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Science of time is born

The Renaissance that came to replace the somber Medieval centuries brought outstanding discoveries in natural sciences. This was the time when Nicolaus Copernicus (1473–1543) developed his theory which was to produce a dramatic transformation in people's view of the world. First of all, this new concept eliminated the impenetrable barrier between the terrestrial and the celestial. Before, everything celestial was a symbol of perfection, of eternity, and of ideals. Heavenly bodies were ideal, as was their uniform motion along circular orbits. This perfection was in opposition with the rough terrestrial matter and its chaotic irregular motion. Copernicus' model showed the Earth to be an ordinary planet which revolves, just as other planets, around the Sun.

Nicolaus Copernicus became a canon of a Catholic church in Frauenberg [Frombork], a small town on the banks of the Vistula in Poland, in 1510. In quiet solitude, he worked on his astronomy. In fact, he spent his free hours on other things as well. He treated patients for no fee. A new monetary system was introduced in Poland following his proposal. He designed and constructed a hydraulic machine to supply water to households.

Copernicus was very careful about publishing his results; he clearly recognized the contradiction with the church's teaching of the singular position of the Earth and man in the Universe. His treatise, *On the Revolution of Celestial Spheres*, dedicated to Pope Paul III (this was agreed upon with the Holy See) was printed in 1543, not long before Copernicus' death. In fact, Copernicus had formulated his main conclusions long before the publication. He wrote in his work 'Smaller Commentary', dated approximately 1515:

> All the motions we observe as those of the Sun do not belong to it but to the Sun and our sphere together with which we revolve around the Sun, as any other planet does; the Earth thus executes several motions. The apparent direct and reverse motions of planets are not theirs but of the

> Earth. Therefore, this one motion of the Earth is sufficient to explain a large number of irregularities observed in the sky.

In our day, it is quite difficult to imagine to what degree a man's way of thinking had to be non-trivial to dare to claim at that time that the Earth was not stationary. The point here lies not only in the disagreement with ecclesiastical dogmas. Indeed, Aristotle's teachings reigned in science, stating that force is constantly required to sustain any motion (science did not yet know anything about motion by inertia). It was assumed, as a result, that if the Earth revolved, this would affect terrestrial phenomena: the air would tend to stay behind, thus creating hurricanes on the rotating Earth; a body dropped off a tower would not fall to its foundation since the ground would fly away from under it, and so forth.

This shows that Copernicus had to argue mostly against the Aristotelian misunderstanding of motion which was rooted in a long chain of centuries before him. There was another reason why these wrong notions were so difficult to overcome. Namely, people thought that no observations or experiments were needed to obtain knowledge about nature: it would be sufficient to think hard and reason by logical inference for the truth to be established.

Using astronomical observations, Copernicus had not only created a new model of the Solar System but was in fact the first to challenge the dogmas of Aristotelian physics. He understood that everything on the Earth moving by inertia must occur exactly as it would on the Earth at rest:

> Why not assign the appearance of the daily rotation to the sky and the reality of it to the Earth? Indeed, when a ship sails on a quiet water, everything outside the ship appears to the seamen as if moving in accordance with the motion of the ship, while they and everything with them on board the ship appear to be non-moving. The same can undoubtedly take place on the moving Earth and one may

conclude that the whole Universe is rotating. What should we say then about the clouds and everything else which somehow hovers, descends or ascends in the air? Only that not only the dry land moves together with the water spaces connected to it but also with a considerable part of the air and everything which is in some way connected with the Earth...
... For this reason, the air contiguous to the Earth and all things hovering in it must appear as quiet to us, provided it is not driven now in one direction and then in another, as often happens, by winds or by any other external force.

This passage clearly characterizes the relativity of motion and the properties of motion by inertia, whose final formulation was given by Galileo a century later.

