Popper on Irreversibility and the Arrow of Time[x]

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(published in Ian Jarvie, Karl Milford and David Miller (eds.):
Karl Popper: A centenary assessment. Volume III: Science
Aldershot: Ashgate 2006, Chapter 45, pp. 57–70)

Abstract

Popper challenges the mainstream account of irreversibility, which refers to thermodynamics, by putting forward three theses: (1) There are irreversible processes of wave-production. (2) These processes are independent of the irreversible processes described by thermodynamics. (3) The irreversible processes described by thermodynamics do not have a cosmic significance. Hence, Popper traces irreversibility back to radiation instead of increase in entropy. However, I shall argue that Popper's account runs into the same problem as the mainstream account: Both these accounts presuppose initial conditions of the universe that seem to be at least as improbable as anything that is explained by referring in the last resort to these initial conditions. Thus, neither thermodynamics nor radiation provides for an explanation of irreversibility. The appropriate place to look for such an explanation is cosmology. Popper's main motivation in favouring radiation over entropy increase as the source of irreversibility is that he regards a statistical theory of the arrow of time as being unacceptable. By the arrow of time, he means the flow of time in the sense of a temporal view of the universe. I shall claim that irreversible processes do not provide an argument for assuming an arrow of time in this sense. A Newtonian world can include an arrow of time without having to contain irreversible processes. Special relativity suggests an atemporal view of the universe, the so-called block universe view. The block universe can include irreversible processes such as the ones of radiation and entropy increase. General relativity does not change that matter. Hence, in order to make a case for a physical basis of the arrow of time in the sense of a temporal view of the universe, other arguments would be needed than Popper's argument building on irreversible processes.

1. Irreversible processes

The laws of our basic physical theories describe all types of processes in such a way that they allow for these processes being reversed. Thus, if there is a process that leads from an event of the type *A* to an event of the type *B*, it is in accordance with the laws of our basic physical theories that there also is a process that leads from an event of the type *B* to an event of the type *A*. I take an event to be whatever is the content of a finite and continuous space-time region – in the last resort and more precisely, whatever there is at a space-time point – and a process to be a continuous sequence of events in this sense. On the other hand, many of the

[x] For comments on the draft of this paper, I am grateful to Claus Beisbart, Christian Heinicke, Claus Kiefer, Vincent Lam, Christian Zemlin, and two anonymous referees for this book.

types of processes with which we are familiar seem to be irreversible: they happen only in one direction, but not in the reverse one. If, for instance, a wine glass falls on the floor, it is broken and does not go back into its former state. It never happens that scattered pieces of glass come together on their own to form a wine glass.

In the first part of this paper, I shall consider the following question: How can we bring the reversibility of all processes allowed for by the laws of our basic physical theories together with the irreversibility of many processes that we experience? The role of thermodynamics and radiation in this context will be examined. Based on an answer to this question, the second part of the paper will go into the relationship between irreversible processes and the so-called arrow of time in the sense of a flow of time. This relationship – and the issue of whether or not there is a flow of time – will be considered with respect to classical mechanics as well as special and general relativity. The paper will not take quantum theory into account.

The most widespread account of irreversibility refers to thermodynamics. According to the second law of thermodynamics, the entropy of a closed system increases in time (or remains constant), but never decreases. Entropy is a measure of disorder, whereby disorder is a way in which energy is dissipated 58 or scattered. When a wine glass falls on the floor and breaks into pieces, energy is scattered into many pieces whose motions are uncoordinated. Entropy has thus increased. The second law of thermodynamics describes the fact that such pieces do not come together on their own and form a wine glass. Thus, the second law of thermodynamics refers to irreversible processes.

The received view regards thermodynamics as being reducible to classical statistical mechanics.[1] Classical statistical mechanics, in turn, is reducible to classical mechanics. According to statistical mechanics, it is not impossible, but extremely unlikely that the scattered pieces of a broken wine glass come together on their own to form a wine glass again. The reason is that it is very unlikely that the initial conditions for such a process, namely a coordinated motion of the pieces of the former wine glass, will ever be satisfied without external intervention. There are by far more states in which the motions of the pieces of the former wine glass are uncoordinated than states in which these motions are coordinated in such a way that the pieces come together to form a wine glass on their own. That is why the probability for the reversal of the process of the wine glass breaking into pieces – and thus the probability for a decrease in entropy – is negligible.

