of physics, including John Stachel, Jürgen Renn, Robert Schulman and Abraham Pais, has shown that scientific collaboration between Mileva and Albert was indeed minimal and one-sided.

The lively discussion of this topic that flared up at the beginning of the 1990s was most probably caused by the thirst of a fraction of the reading public for science-history sensations.