It is quite likely that any person who first learns the laws of mechanics in childhood or youth, has to make a considerable conscious effort to digest the notion that an object dropped from some height in a moving windowless carriage falls to one's feet exactly as it does in a stationary one. In our time, with its frequent travel by train, car or airplane, one gets used to this from childhood. I distinctly remember, nevertheless, my amazement at the age of ten in a truck that was running fast in the Kherson steppe. I watched a ball falling from my hand, again and again, exactly to a point on the floor right below, even though the speed of the truck was huge – by the standards of my childhood. I imagined that the floor of the truck would rush away from under the ball. It was not easy to comprehend that the ball released from my hand continued to move by inertia along with the truck and retained the same velocity that it had in my fist, the velocity of my body and of the truck, before I let it go.

At the beginning, Copernicus' teaching did not cause any special worry for the Catholic Church. The impact was partly cushioned by the unsigned foreword to *On the Revolution of Celestial Spheres*,

written by an anonymous theologian. It claimed that the author only aimed at offering a method of mathematical calculation of the observed positions of heavenly bodies and in no way attempted to determine the actual motion of these bodies. It said: 'His hypotheses may be wrong, may even be improbable, as long as they lead to calculations that fit our observations.'

However, at the beginning of the 17th century when Copernicus' theory began to spread in Europe as actual rejection of the dogmas of the church, the treatise was placed into the 'Index of Banned Writings' where it stayed for more than two centuries.

In this period, Galileo Galilei (1564–1642) developed a new understanding of physics, and formulated the first truly substantiated foundations of the science of time, which were later beautifully developed in the work of Isaac Newton.

Galileo made a great many important discoveries in science that the reader undoubtedly knows about. However, the most important of these was his novel approach to natural sciences, his belief that to study nature one has first of all to set up carefully thought-out experiments. The world around us can only be understood by testing a hypothesis in experiments, by 'asking questions of Nature'. Here he parted ways sharply with Aristotle, who assumed that the world could be understood by purely logical reasoning. Galileo also believed that superficial observations not accompanied by thorough analysis of data can lead to wrong conclusions.

Taken together, this was the beginning of the modern method of studying nature. Einstein said that 'the science relating the theory and experiment was actually born in Galileo's work'.

Galileo's discoveries in physics were based on numerous experiments that he had conducted. Especially important for our story is the discovery of inertia and inertial motion.

Everyday observations on the motion of bodies for many centuries had convinced people that unless the motion is sustained, for example by pushing a rolling ball, the body will stop. Aristotle summarized these observations in the following form: 'A moving body will cease to move if the force pushing it ceases to act on the body.' We know now that the rolling ball stops not because no force keeps pushing it but because it is slowed down by the force of friction connected with surface roughness and air resistance. If the surface is made gradually smoother and flatter and air is removed, the ball will roll farther and farther. In the limit, it may not stop at all. This was Galileo's conclusion: '... horizontal motion is eternal since if it is uniform, then nothing weakens it, or slows it down, or destroys.'

The law of motion by inertia discovered by Galileo is the basis of the principle of mechanical relativity. This principle states, for example, that regardless of whether a ship is at rest or sails at a uniform speed on smooth sea, all processes in a cabin proceed identically. One can walk, one can drop objects, flies can fly freely throughout the air, and the motion of the ship has nothing to do with this. Here are the words of Salviati, one of the protagonists in Galileo's book *Dialogue Concerning the Two Chief World Systems – Ptolemaic and Copernican*:

> Lock yourself with a friend in the stateroom under the deck of a large ship, having brought with you flies, butterflies and other small flying animals. Take with you a large fish tank with fish swimming in it. Suspend a bottle from which water drips, drop by drop, into a wide vessel underneath. As long as your ship does not move, watch carefully how the insects fly through the room at the same velocities in all directions. Fish swim randomly, without preference to any direction. Drops fall into the vessel under the bottle. If you throw anything to your friend, your effort will be the same no matter in what direction you threw it, provided the distances are identical. If you jump pushing with two feet at the same time, you cover the same distance in any direction.