The common answer to the question how the reversibility that the fundamental laws allow is linked with the irreversibility that we experience hence is to say the following: Irreversibility is not a matter of fundamental laws; it is due to the fact that, in the cases of processes which we take to be irreversible, it is very unlikely that the initial conditions for a reversal of the processes in question will ever be met.

Popper challenges the received view. The focus of his challenge is the role of thermodynamics. In four short papers in *Nature* between 1956 and 1958, he argues that it is not true that all irreversible mechanical processes require an increase in entropy. There can be irreversibility without increase in entropy. Popper (1956) gives a simple example. He considers a pond into which a stone is dropped. The stone produces an outgoing wave of decreasing amplitude that spreads concentrically about the point of the stone's impact. Popper (1956) argues that this process is irreversible:

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1 For recent refinements and elaborations of this view, see, however, Sklar (1993), chapter 9, Callender (1999) and Albert (2000), chapters 2 to 4.

> Suppose a film is taken of a large surface of water initially at rest into which a stone is dropped. The reversed film will show contracting circular waves of increasing amplitude. Moreover, immediately behind the highest wave crest, a circular region of undisturbed water will close in towards the centre. This cannot be regarded as a possible classical process. (It would demand a vast number of distant coherent generators of waves the co-ordination of which, to be explicable, would have to be shown, in the film, as originating from one centre. This, however, raises precisely the same difficulty again, if we try to reverse the amended film.)

59 Although Popper claims that the water wave is an example of an irreversible process independent of thermodynamics, he grants that any experimental realization of such a process involves an increase in entropy.[2] His point is that the increase in entropy is not the reason for the process being irreversible: The reason is that the conditions for the reversal of this process cannot be established – independently of whether or not the reversal of this process would also involve a decrease in entropy.[3]

Furthermore, when Popper claims that the described process of contracting circular waves is not a possible physical process, he does not intend to deny that such a process is permitted by the laws of classical mechanics. In a later paper, he says:

> The problem before us … is the clarification of the notion of a 'causally irreversible physical process'; or more precisely, of a process that is (a) 'theoretically reversible', in the sense that physical theory allows us to specify conditions which would reverse the process, and at the same time (b) 'causally irreversible', in the sense that it is 'causally impossible to realize the required conditions.[4]

Hence, the reversal of the process in question is physically possible in the sense that it is not ruled out by physical law. According to the use of terminology that is now widely accepted, anything that is permitted by the laws of physics is physically (or nomologically) possible. However, the initial conditions for the reversal of the process in question cannot be brought about. Therefore, there are processes that are de facto irreversible, independently of whether or not an increase in entropy is involved. Popper (1956) takes this result to be general: although irreversibility is not implied by the fundamental equations, he maintains that it characterizes most solutions. Consequently, according to Popper, irreversible processes have a cosmic significance.

A generalization of Popper's argument is proposed by Hill and Grünbaum (1957). They show that there are some de facto irreversible processes of radiation in any open, infinite system. This result applies to the universe as a whole as well, if we take the universe to be an open, infinite system. They say:

> In open systems there always exists a class of allowed elementary processes the inverses of which are unacceptable on physical grounds by requiring a *deus ex machina* for their production. For example, in an open universe, matter or radiation can travel away indefinitely from the 'finite' region of space, and so be permanently lost. The inverse process would require matter or radiant energy coming from 'infinity', and so would involve a process which is not realizable by physical sources.[5]

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2 See Popper (1958), p. 403.

3 See also Grünbaum (1974), p. 778.

4 Popper (1957a), p. 1297.

5 Hill & Grünbaum (1957), p. 1296.

60 It is debatable whether the universe is an open, infinite system; it may be more plausible to regard it as a closed system. However that may be, Hill and Grünbaum are right in so far as they point out that the example of an irreversible process which Popper discusses illustrates a general phenomenon: what applies to the water waves in Popper's example is true of all kinds of wave-producing phenomena – including electromagnetic waves in particular – and holds on a cosmic scale. In the literature, all these phenomena are discussed as the irreversibility of radiation.

