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INVITED ESSAY

The Nature of Time

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Abstract—One of the most fundamental concepts in our experience of existence is the flow of time—continuously from the past to the future. Yet, the basic nature of time as part of the description of the universe is not understood at all. The conservation laws of physics seem to be time-symmetrical, every detailed action could occur in reverse, which argues that the concept of the passage of time is not needed in nature. Yet, that time flows in one direction remains part of our experience. Can time stop? Can we influence the future? Can we influence the past? The historical and thermodynamic arrows of time are discussed and several enigmas and contradictions about the nature of time are revealed. The concept of "entropy" and its relation to the universe as a whole is explored.

The fundamental changes of our notions of a uniformly flowing time, made by Albert Einstein in his Special and General Theories of Relativity are pointed out, and several "paradoxes" and "anomalous" examples are described.

The nature of time and its relation to the Big-Bang cosmology is discussed, and the question "What was before the Big-Bang" is addressed.

Introduction

How many times have you wished to do something over again? To go back in time and flow through the past once more, to relive a pleasant moment or to change a decision and avoid a calamity. No matter how strong our wishes are, our experience shows that we can never travel back into the past.

One of the most basic notions of human consciousness is the continuous flow of time from the past to the future. This perception defines our psychological arrow of time. The passage of time, however, is not simply an illusion, it is the way that the universe manifests itself for macroscopic phenomena.

Even though everything in our experience happens with the underlying flow of time, we still do not have a basic or complete understanding of the

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nature of time. It is possible that a complete understanding of the nature of time can only occur when we have a satisfactory model of cosmology, of the initial conditions of the evolving universe, and of total existence.

With the spiralling progress in science and technology during this century we have come to recognize that our home in the universe does not occupy or represent any special place or circumstance.

The historical picture relates that the earth was formed about five billion years ago as a by-product while the sun gravitationally contracted from a dense interstellar cloud. This happened in one corner of the Milky Way galaxy which by that epoch had already formed over 100 billion other similar stars like the sun. The physical and chemical conditions on the earth produced what we call a biological evolution during the last few billion years of which we happen to be one of the most complex and sophisticated products.

Our powerful telescopes have shown that the observable universe is filled with millions of other galaxies similar to our Milky Way, each one containing billions of stars more or less like the sun. In this immense universe our galaxy does not occupy a special place and, like a tree in a forest, it seems lost in the crowd of other galaxies. Figure 1 shows schematically our home in the universe.

In the observable universe we have come to understand that the multitude of differences we observe are due to evolutionary changes which behave according to the same natural laws of the cosmos. We have learned, for example, that stars get birth from the gravitational collapse of interstellar clouds, then they live a long life of billions of years primarily by converting hydrogen to helium and in the process releasing large amounts of nuclear energy which keep them hot and luminous. When small stars deplete their nuclear fuel they cool off and fade away, while large ones undergo some violent explosions during the last stages of their evolution. It appears that such evolutionary processes would still take place all over the universe, defining the direction of the arrow of time, even if we did not exist.

For the giant scientists like Galileo, Newton and Maxwell, who constructed the foundations of most of modern physics using the scientific method, all events in the universe were assumed to take place in a uniformly flowing time. However, at the beginning of this century the most famous scientist of recent times, Albert Einstein, presented new theories which were able to predict nature with a much higher accuracy than with previously known physical laws. In doing so Einstein's new theories altered our understanding of the nature of time, and it was no longer necessary to assume that time was a uniformly flowing property of the universe. In fact, Einstein was able to show that the passage of time can be faster or slower depending on the presence and strengths of gravitational fields which are produced by the various masses of stars and galaxies in the universe. That is to say, time flows at different rates depending where it is measured. Einstein's new work constitutes essentially the only major and profound revision of the nature of