> Having carefully observed all this (even though you never doubted that it would be exactly like this in a ship at rest), order the crew to set the ship in motion at any speed, but so that the progress of the ship is uniform and not disturbed by anything. You will not discover any changes in the motions you were watching and will be unable to identify by any of the processes whether the ship is moving or not. Having jumped, you will cover the same distance as before, and a jump towards the bow will not be shorter than that towards the stern, even though the ship was moving under you while you were in the air, and in the latter case in the opposite direction. To throw an object to your friend, you will not need to spend a greater effort if your friend is closer to the bow than you are. The drops will keep falling into the vessel below as before, without deviating towards the stern, even though the ship moves forward several feet while drops fall through the air. Fish continue swimming in their tank with equal ease in all directions and catch bait in whatever corner we choose to place it. Finally, flies and butterflies are flying in all directions without preference, and you never find them clustering at the stern, as if getting tired to keep up with the progress of the ship from which they were separated, being suspended in the air for a considerable time.

This wonderfully expressive description is one of the first formulations of the principle of relativity of motion. Note that Galileo's writings are not only collections of gems of human thought but also outstanding literary work. Schoolchildren in Italy study them first of all as the literary heritage of their country.

No mechanical experiments inside the stateroom can determine whether the ship is moving or is at rest. I have said already that in our era of incessant car, train and air travel, we became used to this a long time ago. It is instinctively clear to us that a statement 'the cup is at rest' is meaningless unless we specify that it is at rest with respect to another object. The cup may not be moving with respect to us in a flying plane but may move together with us at a high speed with respect to the Earth. We can saunter leisurely through the aisle of an airplane while traveling at a great speed relative to the Earth. As for any motion, the rest state of a body and its velocity are relative; these terms are all meaningful only when we indicate the 'laboratory' with respect to which these notions are being used.

This discovery by Galileo Galilei – namely, that everything proceeds identically, regardless of the uniform motion of the 'laboratory' in which the observations are made – was a scientific argument against the belief that the Earth is at rest in the Universe. Following Copernicus, Galileo stated: 'Let us choose for the foundation of our cognition the concept that whatever be the motion of the Earth, the inhabitants of the Earth do not notice it as long as the judgments are based on things terrestrial.'

Galileo firmly believed that Copernicus' teaching was true and became its passionate propagandist. Galileo's discoveries in physics and astronomy made him the most famous scientist in Europe. At an early stage, the Catholic Church made cautious attempts to cajole Galileo to change to the point of view that Copernicus' model was only a hypothesis convenient for calculations (as Osiander claimed in his foreword to Copernicus' treatise). Cardinal Bellormino wrote to Father Facarini, who sided with the Copernican picture of the world:

> It seems to me that You and Seignior Galileo would make a wise and careful move if You chose to be satisfied with *suppositione* statements and not insist on absolute ones; Copernicus' words, and as I always believed, his thoughts agreed with this position. Indeed, when one claims that all the phenomena observed are saved better when assuming the Earth to be moving and the Sun to be at rest than by

> postulating epicycles and epicenters, this claim is very well formulated and not fraught with any pitfalls; and this is all mathematics needs; if, however, someone begins to talk of the Sun as actually being at the center of the world, only rotating around itself but not journeying from east to west, and of the Earth as placed on the third heavenly sphere (being the third closest to the Sun) and moving at high speed while revolving around the Sun, this is a very dangerous thing, and not only because it irritates all philosophers and theology scientists, but also because it harms the Holy Faith, since it implies that the Holy Scriptures are lying.

The Soviet physicist Vitaly Ginzburg remarked that the benevolent permission to 'save' phenomena and do mathematics but shun the reality caused Galileo's fury. Galileo wrote in a letter to the Duchess of Lotharingia:

> Professors of theology should not claim the right to regulate with their decrees such professions that do not fall under their authority, because you cannot impose on a natural scientist an opinion about natural phenomena... We preach the new outlook not to sow confusion in the minds of people but enlighten them; not to destroy science but to give it a sound foundation. Our opponents, however, call everything that they cannot disprove a lie and a heresy. These philistines make themselves a shield out of their hypocritical religious ardor and dishonor the Holy Scriptures by using them as a tool for pursuing their own end... To prescribe to astronomy professors to use their own intellect to seek protection against their own observations and conclusions, as if these were mere deception and sophisms, would be a demand more than impossible to meet; it would be the same as ordering these men not to see what they see, not to understand what is clear to them, and draw from their studies the conclusions that are just the opposite of what is obvious for them.