Thus far, Popper has argued that (1) there are processes which are irreversible and whose irreversibility is not due to an increase in entropy and that (2) such processes have a cosmic significance, that is, are relevant on a cosmic scale. These claims made in Popper's contributions to *Nature* between 1956 and 1958 are compatible with the view that (1*) there are processes which are irreversible and whose irreversibility is due to an increase in entropy and that (2*) such processes have a cosmic significance, too. Radiation may simply include further cases of irreversible processes in addition to processes that are irreversible owing to an increase in entropy. In a later paper in *Nature*, however, Popper goes further and attacks the significance of irreversible thermodynamic processes. He claims that

> With very few and short-lived exceptions, the entropy in almost all known regions (of sufficient size) of our universe either remains constant or decreases, although energy is dissipated (by escaping from the system in question).[6]

Popper does not give any reasons or evidence in support of this claim. Consequently, he denies that the second law of thermodynamics has any importance on a cosmic scale.[7] According to Popper, irreversible processes of radiation are the *only* sort of irreversible processes that have a cosmic significance.

We can thus distinguish three theses that Popper puts forward:

1) There are irreversible processes of radiation (wave-producing phenomena), and these processes are relevant on a cosmic scale.
2) The irreversible processes of radiation are independent of the irreversible processes of thermodynamics.
3) The irreversible processes of thermodynamics are not relevant on a cosmic scale.

The first of these theses is widely accepted. It is not in dispute that there are irreversible processes of radiation and that these processes have a cosmic significance. The third thesis is the least plausible one. Popper's argument of 1965 has been countered by Grünbaum among others.[8] A large majority of physicists and philosophers today assume that entropy increases on a cosmic scale. The second thesis is hotly debated until now: Popper's view that the 61 irreversible processes of radiation are independent of the irreversible processes of thermodynamics is a minority view. But it has some prominent supporters. Adolf Grünbaum, for one, agrees with Popper. Although he rejects Popper's third thesis, he maintains on the basis of the argument in Hill and Grünbaum (1957) that the irreversible processes of radiation are more important than the thermodynamic ones.[9] Huw Price, to mention another example, argues in his book on time that the irreversibility of radiation is independent of

[6] Popper (1965), p. 233.

[7] See also Popper (1957b).

[8] See, in particular, Grünbaum (1974), section 5.

[9] Grünbaum (1973), p. 277. For a discussion of Popper's and Grünbaum's claims see Zenzen (1977).

thermodynamics.[10] The majority view, however, is that the irreversibility of radiation can be traced back to thermodynamic irreversibility.[11]

I shall not take a stance on Popper's three theses here. Instead, I should like to examine the significance of Popper's challenge to what was and still is the majority view. According to the majority view, irreversibility is of thermodynamic origin, consisting in an increase in entropy, and thermodynamics is in some sense grounded in statistical mechanics. Irreversibility and thus the increase in entropy are global phenomena: there is an increase in entropy on a cosmic scale. Therefore, the majority view is committed to admitting an initial state of the universe that is a state of comparatively low entropy. The commitment to such an initial state arises whatever the basic laws may in the last resort be: if one bases thermodynamics upon a particular interpretation of quantum mechanics instead of classical mechanics, one can argue that the fundamental laws provide for irreversible processes.[12] Nonetheless, the assumption of a low entropy initial state of the universe is needed in any case in order to account for the global increase in entropy.[13]

The problem for the majority view is to justify that assumption about the initial state of the universe. One can object that, on the majority view, the problem of giving an account of why some processes are irreversible is simply shifted back: as it stands, an initial state of the universe with low entropy is as improbable as anything that is rejected as being extremely improbable. That the scattered pieces of a broken wine glass do not on their own come together to form a wine glass again is explained by the postulate that the initial conditions for such a process are extremely unlikely to obtain. That explanation takes us in the last resort to an initial state of the universe with low entropy. But that such a state is the initial condition of the universe seems to be at least as improbable as the fulfilment of the initial conditions for the scattered pieces of a broken wine glass to come together to form a wine glass again without external intervention. That is to say, states with a low entropy constitute only 62 a very small minority among the physically or nomologically possible initial states of the universe.[14]

However, Popper's alternative account runs into the same problem. If the irreversibility of radition (wave phenomena) holds on a cosmic scale, it is in the last resort to be explained by referring to initial conditions of the universe. There have to be specific initial conditions at the beginning of the universe that lead to sources of outgoing radiation, stones that can be thrown into ponds to produce outgoing waves, etc. But then we have the same problem again: the required conditions at the initial state of the universe that lead to coordinated outgoing waves among other things seem to be as improbable to obtain as the initial conditions that would be required for the outgoing waves in Popper's example to contract. As Price puts it,

> Why are conditions so exceptional in (what we call) the past? In particular, why does the universe contain the kinds of events and processes which provide the *sources* for the outgoing

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10 See Price (1996), chapter 3, in particular p. 72.