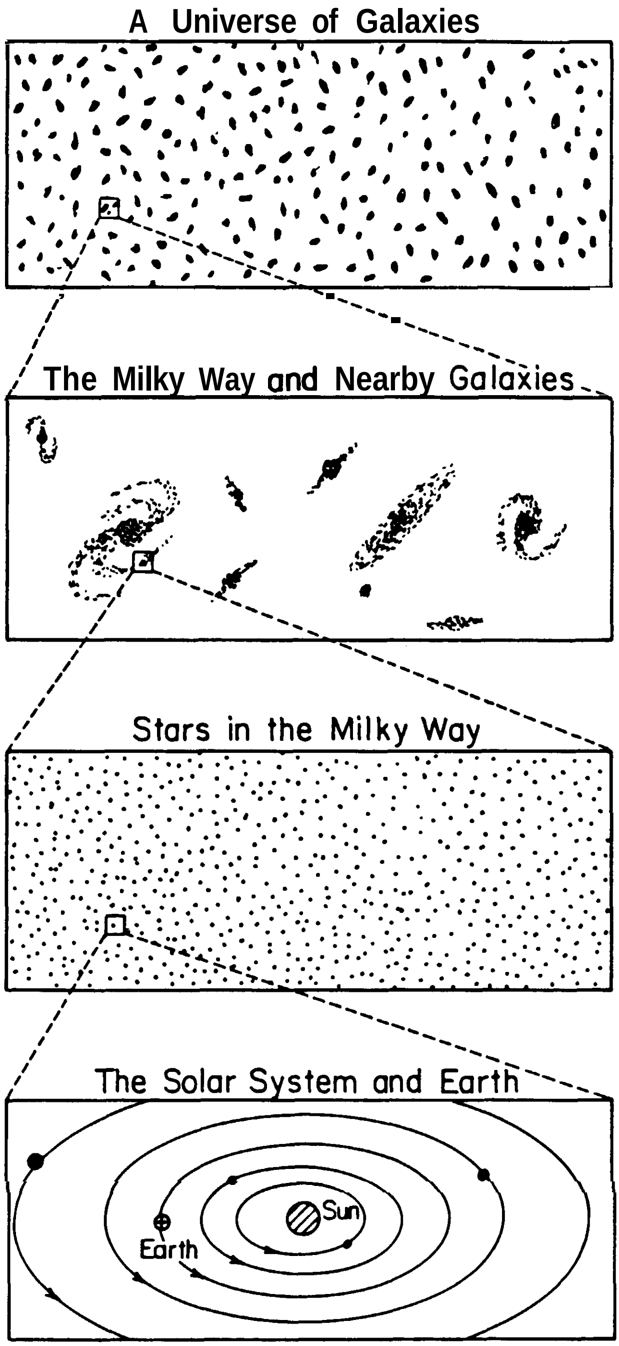

Fig. 1. A schematic representation of our home in the universe.

time in our attempts to understand the universe. Yet it is still not entirely clear what time really is and we do not know how to explain it completely. Time perhaps remains as the most mysterious concept we know and think we experience. On the other hand, we have become very sophisticated in measuring intervals of time with our exotic and accurate clocks.

Through the ages philosophers have certainly asked questions like "why does time never go backwards?" or "can time stop?". They quickly discarded such ideas since the behavior of events in our experience clearly did not permit such possibilities.

What is the difference between past and future? We think we can change and direct the future (or can we?). Can we change the past perhaps under some very special circumstances? We think we can remember the past, but not the future. However, with our scientific progress we can predict the future, and in many instances very accurately. Is this "remembering the future"?

Any possible explanation of the nature of time will most probably be interrelated with cosmology and the origin and evolution of the universe.

The Direction of Time

A. Cosmic Evolution

Modern theories of the universe suggest that the observational evidence is very strong that the universe began about 15 to 20 billion years ago from a primordial fireball explosion in a Big-Bang (Fowler, 1987). The expansion of the universe is still observed today as galaxies are seen to fly apart from each other with very high speeds. The primordial fireball was exceedingly hot, with temperatures of more than 10^{12} K. During the expansion the temperature of the universe decreased to the present very cold cosmic bath of only 3 K. This cosmic background radiation has been detected and accurately measured (Penzias & Wilson, 1965), and constitutes strong evidence in favor of the Big-Bang theory of the origin of the universe.

