Chapter 10
The Direction of Time Ensured by Cosmology

Hervé Barreau

Abstract Cosmology gives us two ways for considering the direction of time, which means an overall development of physical reality from past to the future. Firstly there is an overall development if, coming from a beginning, the evolution of the universe is a function of the cosmic time which gives us the age of the universe. Secondly there is an overall development if cosmic time cannot only date the eras of the universe but also explain the birth of the main complex structures we find inside it. In this second manner, which presupposes the first, the expansion of the universe during cosmic time is a cooling factor which permitted the breaking of the symmetries discovered by theoreticians while studying the different interactions. These breakings were responsible not only of the four distinct interactions but also of the various degrees of physical reality. Some metaphysical reflections are unavoidable in the view of such a history.

Keywords Life-story · Irreversibility · Thermodynamics · Branch systems · Cosmic time · Unification and desintegration of primitive forces · Anthropic principle

We speak of irreversibility for physical processes and of the direction for time. This means that characterizing the irreversibility of these processes and assigning a direction in time are different things. The difference lies in the fact that processes are irreversible in time considered as a natural or space-time dimension, whereas time itself is conceived as a global development, extending only from the past to the future, from a beginning to an end or to infinity. The physicist's problem is to decide whether it is legitimate to believe in such a global development as it was postulated by Newtonian physics in the form of real time, mathematical and absolute.

This problem is particularly evident in the study of nature. In our own individual lifetime the difference between the irreversible processes which we experience and our overall development scarcely presents a problem. Our age makes the dif-

H. Barreau (✉)
CNRS, 23 rue Goethe, 67000, Strasbourg, France
e-mail: hbarreau@noos.fr

S. Albeverio, P. Blanchard (eds.), *Direction of Time*,
DOI 10.1007/978-3-319-02798-2_10,

ference. Of course it is easy to isolate ongoing and irreversible processes such as the progress of a career or a scientific achievement, but it is scarcely more difficult to assign a tangible and immutable place to any event in a lifetime. Historical biographers are guided in their work by the fact that every human life follows a unique course from birth to death and the impact and effect of events, predictable or otherwise, on the life of the individual depends first and foremost on the exact time location upon which they take their place. If a historian cannot date an event in a life precisely he cannot claim to have reconstituted the unique life history of a particular individual, but this task is possible of achievement in principle and we can always give reasons why it has not been achieved in a particular case (generally by lack of documents).

Could this be the same for the study of Nature? We see the difference immediately. In the biography of an individual it is his legitimate postulated identity which enables us to assign him a life history, tangible to the extent that it has been lived; nothing allows us, a priori, to assign such a life history to Nature, based on a unique support, oriented in a single and irreversible direction. We can even say that, despite Newton's reassuring stance in making time an absolute development, modern physics has conspired to cast doubts on the unity of a global process by linking time to concrete processes subject to specific laws. With Einstein's relativity theories, the doubt even seems to have given way to an opposing belief. In the context of special relativity, each reference system refracts the development of the others in its proper perspective, so that the temporal order of two space-like separated events may differ from one reference point to another. In the context of general relativity the space-time curve imposed by the presence of mass-energy obliges us even to measure time differently at each point in space-time, so much so that individual futures can no longer be compared. For Einstein himself, these individual futures were pure illusion, at least in the final expression of his thinking.

Nevertheless it is relativity itself which has enabled the reintegration of a universal past and future and, thereby, of a single direction for time. This is a paradox worth considering. On one hand, in linking the measurements of time ever closer to phyisical processes, relativity has obliged us to abandon the belief in Newtonian metaphysical time; on the other, in rethinking the approach to cosmological problems, it allows us to look at the universe as a developing whole, a global process with a unique history and oriented in a single direction, like a living being.

We can see, therefore, that there are two problems regarding the direction of physical time as revealed by cosmology and we must take account of the fact that the solution of the first authorizes the onset of the second. The first problem is this: how can we be sure that relativist cosmology offers us a unique universe with a beginning and a future, thus confirming the irreversibility of the processes which unfold in it? The second problem is the following: on this basis, can we imagine solutions to the various problems in theoretical physics, such as the diversification of forces and the formation of chemical elements, for which we have been unable to offer a plausible justification up to now? We will see how relativist cosmology answers these two questions.

1 The Cosmic Arrow of Time

The answer to the first question invites us to review the historical stages of contemporary cosmology and the successes it has obtained from our point of view.