Ginzburg added that these words sound as if written by a contemporary.

It is left for me to emphasize that not all movement of the 'laboratory' is unnoticeable to people and objects inside it, far from it. For instance, if a car accelerates abruptly, or makes a sharp turn, we feel it very distinctly. Only uniform motion along a straight line is unnoticeable. Such motion of a 'laboratory' or a body occurs by inertia, without any forces acting, or when all the 'pushing' and 'resisting' forces, and those forcing a body off the rectilinear trajectory, exactly balance one another out; such motion is known as inertial motion and the 'laboratories' as 'inertial laboratories'.

Of course, a 'laboratory' found in nature can only be inertial to within a greater or smaller degree of approximation. A ship going slightly up and down on gentle waves is obviously not an 'ideal inertial laboratory'. This rocking of the ship is detectable. However, the smaller the accelerations and the smoother the turns, the closer the 'laboratory' is to an inertial one. The Earth's surface is also a mere approximate inertial laboratory. We know, for instance, that it undergoes a circular motion around its axis.

Specially designed experiments can and do detect this. The reader may have observed, or at least heard of, the Foucault pendulum. The pendulum is a heavy object (ball) suspended in a high-ceilinged building on a long string. When the load swings, it tends to preserve the plane in which it moves with respect to the stars. The surface of the Earth, together with the building, performs its diurnal rotation, and we discover that the direction of swing of the pendulum gradually changes with respect to the walls of the building. Such experiments were first set up many years after Galileo's time, in 1851, by the French scientist G. Foucault, who suspended one in the dome of the Panthéon.

But let us return to the 17th century. True knowledge was clearing its path by a passionate struggle with deeply rooted dogmas, with very profound difficulties that nature always erects for humans in search of truth, and finally, with social conflicts involving the interests of numerous groups of people.

Some time after the notorious trial in 1633 which made Galileo 'Inquisition's captive', he published *Discussions and Mathematical Proofs Concerning Two New Sciences....* In this book which presented the foundations of dynamics he wrote: 'This treatise only opens the door to these two new sciences so rich in applications; they will in the future be expanded immeasurably by inquiring minds... one of the sciences concerns an eternal subject, one of a paramount significance in nature.'

A year after Galileo died, another genius was born: Isaac Newton (1642–1727). His work completed the creation of classical physics and also of the first physical theory of time (in the sense acceptable to us).

In contrast to the lives of philosophers of antiquity, we know Newton's life rather well. At first glance, it was strikingly meager in events. Beginning his story of Isaac Newton, Boris Kuznetsov remarked: 'There was no family, no voyages, there were no major changes in his way of life, almost no friends, almost non-existent social activity. To a superficial view, this list is in stark contrast with an unbelievable intensity of the creative path of this thinker, with true tragedies in the cognitive process. Actually, the two sides are in profound harmony.'

Newton was born in the village of Woolsthorpe in Lincolnshire, England, in the family of a yeoman farmer. His father died several months before the son was born. The boy attended the King's School in the small town of Grantham not far from Woolsthorpe and entered Cambridge University at the age of nineteen. Even at this age he was punctilious, inclined to systematization and order. He began as a poor student of Trinity College, one of the most famous in England, graduated in three years and soon developed into a thinker of exceptional genius. In 1669 he became the Lucasian Professor of Mathematics. The Henry Lucas Chair of Mathematics was established in 1663 on the donation of Henry Lucas and still remains one of the most famous and respected chairs of theoretical physics in the world.

Within the very short period of 1665–1667, while staying in his native Woolsthorpe, Newton formulated the basic physical ideas that gave a new impetus to the progress of physics; he published them much later.

During this period, a plague epidemic was raging in England. Newton left Cambridge, where he had just obtained his BA degree, moved back to Woolsthorpe and there spent about eighteen months. He was working hard, trying to improve the precision of glass polishing, designing physical instruments and conducting chemical experiments. At the same time, he was thinking with great intensity about the main problems of physics, astronomy and mathematics. The results of his work were truly fantastic and deserve being called a revelation. Still staying in the village, he formulated the fundamental laws of physics and created the theory of gravitation. According to this theory, the weight which forces a body to fall down onto the ground is identical to the force which sustains cosmic bodies in their orbits; the magnitude of this force decreases in proportion to the inverse square of distance.