After the initial stages of the Big-Bang the expanding and cooling matter separated into giant clouds which formed the millions of galaxies we see (Figure 2). Galaxies in turn formed countless stars. Almost five billion years after the formation of the Milky Way galaxy, the sun was formed with its surrounding planets. On one of these minor planets, the earth, complex molecular systems were formed that led to the development of biology and life. All these processes indicate a progression from the simpler to the more complex, the generation of order or information from relative chaos or disorder. This evolutionary progression in one direction indicates one possible arrow of time. Such a time direction can be defined as the "Historical Arrow of Time," the major steps of which can be traced as follows:

(a) Evolution of Matter.
Big-Bang explosion, formation of galaxies and stars, formation of heavy elements, formation of planetary systems, and the evolution of life.

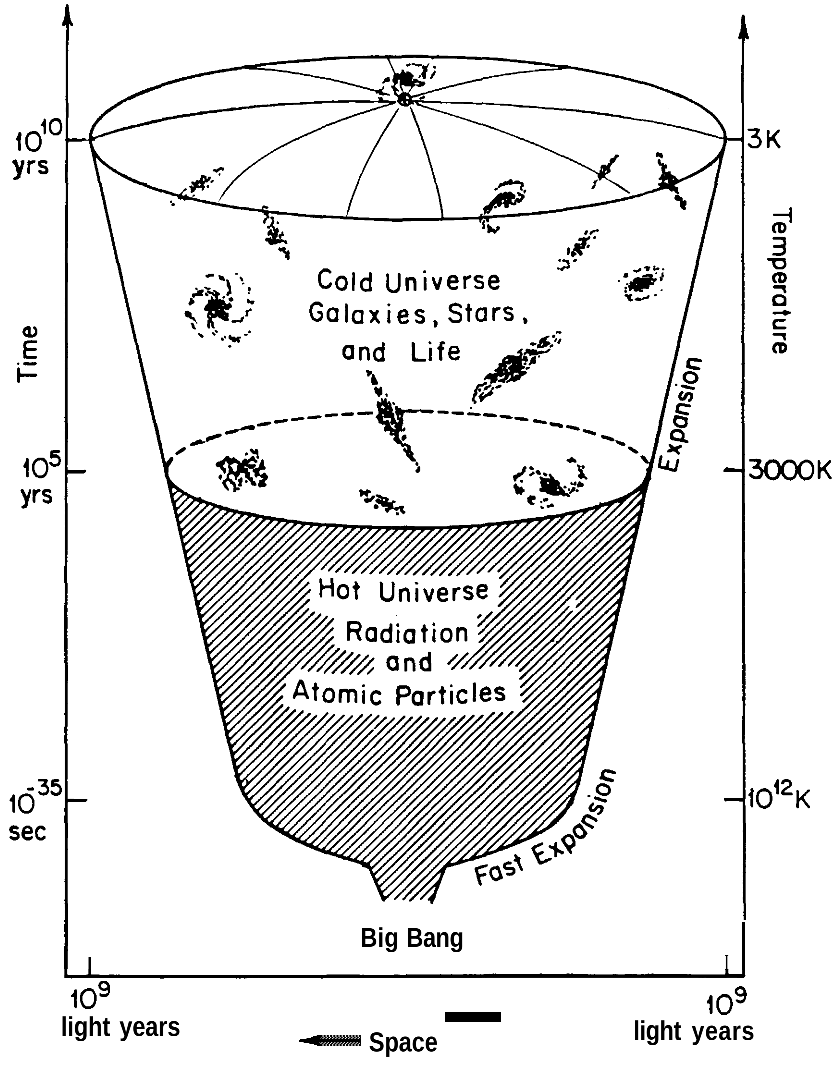

Fig. 2. The Big-Bang model of the evolving universe.

(b) Evolution of Life.
Complex organic molecules, bacteria and multicell organisms, development of fish and mammals, and humans.

(c) Evolution of Humans.
Cave humans, development of fire and language, settlements and agriculture, writing, science and technology, and the conquest of space.