11 See, in particular, Zeh (2001), chapter 2, especially p. 36. But see also Frisch (2000), pp. 399-404.

12 See Albert (2000), chapter 7.

13 See the overview in Price (2002).

14 SeePenrose (1989), chapter 7, for a calculation of the probability of such a state. Compare also Price (1996), chapter 2, in particular pp. 27, 36-40.

radiation we observe around us? Why does it contain stars, radio transmitters, otters slipping into ponds, and so on?[15]

The same point applies if we take the universe to be an open, infinite system (as Hill and Grünbaum (1957) do in their extension of Popper's argument): coherent radiation coming in from infinity in contrast to coherent radiation being emitted into infinity can be ruled out only on the basis of certain special initial conditions holding in the universe.[16]

Hence, the point at issue is in the last resort not whether the irreversibility of radiation can be traced back to thermodynamic irreversibility or whether both sorts of irreversibility are independent of each other or whether, as Popper claims, radiation is the only source of irreversibility on a cosmic scale. The point at issue is to justify the assumption about the initial conditions of the universe to which one is committed if one takes any of these views. Thus, in the last resort, neither thermodynamics nor radiation provides an explanation of irreversibility. The appropriate place to look for such an explanation, if there is any, is cosmology and quantum gravity in particular. There are a number of ideas how to justify the assumption of an initial state of the universe that is at the origin of the irreversible processes which we experience.[17] None of these ideas, however, is as yet wholly convincing.

Alternatively, one can argue that the call for a justification of this assumption about the initial state of the universe is inappropriate. One may reject this call on empirical grounds, claiming that our empirical evidence may guide us to a particular assumption about the initial state of the universe, but that the total empirical evidence that we can acquire cannot provide any basis for 63 an explanation of the particular features of the initial state of the universe. Another possibility is to call into question the distinction between laws and initial conditions against the background of which the assumption of a particular initial state of the universe is seen not as a matter of law, but as a matter of initial conditions. On the best-system view of laws,[18] that assumption may well acquire the position of an axiom. One can then argue that if this assumption is an axiom of the best system and thus lawlike, any further explanation is neither required nor possible.[19]

2. The arrow of time

Let us now enquire into the relationship between irreversible processes and the so-called arrow of time. Let us take for granted that there are irreversible processes which are relevant on a cosmic scale, whatever their ground may in the last resort be. Popper's motivation for suggesting that (a) there are irreversible processes which do not have thermodynamic origins and that (b) these are the foremost example of irreversible processes is that he considers a statistical theory of the arrow of time to be unacceptable.[20] He thereby assumes that thermodynamics is reducible to statistical mechanics. He sees the arrow of time as having a cosmic significance[21] and regards it as a fundamental feature of the universe.[22] He takes the

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15 Price (1996), p. 57. See also Arntzenius (1994), section 4; Zeh (2001), p. 16; Callender (2001), section 2.2.

16 See, for instance, Sklar (1993), pp. 305-306.

17 For a philosophical assessment of these ideas, see, for instance, Sklar (1993), chapter 8, and Price (1996), chapter 4.