Nearing the end of his life, he recalled that he had noticed an apple falling off a branch, which set him thinking about the causes behind the fall of bodies towards the ground. The answer seemed to be well known to anyone: the weight of a body. But what is the weight? Newton concluded that the weight is the force of attraction to the Earth. The same force must extend further away from the Earth, holding the Moon on its orbit and not allowing it to fly away by inertia into cosmic space.

Newton published the exact formulation of the universal law of

gravitation much later, in his famous treatise *Philosophae Naturalis Principia Mathematica* (1687), often referred to in short as *Principia*. (In fact, Newton was always very slow in publishing his results, even though he was definitely not indifferent to priority arguments.) Why did he hesitate? It is likely that the main reason was his very different attitude to gaining knowledge, his concept of the stage at which a result can be recognized as the established truth.

If we can briefly describe his attitude in this respect, it could be: try to achieve total order in the knowledge of nature, try to gain knowledge which is accurately supported by experimental data and adequately described by logic and mathematics. These are exactly the requirements that science sets for us today.

As many other great ideas, the theory of gravitation had its precursors. For instance, Giovanni Borelli concluded that there was mutual attraction between all bodies in the Universe; also, he conjectured that as planets revolve around the Sun, its attraction balances out the centrifugal forces that were discovered by Huygens. Another contemporary of Newton, Robert Hooke, came to the conclusion that the force of attraction between bodies is inversely proportional to the squared distance separating the bodies. We believe, nevertheless, that it was Isaac Newton who created the theory of gravitation.

We do give the highest regard to the vision of other researchers but we recognize Newton as the true discoverer. Why? Because he and no one else gave a proof of his constructs. From abstract arguments, Newton made the step to mathematical calculations, to physical experiments and to the interpretation of astronomical observations.

That was the beginning of the new physics.

Later we will discuss how Newton first formulated the most important properties of time, which constitute the main subject of this book. I wish to remark at this juncture that the discovery of the law of universal gravitation was very important not only for the development of celestial mechanics (describing the forces that control the motion of all celestial bodies in the Universe) but also for understanding what sort of phenomenon time is. In fact, this became clear after a considerable period of time – about three hundred years later, in this century, when it was proved that gravitation affects the rate of flow of time. However, let us again return to the 17th century.

While staying in Woolsthorpe in 1665–1667, Isaac Newton was not only occupied by the problems of gravitation; he also worked in mechanics, optics and mathematics, in which he made fundamental discoveries.

In the post-Woolsthorpe period, until the 1680s, he was mostly interested in optics and also in chemical experiments. In the mid-1680s he wrote and published the main accomplishment of his life: the famous *Principia*. This treatise summarized the fruits of thinking in his Woolsthorpe period and the results of the subsequent development of the ideas conceived at that time.

About two decades separated the time of obtaining the main results and the time of their publication! I have mentioned already that Newton was never in a hurry to publish, always striving for the maximum accuracy of all conclusions and to their logical impeccability. The following events happened to provide a stimulus to writing the *Principia*.

Some time at the beginning of the 1680s, three well-known scientists got together in a London café and were eagerly discussing the problems of the motion of planets around the Sun: Edmund Halley, Robert Hooke and Christopher Wren. By that time it was already known that, as established by Kepler's laws, the planets follow elliptical orbits. The problem that attracted the three scientists was whether it is possible to prove, under the assumption

that the Sun's gravitational pull decreases in inverse proportion to the squared distance to the planet, that the orbits must indeed be elliptical. They did not know the solution of this problem. Wren suggested that they set up a symbolic prize – a book at a price of 40 shillings – to the person coming up with the solution. On a visit to Cambridge in 1684, Halley described to Newton their café discussion, to which Newton remarked that he had known the solution for quite some time already! After this Halley succeeded in convincing Newton that he must write a book presenting the proof. This was how the *Principia* was born, edited and published by Halley at his own expense. As we know from the reminiscences of Newton's secretary – incidentally, his namesake – Newton's life in the period of creation of the *Principia* was exceptionally intense. He was never seen to rest, never rode a horse, never played skittles, almost never entertained visitors, slept at most five hours a day, and tried to spend as little time taking meals as possible. He was lucky in one respect: lectures took very little of his time since they were so boring that students did not attend them.