In all the examples listed above, as the arrow of time is pointing to the future, simple things become more complex and matter seems to get more and more organized, from disorder into a higher order. (As we shall see below this happens at the expense of increasing disorder in other parts of the universe.)

B. The Thermodynamic Arrow of Time

Paradoxically, the arrow of time can be defined with the opposite processes than the ones discussed in the Historical Arrow of Time, that is with processes which destroy information and create disorder. Such behavior is also well understood in nature and derives its attribute from the expansion and cooling of the entire universe. Heat flows always in one direction, from hot to cold. This is the celebrated physics principle called "The Second Law of Thermodynamics." Hot stars radiate their energy into cold interstellar space, and whereas stars are complex systems of atomic particles undergoing various atomic and nuclear interactions, the interstellar and intergalactic space is much simpler and is less organized.

It is easy to observe what happens when an ice cube is put in a cup of hot tea. The information and order which exists in the structure of the crystal which represents the ice cube is soon lost in the melting process, while the arrow of time points from the past to the future. We can also observe that the liquid of a perfume evaporates from an open bottle and the structure or order existing in the liquid gets lost and instead we have the random motion of gaseous molecules in the air. In both of these examples, order was transformed into relative disorder while the arrow of time was progressing in the direction of the future. Such examples have been described in detail by Layzer (1975).

Both the thermodynamic and historical arrows of time seem capable of defining time's direction—albeit with exactly the opposite physical processes.

Entropy

One convenient method of measuring order or information relative to disorder or chaos is the concept of entropy. Low entropy corresponds to relative order and high entropy to disorder. Within this framework, the arrow of time suggests that the historical universe progresses from high entropy to low entropy, while the thermodynamic arrow of time from low entropy to high entropy.

From the cosmological point of view, however, the expanding and cooling of the Big-Bang clearly indicate that entropy is constantly increasing, as is described by the Second Law of Thermodynamics. One is therefore forced to conclude that the Big-Bang began with low entropy or maximum order and information. As the universe expands the net order is continuously being converted into disorder or chaos—things get worse! It is important then to realize that the universe began from a smooth and orderly state. This maximum order is probably a characteristic of the required perfect symmetry at the moment of the Big-Bang, when all the forces of nature were combined into one.

Paradoxically soon after the Big-Bang, while the universe was still in a very hot state, matter was mostly in thermal equilibrium and atomic particles were moving chaotically in a great disorder—that is, the universe seemed to be in a high entropy state! The answer to this paradox probably lies in the unknown nature of gravitational entropy and the local space–time conditions prevailing at the time of the Big-Bang. These conditions, sometimes referred to as quantum gravity, remain very obscure and mysterious (Penrose, 1979).

It is also clear from observing the universe, and from our discussion of the historical arrow of time, that during the Big-Bang expansion, entropy fluctuations began to grow and some parts of the universe decreased in entropy and increased in order and information. The formation of galaxies, stars, planets and life are clear examples. However, it is important to realize that the net entropy of all these systems together with the rest of the universe also increased as the time arrow progressed into the future. It appears that for every ordering of things there is, on a larger scale, a greater increase of disorder. Hence, the net entropy of the universe always increases, and eventually all information will change into chaos for an ever expanding universe.

Time Asymmetry and Irreversibility

Both the historical and thermodynamic arrows of time define preferred directions in time, which seem irreversible. We have never been able to travel back into history, nor do we observe the molecules of the evaporated perfume all gather back into the perfume bottle to form a liquid, nor does the ice cube in the cup of hot tea get colder and the tea hotter by extracting energy from the ice cube. These processes seem irreversible in the observable universe.

However, an examination of the conservation laws of physics indicates that these processes are not forbidden. The equations of physics are time-symmetrical, they do not distinguish between past and future. The laws of physics indicate that every detailed action could occur in reverse. It seems that the concept of the passage of time is not essential. At the microscopic level of atoms, the world changes but does not necessarily evolve.