18 See, for instance, Lewis (1986), pp. XI-XVI, 121-131.

19 Compare Callender (2001), section 2.8, Callender (forthcoming), section 6, and see also Albert (2000), pp. 160-161.

20 See Popper (1958), p. 403; Popper (1965), p. 233.

21 See, in particular, Popper (1965), p. 233.

existence of de facto irreversible processes to be sufficient for speaking of the arrow of time and the flow of time.[23] As he makes clear in his reply to Grünbaum, he means by the arrow or flow of time a temporal view of the universe: the universe is in time in the sense that there is a present state of the universe and that the universe develops from past states via the present state to future states (so that time flows from past states of the universe via the present state to future states):

> I conjecture that it is part of the structure of our spatiotemporal universe that time is not only anisotropic but has in addition a direction; that there is not only the relation of betweenness in its topology, but also the relation of before and after. And that the *words* "before" and "after" are of course as conventional as the numerals by which we may characterize time, but that the relation denoted by these words is part of the structure of reality, so that time has an arrow. … I shall say something in defence of the usefulness of the notions of the past, present, and future for the description of reality. … "The present age of the universe" is a perfectly good term in cosmology … In other words, the past, present, and future are perfectly good terms in cosmology and astronomy …[24]

64 Note, however, that this view as such does not imply that only the present state of the universe exists. Note furthermore that Popper's use of the expression "the arrow of time" says more than what most physicists and philosophers today mean by their rather loose use of this term:[25] whereas Popper means by the expression "the arrow of time" a temporal view of the universe, most physicists and philosophers mean by the expression "the arrow of time" no more than that there are irreversible processes in time.

Popper makes clear in the quotation above that the temporal view of the universe goes beyond the admission of irreversible processes. In addition to irreversibility, there is a direction of time in the sense of a flow of time from past via present to future. Let us therefore examine whether the existence of irreversible processes on a cosmic scale is necessary and / or sufficient for the arrow of time, as conceived by the temporal view of the universe. If there are irreversible processes, there are processes that are asymmetric or anisotropic in time. The asymmetry or anisotropy of processes in time is conceptually not the same thing as the asymmetry or anisotropy of time. Properties of something in time cannot be regarded as properties of time itself without further argument.[26] Moreover, the property in question here – irreversibility – seems to be a matter of fact rather than a matter of a fundamental physical law. Hence, even before it comes to the conclusion from the anisotropy of time to the flow of time, the first step is to go from anisotropic processes in time to the anisotropy of time itself. Nonetheless, one may justify this step on the basis of the view that time is not an entity over and above of what there is in time. If one takes this view of time, one may consider irreversible processes on a cosmic scale to be sufficient for speaking of the anisotropy of time.

Popper does not employ the notion of the anisotropy of time in his papers in *Nature.* Grünbaum makes use of this notion in his discussion of Popper's claims, and Popper then takes up this notion in his reply to Grünbaum quoted above. Grünbaum regards irreversible

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22 See, in particular, Popper (1967).

23 See, for instance, Popper (1956) and Popper (1965), p. 233.

24 Popper (1974), pp. 1141-1143. See also Popper (1998), pp. 166-171.

25 Compare, for instance, the title of Savitt (1995).

26 Compare Horwich (1987), in particular pp. 45-47.

processes of radiation and / or thermodynamics as sufficient for taking time itself to be anisotropic. He maintains, however, that the anisotropy of time is all that can be built on irreversible processes.[27] Following Grünbaum, my thesis in this part of the paper is that drawing attention to irreversible processes – such as the ones of radiation and / or thermodynamics – does not provide an argument for assuming an arrow of time in the sense of a temporal view of the universe.[28]

Imagine a Newtonian world. In this world, there is a universal time in the sense of an unequivocal temporal ordering of all events: For any two events e_1 and e_2, e_1 is either simultaneous with e_2 or earlier than e_2 or later than e_2. Moreover, assume that Newton's philosophy of time holds in this world: there is absolute time. Absolute time has an arrow in the sense that it flows from past via present to future. There is a present state of the universe as well as past and future states. Note, however, that this philosophy of time is 65 not required for Newtonian physics. Let us, furthermore, assume that there are no irreversible processes in this world. This assumption is consistent with Newtonian mechanics as well as with Newton's philosophy of time. Nonetheless, absolute time is anisotropic in this world – its flow cannot be reversed, although, in this imagined Newtonian world, all processes are reversible in time. Hence, irreversible processes are not necessary for the metaphysics of an arrow of time in the sense of a temporal view of the universe. (Nevertheless, such processes may be necessary for our experience of what is called the flow of time.)