I recall now how I was impressed by stories declaring without a shadow of doubt that success in any field of activity is the result mostly – up to 95% – of a capacity of the person for hard work. Ever since that time, I have blindly believed in this maxim, have found numerous confirmations of it in the experience of my friends, and try to persuade my students and colleagues that everyone needs to follow this principle. 'To work well is to work hard' – I believe, this was said by Newton (or another genius).

After the publication of *Principia*, Newton's way of life began slowly to change. He kept working intensely and fruitfully in science but other fields were also becoming important. His social and political activities seriously occupied him. The more widespread anecdote about Newton's life is that, as a Member of Parliament, he made a single speech, requesting to close a window which caused a draught. The message seems to be that Newton was completely absorbed by his research and neglected all other facets of life. This is not very likely. I am inclined to think that he was quite serious about the non-scientific side of life.

Until the end of his life (he lived to be 84) Newton changed very little. He was rather short, somewhat stocky, usually withdrawn and reserved; his appearance was quite ordinary, very much that of a typical Englishman. True, he was far from easy to get along with.

Another side to Newton's personality must be mentioned. He was very religious. In my country – the former Soviet Union – it was a rule to tacitly turn a blind eye to this fact, especially in books for the young, or at least mention it in passing, as something unimportant. Presumably, exposing it seemed to harm the 'atheistic propaganda', even though suppressing or distorting some traits of the personality of a great man seems to me a far greater evil that cannot be justified by any 'well-meant' intentions.

Yes, Isaac Newton believed in God. This was not unusual for his time. For long decades of unlimited supremacy of communist ideology, this did seem strange both to myself and to most of my peers in the USSR. The system treated religious belief as not only inadvisable and a social risk but, according to the official standpoint, indicated a certain flaw of the intellect.

A reader in the West may regard this attitude to religion in the former USSR as more than peculiar. This was definitely not the strangest thing we find in the history of my country in this century. The attitude to religion is just another example of deliberate, merciless and unqualified warping of souls in the soul-numbing bolshevik epoch. A Western reader will definitely see nothing surprising in Newton's religious beliefs. I know a number of outstanding physicists in the West who are also believers; however, this is a topic for a discussion elsewhere. I only wish to mention in this context Einstein's point of view, whose attitude appears to be fairly

close to the position of a number of genuinely great thinkers of our time. He wrote that

> the most sublime and profound emotion that may befall a man is the sense of the mysterious. It lies at the basis of religion and of all most deeply running tendencies in art and science. A person who has never gone through these feelings seems to me to be – if not dead – at least blind. The ability to perceive that which is inaccessible to our reasoning, which lurks hidden below our immediate responses, and whose beauty and perfection reaches us only as weak indirect reflection – *this* is the sense of religion. In *this sense*, I am indeed religious.
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> My Glaubensbekenntnis (1932),
> in F. Herneck, *Albert Einstein*, Berlin, 1967, p. 254

But we should return to Newton. He was doing research in theology and the history of religion. He believed that God gave the 'primary push' to heavenly bodies, after which all motions in the Universe rigorously followed strict physical laws. From time to time, though, God finds it necessary to intrude and correct the grand 'clock of the Universe' if 'irregularity is anticipated'. In his picture of the world, Newton appealed to God each time he was unable to find a scientific explanation of a phenomenon. This was the case with an attempt to explain the origin of the Solar System and the origin of the initial velocities of the planets. The same happened when trying to explain the beginnings of the history of mankind.

Let us now turn to Newton's contribution to the understanding of time and space.

We begin with space. Newton taught that everything happening in the Universe occurs in empty space, which holds in itself all bodies and all processes. In fact, this space can be pictured as a gigantic laboratory room whose walls, ceiling and floor recede to infinity. Newton referred to this 'absolute', unlimited emptiness as 'absolute space'. In *Principia*, he wrote: 'Absolute space of its own nature, without regard to any thing external, remains always similar and immovable'.