Yet in the macroscopic world there is no doubt at all that time flows only in one direction—and this needs an explanation. What is the reason for the irreversibility of time which we observe? If the origin of irreversibility is not in the mathematical presentation of physics it must then be related to the boundary conditions and the initial conditions prevailing during the Big-Bang explosion of the universe. What happened at the moment of the Big-Bang to give a direction to the arrow of time?

If we could isolate a perfectly insulated enclosure and make sure that it has the same temperature all over, then it would not be possible to define the passage of time within the enclosure. It would not be possible to determine what is past and what is future within the enclosure, and time's arrow would have disappeared. In this hypothetical system we find a time-symmetrical static world, where time has no flow or passage or meaning. In the real world however, we can never isolate an "enclosure" or anything else completely from the rest of the universe. If systems are left alone, there is always a heat sink described by the cooling of the universe and the Second Law of Thermodynamics. Any system that has a possible heat sink, so that its temperature decreases, will always show the anisotropy of time.

In the macroscopic world effects occur after causes, entropy is increasing, and psychologically there is a sense of advancing time, which seems irreversible—even though the laws of physics do not prevent a time symmetry for microscopic processes, that is, a few perfume molecules may always find their way back into the perfume bottle.

Natural physical processes indicate that they operate in a basic symmetry. A fundamental theorem of physics requires that physical processes remain invariant with respcct to the direction of the flow of time T, with respect to the electric charge of matter C, and with respect to the positions and motions of matter P (parity). This CPT theorem indicates that a universe with the reversed CPT properties will be indistinguishable from the one we started with. However, there is one known exception to CPT invariance, which may indicate a preferred direction of time. This is the decay of the unstable subatomic particles known as K-mesons. It appears that the natural decay rate for the K-mesons may be slightly different in a time-reversed world, as indicated experimentally by the observed CP symmetry violation (indicating a possible T-symmetry violation, assuming CPT invariance). This is the only known time asymmetric physical process, but it is deduced by indirect reasoning.

In the description of a flowing time we find interesting paradoxes which point out our limitations in understanding completely the nature of time.

The following are examples describing time asymmetry and irreversibility. Suppose we were given three colored snapshots of a hot, warm, and cold iron bar that were taken in an isolated enclosure and we were asked to arrange them in the time order that they were taken (Figure 3). One snapshot, labelled B, showed a blue iron bar. The second snapshot Y, showed a yellow iron bar, and the third snapshot R showed a black iron bar. It is easy to conclude that the time sequence of the snapshots were BYR, since the second law of thermodynamics clearly proceeds from hot to cool. Now assume that we were given three more snapshots of the iron bar all of which looked alike—that is, they were taken after the iron bar had cooled and was at the same temperature as its surroundings. In this case it would be impossible to deduce which snapshot was taken first, second, or third, and the direction of the arrow of time would be undetermined.

In another example consider that we make a movie of randomly moving molecules of a gas in an enclosure. We can then play the movie forwards and backwards and it would look pretty much the same, and we would not be able to tell which direction time was flowing when the movie was taken.