First of all, to be sure, we must consider the universe as a whole. The cosmological principle that the universe is, on the whole, homogeneous and isotropic, is sufficient. It is a reasonable assumption and Einstein himself had recourse to it in his *Cosmological Considerations* (1917). However, in predicating a static and homogeneous density of matter in a finished though endless universe, Einstein came up against the problem that Newtonian cosmology had failed to resolve even in his time: the intensity of the gravitational field must increase to infinity. Einstein met this difficulty, firstly, by distinguishing time from the three spatial dimensions, and secondly, by imagining a cosmological constant Λ which must prevent the universe from collapsing in on itself—hence the image of a "cylindrical" universe with neither beginning nor end. We should remember that time, distinguished from the three spatial dimensions, becomes "cosmic time", to use the terme applied to it by H. Weyl in 1923.

However, in 1922, Friedmann noted that there was no static solution to the ten equations of the new relativist theory of gravity, as applied to the universe as a whole. This, furthermore, was one of the reasons for which Einstein had been obliged to introduce a cosmological constant. Friedmann suggested various models of relativist cosmology (taken up later by Robertson and Walker), by supposing that the average density of the matter which filled the universe varied with time. Three-dimensional space corresponding to the model would be spherical and closed, hyperbolic and open or else Euclidian, depending on the value of a cosmological constant k.

Up to then cosmology had been purely speculative, as in Gödel's later cyclical model. It was Lemaître who, in 1927, imagined putting the expanding universe model which he had adopted in correspondence with the distancing of the galaxies, demonstrated by the red shift of their atomic spectra, which he interpreted as a Doppler effect. This distancing of the galaxies, which Hubble had demonstrated in 1924, received outstanding confirmation in 1929. An expanding universe has been the relativist cosmological model ever since.

It was very fortunate that this expanding universe model was confirmed in 1965 by the discovery of fossil cosmological radiation of 2.7 K. It was also confirmed from other sources, such as the probable age of stars and galaxies and the proportion of chemical elements in the cosmos, not to speak of the Olbers paradox regarding the scattered brilliance of stars in the cosmos, which is explained by this expansion. All these facts enabled us to calculate the age of the universe, estimated between 13 and 15 billion years.

What concerns us more closely in our investigation into the direction of time is that the expansion theory (the "Big Bang") itself offers the direction we lost when we were obliged to abandon Newton's absolute time, which science rejected as metaphysical. Expansion involves the dispersal of the initial energy and an increase in the global entropy of the universe as it proceeds to cool. In our opinion it is this cosmic need for increasing entropy which must be regarded as the ultimate source of any detectable increase in entropy in any experiment, regardless of the level.

This question is worth discussing, as physics, a science based on experiment (even more than on principles, no matter how necessary and reasonable these must be), is in a delicate situation regarding the direction of time. For all human experience, whether physical or moral, is irreversible. We cannot imagine that the repetition of the same act can constitute an objection to the general application of such a law, as this repetition creates a habit. In any event we must acknowledge that everything we observe in the universe bears the stamp of irreversibility from the very fact we observe it, as we never observe exactly the same event twice. It is significant, furthermore, that Bertrand Russell thought that our belief in the direction of time was based on the generalization of this subjective experience of irreversibility. However, this means that the belief is based on the future-oriented nature of this experience, as we noted earlier, and this is obviously not the experience of the entire universe. This basis has always seemed insufficient to physicists who aim at an "objective" science dealing with physical reality, and therefore independent of human observation, and it is understandable that they were not content with classic thermodynamics, which is phenomenological, even in the expression of its second law on the increase of entropy in a closed system. They wanted to base thermodynamics on statistical mechanics, which also brought new results. But with regard to the second law, in particular, the recourse to statistical mechanics is both despairing and desperate and Boltzmann, among others, lost his robust faith in it. When we have effectively reduced entropy to a probability, we have not taken a step towards objectivity—we have aggravated the problem. The question is not that the notion of probability introduces an approximate and subjective element of knowledge, as this subjectivity can almost be reduced to objectivity if we examine it closely. It is that probability, regarded in its most objective aspect as a carefully defined mathematical notion, is indifferent to the flow of time. Probability makes entropy intemporal. We have not gained the direction of time—in fact we have lost it. The Ehrenfests [1] and van der Waals [2] were aware of this, as was the philosopher Reichenbach, who was confident at first of the habitual direction of causality, and finally became sceptical regarding the theoretical advantage to be gained from the physical experience of time. All these authors believe that entropic growth is due to the initial conditions of a system which finds itself relatively isolated thereafter. We must therefore introduce the theory of *branch systems* developed by Reichenbach [3] and Grünbaum [4] to complete the mechanistic theory of entropy. It must be admitted that the branch systems in which entropy increases find themselves in a state of relatively low entropy when separated from their environment. For the greater majority of them, therefore, there is no doubt at all about the direction of time.