In Newton's physics, time is a flow of duration which involves all processes without exception. It is the 'river of time', whose flow is not influenced by anything:

> Absolute, true and mathematical time, of itself, and from its own nature, flows equably without regard to any thing external, and by another name is called duration.
>
> I. Newton *Mathematical Principles of Natural Philosophy*

Newton's picture of the world was thus clear and obvious: the motion of heavenly bodies takes place in time in infinite empty space. Processes in the Universe can be very complex, diverse and tangled, but regardless of their complexity, they do not affect the eternal stage – the space – and the unchangeable flow of time. Newton postulated that neither time nor space can be influenced, hence the attribute 'absolute'. He emphasized the unchangeability of the flow of time in the following manner:

> All motions can be accelerated and retarded, but the time, or equable, progress of absolute time is liable to no change. The duration or perseverance of the existence of things which exist remains the same, whether the motions are swift or slow, or none at all.

Albert Einstein gave a very illustrative description of Newton's concepts: 'The idea of the independent existence of space and time can be expressed like this: If matter vanished, only space and time would remain (a sort of stage on which physical phenomena are acted out)'.

The reader may exclaim at this point that this is all so obvious, simple and clear that surely everyone interprets space and time in this manner!

This remark is justifiable, but only because these concepts follow from the observation of the motion of the bodies that surround us on the Earth, from observing the motion of giant heavenly bodies and from numerous physical experiments. It is because Newtonian physics generalized the entire experience of science with the motion of objects, and because this accumulated experience is mastered by us when we read school textbooks, that we tend to regard the Newtonian concepts of space and time as 'innate' to us.

One should not forget that any experiment is limited in scale, duration etc. In Newton's time, as well as much later, all experiments and all observations involved bodies which, judging by today's knowledge, move rather slowly. Gravitational fields known in Newton's time must be characterized from our standpoint as weak; finally, the energy of processes known then must also be classified as low in comparison with those that physics deals with in our time. In this framework, everything that Newton said about space and time holds and the motion of matter indeed leaves time and space unaffected. We shall see, however, that this 'indifference' of space and time to what happens inside them takes place only while the above constraints are satisfied.

However, this is a subject for later discussions. For the moment, I wish to stress that Newton's theory gave no reason for raising a question about any special properties or structure of time. Time is a uniform 'river' without beginning or end, without 'source' or 'sink', and all events are 'carried' by the river's flow. Time had no other properties but the property of always being of the same duration. The 'absolute time' is identical throughout the Universe.

In Newton's picture of the world, the meaning of the words 'now', 'before' and 'after' is quite clear for any events in the Universe, whether these events occurred at the same point in space or were separated by hundreds of millions of kilometers. If everything is clocked using the same absolute time, then everyone understands, say, the phrase 'A supernova has exploded at this moment in a galaxy in the Triangulum constellation'. Even though this galaxy is awfully far away from us and we shall see the light of this explosion only millions of years after when it ultimately reaches us, this understanding does not stop us from imagining that the explosion did take place 'now', at this moment of the absolute time of the Universe.

The absolute coincidence in time and the time that is common for the entire Universe are possible because according to the Newtonian theory there are signals which travel from one point to another 'instantly', that is, they propagate at infinite velocity. Gravitation is an example of such signals. If the mutual positions of gravitating masses change, gravitational forces between these masses change instantly throughout infinite space.

In this Universe, if masses have shifted somewhere, it is possible to 'be informed' of this event at any great distance. In this situation, the notion of 'now' is impeccably clear. Even though gravitational forces at large distances from gravitating stars become very weak and extremely difficult to measure, this could be regarded as, so to speak, our technical problem. Such technical obstacles cannot cancel the possibility of instantly determining – in principle – that masses have shifted somewhere far away.