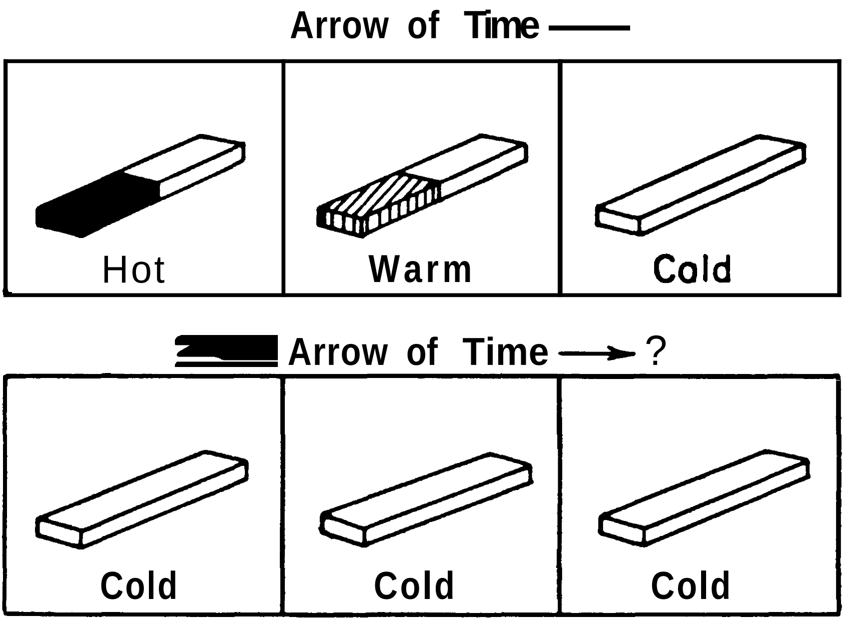

Fig. 3. The arrow of time. Snapshots of a cooling iron bar, and an iron bar at the same temperature in an isolated enclosure.

Another unusual experiment was suggested by Philip Morrison (1967). How can we make a film where a hen becomes smaller, becomes a chick, crawls into a shell and becomes an egg? Running the film backwards is cheating, of course! But, if we take an incubator with 10,000 eggs, and while our clock is running forwards, the first frame we take is that of an old hen, the second of another hen a little younger than the first, and so on to a newly hatched egg, then playing the movie forwards will produce the effect of seeing an old chicken become younger. Provided that we cannot distinguish one chicken from another, this would have the effect of statistically backward running time. Such a movie made with people probably does not work, for hens it might work if they all had the same color and looked alike, but such a film made for electrons will always work since there is no known way to distinguish one electron from the other.

Although it is evident that for macroscopic phenomena time runs only in one direction, into the future; it is also clear that the laws of nature are time-symmetrical and at the microscopic level of atomic particles the direction of time, or even its meaning and reality, remain ambiguous.

We can summarize the universal direction of time in the following somewhat related ways:

(a) From the Big-Bang to total expansion to infinity (or expansion to zero velocity followed by collapse back to the Big-Bang if the universe contains enough mass for gravity to stop the expansion).

(b) From a universal maximum temperature to a minimum temperature.
(c) From minimum entropy to maximum entropy.
(d) From relative order to disorder.
(e) From perfect symmetry (information) to chaos.

Time and Relativity

In the introduction it was mentioned that Albert Einstein's theories of relativity constitute the only major advancement in our notion of the nature of time. Einstein (1905) put forward his Special Theory of Relativity in 1905 where he described the relative uniform motion of objects, and defined the physical world with four dimensions, three of space x, y, z, and one of time t. Any point in this four-dimensional system with a specific set of x, y, z, t coordinates is defined as an "event." An event then is unique in the entire history of the universe, and it occurs only once since at best one of the four coordinates is assumed to change. One can then think of all events, past and future, in the universe by their x, y, z, t coordinates. That is we can imagine a four-dimensional map of everything in all of time. In such a space–time map, as pointed out by Gold (1974), there is no movement or passage of time, rather the objective world simply is, it does not happen. In the words of Penrose (1979, p. 592) the Special Theory of Relativity "leads to a picture in which potentialities becoming actualities is either highly subjective or meaningless."

This celebrated new physics resulted in the famous Twin Paradox, where one twin leaves the earth for a long interstellar voyage and when he returns he finds that his twin brother has aged much faster than he. This illustrates how motion makes the rate of the passage of time to be non-uniform.

The General Theory of Relativity published by Einstein in 1916, described a new theory of gravitation. Gravity in this theory is viewed not as a force between two masses, but as the curvature of space–time that these masses create around them. That is, objects fall towards each other not by a real gravitational attractive force, but by the nature of their masses producing a curved space around them where nearby objects roll towards them. This theory deals not only with uniform motion, but with accelerated motion as well. It predicts that the rate of time passage is not the same from place to place and that it depends on the strength of gravity felt at a certain location, more explicitly on the degree of the curvature of space–time at that place.