When it comes to today's physics of time, we have to consider relativity theory. Special relativity, as introduced by Einstein (1905), is based on two principles: (1) All inertial systems are physically equivalent. That is to say, the physical laws are independent of which inertial systems are employed to define a reference frame in which physical events and processes are described. (2) In any inertial system, light expands in the same way, independently of the state of motion of the source from which the light is emitted. This is the principle of the constancy of the velocity of light. Starting from this principle, Einstein is able to conceive dynamics without employing the notion of an absolute time. Simultaneity has to be defined on the basis of this principle without invoking the notion of an absolute time. The result is that there is no universal simultaneity. For any two events e_1 and e_2 that are simultaneous relative to one reference frame, there is another reference frame relative to which e_1 is earlier than e_2 and yet another reference frame relative to which e_1 is later than e_2. Temporal duration, as well as spatial length, is relative to a reference frame. There is no universally preferred reference frame. Nonetheless, for any two events, a spatio-temporal distance can be defined that is independent of any reference frame: it remains the same whichever reference frame is considered.

Einstein's considerations result in the famous light cone structure of special relativity: For any event e_n at a space-time point, there is a future light cone and a past light cone which contain all and only those events at space-time points that can be reached from e_n with a velocity that is lower than the velocity of light. Thus, for any event e_n at a point in space-time, there is a relative future and a relative past. The events in both the future and the past light cone are all separated from e_n by a timelike distance. The events in the future light cone are later than e_n and the events in the past light cone are earlier than e_n in all reference frames.

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27 See Grünbaum (1973), pp. 209-210, 314-315, and Grünbaum (1974), section 2.

28 See also the criticism that Ghins (1986), pp. 87-92, addresses to Popper.

Furthermore, there are events that could be connected with e_n only by a velocity that is higher than the velocity of light. These events lie outside the light cone of e_n. They are separated from e_n by a spacelike distance. There is no objective temporal order of these latter events. Which of these events are simultaneous with, earlier than or later than e_n depends on the choice of a frame of reference.

If simultaneity is relative to a reference frame and if there is no universally preferred reference frame, then there is no universal present. Any point in space-time can count as here-now. Special relativity therefore speaks against 66 a temporal view of the universe. Since there is no unique temporal order that encompasses all events, there is no flow of time. The resulting view is known as the conception of a *block universe*, that is, an atemporal view of the universe: everything exists at a space-time point or region, and all there is in space-time simply exists.[29]

This conception leaves open what the content of the so-called block universe is: The block universe admits not only events at space-time points and processes, which have temporal parts, but also things that exist as a whole for a certain time and that do not have temporal parts.[30] For instance, only a thing can be in motion, and only a thing can be accelerated. It is sometimes claimed that the block universe does not admit time and change. This is not quite correct: the block universe is not in time in the sense that it does not develop in time; but it includes time. Furthermore, it may contain things whose properties can change. What the block universe lacks is one unequivocal temporal order for all events.

The conception of a block universe is not committed to determinism. The definition of determinism that is now widely accepted is this one: take all those possible worlds in which the same natural laws as in our world obtain, that is, all nomologically possible worlds. Consider any two such worlds and imagine a distinction between space and time for both worlds such that we define a unique temporal order that is the same for both worlds. These worlds are deterministic if and only if the following holds: if these two worlds agree at any time, then they agree for all times.[31] Determinism thus is a metaphysical thesis that is independent of whether and to what extent predictions are possible. Possible worlds that are a block universe need not satisfy this definition.[32]

For any point in space-time, there are a past and a future light cone. There are no causal relations between events that lie outside each other's light cones. Let us assume, for the sake of argument, that causation is asymmetric in the sense that only events in its past light cone can be causally relevant to an event. The conception of a block universe leaves open whether and to what extent the event at a given space-time point is determined by events in its past light cone. In the same way, this conception leaves open whether and to what extent events in the future light cone are determined by the event at the space-time point under consideration. The claim that the events in the future light cone are as determinate as the events in the past light cone does not imply that these events are also determined.[33] Given some unique temporal order relative to a reference frame that is the same for two worlds which are a block

29 See, for instance, Price (1996), pp. 12-15.

30 See, for instance, Mellor (1981), pp. 128-132.

31 See Earman (1986), p. 13.

32 See Dorato (1995). Popper (1982), § 26, by contrast, takes the view of a block universe to imply metaphysical determinism.