Einstein was fascinated with the clarity and simplicity of Newton's picture of the world, and called Newton's time 'the happy childhood of science'. He wrote that for Newton, Nature was as an open book that he read without effort. The concepts that Newton used to specify his data seem to follow naturally from human experience and from wonderful experiments that Newton described in numerous details and arranged in careful order as precious toys.

In fact, this sunny picture did have a slight 'cloud' which obviously troubled Newton. The point was that no mechanical experiment could detect whether a body is in motion or at rest in this empty space. Indeed, we remember that all processes in a cabin

of a ship occur identically whether the ship is stationary or moving. Isn't it really strange that absolute space is there but a linear motion with respect to it can not be measured? This is a flagrant 'ugly', or un-aesthetic facet of the theory.

As our story unfolds, it will be clear that attempts to chase away this 'ugly' cloud finally led to fundamental discoveries in physics a few centuries later.

It should be mentioned that Newton's views on space and time were not the only ones held in Newton's time. Of special interest are the beliefs of the famous German philosopher Gottfried Wilhelm von Leibnitz, Newton's contemporary. Leibnitz worked not only in philosophy but also in physics, mathematics, history, natural law, historical jurisprudence, theology and diplomacy. The unparalleled scope of his interest was at the same time a cause of a certain patchiness of his scientific results. He discovered new approaches, he pioneered novel ideas but rarely pursued these paths thoroughly, bringing them to logical and detailed completion. He tried to integrate most different beliefs of his time and resolve all disputes and contradictions. Leibnitz dreamed about a peaceful accord of science and religion, catholicism and protestantism; he tried to make science international and even to work out a universal world language. On his initiative, the Academy of Science in Berlin was founded in 1700, of which he became the first president. He worked much to help found academies in Vienna and Dresden; he met the Russian tsar, Peter the Great, with whom he discussed the way to plant the seeds of scientific research in Russia and the measures needed to organize the St Petersburg Academy of Science.

This great scientist rejected Newton's absolute space. He maintained that the space is merely a manifestation of an order in the existence of objects and phenomena, that nature has no absolute space free of physical bodies. Leibnitz concluded that space was relative. In the same vein, he rejected absolute time which would flow irrespective of physical properties; he taught that the world is described by a sequence of phenomena following one after another and this is what people call time.

Once, during a joint work with German colleagues at the Central Astrophysics Institute in Potsdam, I had a long talk with the deputy director of the Institute, Professor D. Libscher; we discussed the general properties of time in the light of the discovery of black holes and their fantastic characteristics. Professor D. Libscher drew my attention to the surprising closeness between some predictions of Leibnitz, made three centuries ago, and our current understanding of time. It seemed especially impressive that Leibnitz insisted that there is simply no such thing as the absolute time introduced by Newton. Leibnitz developed a sort of theory on the relativity of time, space and motion. As a result, Libscher and I wrote an article about time in black holes for the Russian journal *Nature* (no. 4, 1985) and I refer those who are interested in a more systematic presentation to this publication.

Having formulated these intriguing arguments, however, Leibnitz went no further; at the time, he was unable to construct a concrete physical theory based on his philosophical thesis. In contrast, Newton's understanding stemmed from a stringent physical theory that he had developed. This theory was the foundation of mechanics, and mechanics was the scientific platform for the industrial revolution to come. Newton's point of view has prevailed.

Newton's physics withstood the test of time. Physics as we know it today has pushed the limits to which the Universe can be scrutinized much further than was possible in his time. Our image of space and time has become much more profound and multifaceted. However, as we have mentioned already, the science of today does not sweep aside anything that Newton accomplished. The properties of space and time and the laws of physical motion that he

established for the scope of phenomena apparent to him remain and will remain valid.

However, we can now reach phenomena that Newton could not investigate; they open for us the previously unknown laws of nature and unanticipated properties of space and time.

To conclude this section, it is necessary to mention another very important property of time, first emphasized by the philosopher John Locke with whom Newton was acquainted and who was greatly influenced by the new physics. The property is that the mathematical image of time is a straight line. In contrast to space which is three-dimensional (its three dimensions are length, width and height), time is one-dimensional, formed by a sequence of events following one another.

This image of time as a mathematical straight line proved to be very important for the further evolution of our picture of the world.