This theory has been used to describe the existence of the mysterious black holes, as mass entities where the curvature of space–time is complete. Such objects of extreme gravity are wrapped around space–time, and all space and time avenues with the rest of the universe are cut-off (Misner, Thorne & Wheeler, 1973). All communications with the inside of the black hole cease to be physically possible. To a distant observer a time clock near the black hole would appear to advance very slowly, and on the surface of the black hole time would appear to stop. This most fascinating result creates fundamental questions about the relationship of black holes with the evolving universe, which appears to have an arrow of time.

Clearly the gravity, or the space–time curvature, of a black hole is so extreme that not even a ray of light can escape from it. A distant observer then receives no light from a black hole and it appears black to him. The existence of the black hole however, can be felt by its attractive gravitational potential that it exerts on its surroundings. Any object close to a black hole will deduce its presence by the pull that it would feel on itself. We cannot see black holes, but we can be sure that they are there! It should also be mentioned that in 1974 Steven Hawking (1974) unexpectedly showed that black holes are not entirely black. Due to quantum mechanical effects black holes may evaporate, but for a black hole the mass of a typical star, this Hawking radiation is completely unimportant since the time of evaporation is computed to be much much longer than the age of the Big-Bang universe.

The General Theory of Relativity also presents paradoxes which appear to defy our psychological common sense. Thomas Gold (1975) has described the Mother and Baby Paradox where a loving mother does not wish her baby to grow old. Hypothetically, every night when the baby sleeps she surrounds the baby's crib with huge masses, creating a strong gravitational field—where time passes slowly. She then goes out in space and spends the nights and in the mornings she takes the masses away, and repeats the process every night thus achieving a cumulative slowing of the passage of time for the baby. However, I think that an even deeper paradox results if we exchange the baby with the mother, then the mother eventually becomes younger than her baby! Beware! This is not equivalent to travelling into the past. Nature seems to permit such behavior and the meaning of time becomes even more mysterious.

It is not unusual to think that there is a relation between the very early Big-Bang and a super black hole. How is time to be understood during the early instances of the formation of the universe?

Relativity puts an inseparable bond between the notion of time passage and the existence of matter and energy in the universe. Time seems to pass at different rates depending on what masses are available. Time passes slowly near masses, and in vast empty spaces time would go faster compared to ours. The whole concept of time passage seems to be entirely due to the fact that there are masses around in the universe.

Conclusions

For living beings, for stars and galaxies, and for the evolution of the universe there seems to be an arrow of time, yet in detail the concept of the nature of time remains uncertain. The best observation about time is presented by the Second Law of Thermodynamics, and the best description of time is given by the Theories of Relativity. A deeper understanding of the nature of time may come when we are able to explain the physics of the Big-Bang in much more detail.

One could ask, what was before the Big-Bang? Or did space and time, and energy and matter begin at the Big-Bang with zero space, zero time, and with no matter or energy? As Stephen Hawking (1988) has described, if time had no boundary than it ceases to be well defined at the Big-Bang. Just like the direction of North is not well defined at the North pole. Asking what happened before the Big-Bang is like asking for a point say one kilometer North of the North pole! Since in relativity the time coordinate is equivalent to the other three space coordinates, then this analogy is a particularly vivid one.

A more complex model of the Big-Bang is the model of an oscillating universe, where the universe continuously expands and contracts in an infinity of time. In such a model it is not possible to define the direction of time. Perhaps time runs forwards during the expansion phases and backwards during the contraction phases—that is, cause and effect may be reversed during the contractions. Such models remain very hypothetical, and may not be realistic since it is possible that consecutive Big-Bangs may damp out the expansion in only a few cycles.

Our understanding of the physical world has been enormously enhanced with the spiraling progress of science and technology. The unity of knowledge has revealed a mysterious and highly sophisticated universe. While we still interpret all things in terms of a subjective flowing time, we do understand that the nature of time remains unknown. Any deeper understanding of the origin of the universe will have to include a coherent explanation of the nature of time.

The somewhat confusing state of our understanding of the nature of time was perhaps best put by T. S. Eliot (1971, p. 121) who once reflected as follows:

Or say, that the end precedes the beginning,
And the end and the beginning were always there,
Before the beginning and after the end.
And all is always now.

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