33 But compare Popper (1998), pp. 174-175.

universe, these worlds may agree up to a certain point of time and then 67 diverge. Hence, the issue of determinism vs. indeterminism is independent of the issue of an atemporal vs. a temporal view of the universe. As the above mentioned example shows, there can be a flow of time in a deterministic Newtonian world. As the considerations in this and the preceding paragraph show, a block universe may admit indeterminism.

General relativity combines special relativity as a theory of space-time with a theory of matter insofar as matter is a source of gravitation. Matter-energy influences the geometrical structure of space-time: as a result of the presence of matter-energy, space-time is curved. Gravitation (the gravitational field) and the curvature of space-time are the same thing. General relativity is relevant to cosmology in particular. The mainstream interpretation of the data in cosmology is that all galaxies move away from each other, whichever point in space-time one considers and if one uses a local reference frame that is in free fall in the gravitational field. This is the basis for the majority view in cosmology according to which the universe is expanding and its expansion can be traced back to a singularity, the so-called big bang. It is an open question whether expansion continues indefinitely or whether there may be a state of maximal expansion which is followed by contraction. The cosmological theory of an expanding universe adds geometrical structure to the concept of a block universe in that space-time is regarded as being curved. However, this theory does not presuppose that there is a universally preferred reference frame. Although there are considerable changes in general relativity as regards the treatment of time, what special relativity says about the relativity of simultaneity and the relativity of temporal durations and spatial lengths remains valid in general relativity. Consequently, general relativity is no basis for claiming that there is an arrow of time in the sense of a flow of time. Furthermore, if the expansion of the universe is seen as one big process, that process may even be reversible, as long as contraction of the universe cannot be excluded. If the expansion of the universe turns out to be reversible, however, this does not imply that entropy will decrease; an increase in entropy is possible even in a contracting universe.

The irreversible processes of entropy increase and radiation can be incorporated into the concept of a block universe that special relativity can be taken to suggest as well as into all the cosmological models to which general relativity gives rise. Consider an event e_2 at a space-time point. Imagine that there is a process from an event e_1 in the past light cone of e_2 to e_2. If this process is irreversible, then, without any external intervention, there is no process from e_2 to an event e_3 in its future light cone that is of the same type as e_1. Such restrictions may be ubiquitous in a block universe. They may even be lawlike. Irreversible processes do not imply one unique temporal order for all events any more than the expansion of the universe that is at the core of today's mainstream cosmological theory implies this. Hence, there can be irreversible processes such as the ones described by thermodynamics as well as the theory of radiation on a cosmic scale – and there may even be an irreversible process of the expansion of the universe – without there being a physical basis for 68 an arrow of time in the sense of a flow of time as an objective feature of the universe.

Consequently, in contrast to what Popper claims, irreversibility and the arrow of time in the sense of a temporal view of the universe are logically independent of each other: there can be an arrow of time in this sense (flow of time) without irreversible processes occurring in time as in the imagined Newtonian world. And there can be irreversibility without an arrow of time in this sense as in the described block universe. To make a case for a physical basis of an arrow of time as an objective feature of the universe, other arguments are needed than Popper's argument drawing on irreversible processes. It may be possible to integrate into general relativity a cosmological model that contains a universally preferred reference frame, and considerations in connection with the notorious quantum measurement problem and quantum non-locality may speak in favour of such a model. A cosmological model that contains one unequivocal temporal ordering of all events due to a universally preferred reference frame would certainly be a physical basis for a philosophy of time that assumes an arrow of time in the sense of a flow of time without, however, implying such a philosophy of time. But arguments for such a model are another topic.

To conclude this paper, we can sum up the main results in the following two theses:

1) Whatever may be the source of the irreversible processes with which we are familiar – whether thermodynamics or radiation or both –, if these processes are relevant on a cosmic scale, the problem is to give an account of why there are the specific and very improbable initial conditions of the universe that give rise to these processes (or to make plausible why the call for such an account is misplaced).
2) Irreversible processes are not a physical basis for the philosophical position that there is an arrow of time in the sense of a flow of time. Such processes are neither necessary nor sufficient for an arrow of time in this sense.

Popper's merit is to have drawn attention to processes whose irreversibility may not be due to an increase in entropy. However, he did not consider the problem of the initial conditions of the universe that are necessary for these processes to obtain, and he is wrong in conceiving a link between such processes and a flow of time as an objective feature of the universe.

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