It is the expansion of the universe, therefore, which provides the most general framework and ensures the effectiveness of the speculative branch systems theory. Entropy was low in the universe in the past—it is the general dispersal of energy which will entail a general rise in entropy and a fall in the intensity of cosmic radiation in the future. Even if the Big Bang is followed by a Big Crunch for obvious gravitational reasons, the second universe born of the first (if rebirth is possible), will be generally in a higher entropic state than the first from the outset, as Tolman [5, 6] had demonstrated. As all forms of physical irreversibility appear to be closely linked to thermodynamic irreversibility, we see that the direction of cosmic time involves all forms of irreversibility and ensures the prevalence of the cosmic time arrow, the only thing which gives it direction. This is the "master arrow time" as Professor Zeh wrote [7].

2 The Effects of the Cosmic Time Arrow

Relativity had consequences for research in two directions: cosmology, as we have just seen, and the unification of physical interactions, as we will also see, as this question brings us back to cosmology and the cosmic time arrow. In this direction, however, the first attemps were disappointing. Einstein devoted the last 30 years of his life to them without success. H. Weyl failed to unite relativist gravitational interactions with classic electromagnetic interaction, though he discovered the promissing role of gauge symmetries during his attempt. Things took on a new perspective when quantum field theory was accepted as the appropriate theoretical framework for union. Glashow, Salam, and Weinberg were therefore able to unify quantum electrodynamics and weak nuclear interaction in 1967. Then came the idea of combining them with strong nuclear interaction in a "great unification" theory. Then it was hoped to combine this unification with gravity by using string theory. However, combining fermions and bosons in "great unification" called for a particular kind of symmetry, the supersymmetry—hence the superstring theories arose around 1985, later revived in their combination in the M theory and their application to gravity in 1995. Theoretically speaking, therefore, we seem to be close to unifying the four fundamental forces and we refer to a "theory of everything", but it is impossible to obtain experimental data. This is because we are dealing with the conditions which must present at the very beginning of the universe, even before the "Big Bang". Thus cosmology obtains a new role, which we can describe, if not explain exactly, and this description runs like the following scheme.

The Big Bang we place after the "Planck's Time", when the age of the universe was 10^{-42} s in the classic model. It is clear that general relativity and quantum theory must have been intermingled during this "Planck's Time", as the theoreticians imagine. They believe that this theory implies that the primordial strings were twisted through 10 or 11 spatial dimensions, which were rolled in on themselves. The "Big Bang" can then be explained by the fact that strings which twisted through only three spatial dimensions could collide and be annihilated (between strings and anti-strings) and could free these three dimensions, which then dilated to produce an universe. It was the first break in symmetry and it inaugurated cosmic time. Planck's "nut" was broken and the universe as we know it was born with cosmic arrow pointing towards expansion. It is to be observed that with the theory of quantum gravity we obtain the same phenomenon, as Professor Kieffer has here demonstrated.

What we must remember in such a hypothesis is that the direction of time was not only the prime director for all the time arrows that experimental or theoretical physics can detect, as we have tried to show earlier, but that it also governed all the remarkable events which shaped our universe; the universe cooled as it expanded and the progressive drop in temperature was responsible for all the structures we know today.

The first question relates to the disintegration of forces by successive breaks in symmetry. It seems that gravity was separated from the other forces when temperature fell to 10^{32} K and the strong nuclear force separated from the electro-weak at 10^{28} K. These two disruptions gave rise to a phenomenon of very sudden expansion, which we term "inflationary" and which Guth and Englert postulated in the 1980s to explain the similarity between very distant regions of the universe which we cannot connect by causal influence because of the finitude of c. This brings us to 10^{-32} s in the age of the universe. The X bosons and anti-X bosons, which were exchanged when the strong nuclear force combined with the electro-weak force, disintegrated over two short but different periods of time, and this difference was sufficient to annihilate the antiquarks by fusion with quarks, leaving a persistent residue of surplus quarks. This can explain why anti-matter only exists in cosmic radiation and under the artificial conditions of some giant accelerators. The weak nuclear force separated from the electromagnetic force at a temperature of 10^{16} K and quarks fused to form nucleons (i.e. protons and neutrons) at 10^{12} K. This brings us to around 10^{-7} s in the age of the universe. This era has been called the "particular" or "first second" era [8]. As far as we are concerned it is the era when the four fundamental forces were separated one after the other.

Thereafter we must wait until the temperature reaches 10^{10} K for the beginning of a new era, known as the "nuclear era", and the formation of deuterium nuclei, and subsequently of tritium, helium 3 and lithium 6, all of which were formed from deuterium. We call this the primordial nucleosynthesis; it lasted for the first three minutes of the life of the universe. We know that the nucleosynthesis of the other elements occurred later inside the stars.

During the third or "radiative" period the temperature fell by several million degrees to 10,000 K. Photons were emitted constantly and absorbed by electrons, which formed a cloud which was independent of that of the protons and the few nuclei formed during the primordial nucleosynthesis. At the end of this era hydrogen ceased to be ionized and became "atomic"; electrons began to orbit protons and lost their power to interact with photons, which they left to circulate in space thereafter. Such was the beginning of diffuse cosmic radiation, which appeared when the universe was 300,000 years old and which we discovered in 1965.

We could continue this genesis of the universe as we know it by describing the fourth "material" ou "stellar" era and the formation of the galaxies, the stars and the planets which might support life but as far as the direction of time is concerned it has nothing further to teach us about its evident power to generate the forces and shape the principal structures of our environment. These were conditioned by the fall in temperature during the expansion and we have seen that this was decisive. This seems to be the "true story" of the birth of our universe, and we see that the expansion and cooling time was the regulator.

3 Conclusion

In conclusion I would like to return to our initial comparison between physical/cosmological time and personal time. The unity of time for a person lies in the fact that it continues from his/her birth to his/her death, constantly enriching him/her, constantly changed by his/her memories, his/her anticipations ans his/her experience of present events. Apparently there is nothing like this in cosmic time. Nevertheless the universe also has an age, and we have seen that this age is very important because the progressive cooling factor.

Also some reflexions seem appropriate and in some manner inescapable. When we consider the marvels which were created as the universe cooled we cannot help but share Dyson's opinion: "When we look at the universe and identify the multiple accidents of physics and astronomy which have worked together for our benefit, it all seems to have happened as if the universe must somehow have known that we had to appear" [9]. Steven Weinberg echoes this comment, even if he does not agree with it, when he writes: "It is almost impossible for human beings not to believe that they have a special relationship with the universe, that life is not just the grotesque result of a series of accidents extending back into the past to the first three minutes, that somehow we were intended from the beginning" [10].

Obviously such reflexions are metaphysical and do not belong to physical science. Nevertheless they have their use in assessing our must speculative physical theories. Because they are mathematical these theories have a tendency to neglect the course of time and to see it only as an accident, but Brian Greene, who not only contributed to the string theory, but also to our thinking about its scope, does not believe that such theories can replace the considerations which stem from the *anthropic principle* and from the imagination of *multiuniverses*, which he places (quite rightly as it seems to me) in the same thought register [11]. Certainly it is doubtful that a future theory can encompass all the initial conditions necessary for the development of the universe. On the other hand it is obvious that this evolution presents us with cosmic time, which produced formidable results from limited resources. Far from tending to discourage us, the vision of an *elegant universe* should enable us to give the appreciation it deserves to this time direction. For the future of earth and mankind, this time direction is largely in our hands and we seem to be called upon to use it in a manner worthy of the great epoch of which we are the heirs. In any event, we can no longer profess ignorance of this heritage.

References

1. Ehrenfest, P., Ehrenfest, T.: Begriffliche Grundlagen der statistischen Auffassung in der Mechanik. Encyklopädie der mathematischen Wissenschaften, vol. IV, 2, II, pp. 41–51 (1909)
2. van der Waals, J.D.: Über die Erklärung der Naturgesetze auf statistischen Grunlage. Z. Phys. **12**, 547–549 (1911)
3. Reichenbach, H.: The Direction of Time, pp. 135–143. University of California Press, Berkeley (1971)

4. Grünbaum, A.: Philosophical Problems of Space and Time, pp. 254–264. Reidel, Dordrecht (1973)
5. Tolman, R.C.: Relativity, Thermodynamics and Cosmology. Clarendon, Oxford (1934)
6. Davies, P.C.: The Physics of Time Asymmetry, pp. 80–109, 185–202. University of California Press, Berkeley (1977)
7. Zeh, H.D.: The Physical Basis of the Direction of Time, p. 124. Springer, Berlin (1989)
8. Audouze, J.: L'Univers. Que sais-je?, vol. 687, pp. 105–111. PUF, Paris (1997)
9. Dyson, F.J.: Sci. Am. **225**, 51 (1971)
10. Weinberg, S.: Les trois premières minutes de l'univers (french edition), p. 179. Seuil, Paris (1978)
11. Greene, B.: L'Univers élégant (french edition), pp. 394–401. Laffont, Paris (2000)