Time After Time — Big Bang Cosmology and the Arrows of Time

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Abstract Time, as familiar as it seems to us in everyday life, is one of the greatest puzzles of science and philosophy. In physics and cosmology it is especially mysterious why time appears to be "directed", that is, why there seems to be an essential difference between the past and the future. The most basic known laws of nature do not contain this asymmetry. And yet, several arrows of time can be distinguished – at least ten, in fact. However, it is unclear whether any of them are fundamental or whether others can be reduced to these, and it is not known how the direction of time could be explained convincingly. From the growing but still astonishingly low entropy of the observable universe, it seems plausible that the solution of the mystery is connected with cosmology and an explanation of the big bang. This could require a new fundamental law of nature (which might be related to a particular geometry) or specific boundary conditions (which might be comprehensible within the framework of a multiverse theory). Or it may be that time's direction is fundamental and irreducible, or an illusion and not explicable, but can only be "explained away". It is even more confusing that not all of these alternatives are mutually exclusive. Furthermore, there is a plethora of approaches to explain the big bang. Some models postulate an absolute beginning of time, others an everlasting universe or multiverse in which the big bang is a phase transition, and maybe there are myriads of big bangs. So the low entropy of the observable universe might be a random fluctuation – whereas elsewhere even opposite thermodynamic directions of time may arise. Perhaps the (or our) big bang just created the arrows of time, if it originated as some sort of pseudo-beginning in a quantum vacuum that has no direction of time. Thus it seems useful to conceptually distinguish an undirected microtime and a directed macrotime. It is even possible that time ends – although paradoxically, it may do so only temporarily.

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Man is ... related inextricably to all reality, known and unknowable ... plankton, a shimmering phosphorescence on the sea and the spinning planets and an expanding universe, all bound together by the elastic string of time. It is advisable to look from the tide pool to the stars and then back to the tide pool again.

John Steinbeck: The Log from the Sea of Cortez (1951)

Talkin' bout that youthful fountain
Talkin' bout you and me
Talkin' bout eternity
Talkin' bout the big time

Neil Young: Broken Arrow (1996)

1 The Direction of Time

"Time flowing in the middle of the night, / And all things creeping to a day of doom," wrote the British poet Alfred Lord Tennyson. Yet this unceasing stream of time, existing apparently without dependence on its recognition, is perhaps only an illusion – but also a problem. Because the known laws of physics are time-symmetric. So they neither entail nor prefer a direction from past to present.

However, our everyday experience teaches us the opposite. For only processes with a clear direction are observed in the complex systems of nature and culture: blossoms become apples that later decompose; milk drops into black coffee, making it brown; a glass falls from the table and bursts into a thousand pieces. Even cyclic processes of nature such as the seasons or the phases of the moon are parts of irreversible dynamics. Whoever watches mold turning into a red apple, milk drops hopping from a coffee cup, or shards being resurrected into a glass probably would feel like he is in the wrong movie – or simply watching one that is running backwards.

Irreversibility is why – or how – the formation and development of complex structures is much less likely than their decay or something turning into dust and ashes. By use of the concept of entropy this can be quantified physically: it is a measure of a system's degree of disorder. And disorder is much more probable than order. There are, for example, significantly fewer possibilities of molecular combination for a small drop of milk in coffee than for a good mixing. This is why entropy only increases on average, as the second law of thermodynamics states, while the first law expresses the conservation of energy (see [28, 29, 32, 91] for a historical introduction to thermodynamics).

The development of local order does not contradict the second law of thermodynamics. Contrariwise, it creates more disorder within the entire system. In general, entropy does not decrease globally, but can do so locally. Therefore, the formation of complex structures, in other words order, is not impossible, but it occurs only at the expense of a greater amount of disorder in the environment (see, e.g., [65, 66]). Cleaning your desk, for instance, means eating more lettuce, the leaves of which gain their energy from nuclear fusion in the sun – local order increases, yet so does the amount of chaos in the solar system.

So the second law marks a direction of time – or developments in time, which does not necessarily mean the same thing. Yet the second law is not the solution of the problem, but its core. Because all of the known apparently fundamental laws of nature are time-symmetric: they don't include entropy increase; they don't contain a preferred direction of time; they don't differentiate between future and past in principle. This time-reversal invariance means that every macroscopic process could also run in reverse. So why doesn't it in our universe?

This question could be rejected as meaningless if one argues like this: disorder increases with time because we measure time in the direction in which disorder increases. However, this does not solve the problem, because it would still remain unclear why the thermodynamic direction of time exists in the first place. The developments could, after all, also alternate between forward and backward – or not take place at all (see [116]).

It is important to bear in mind that time-reversal invariance and reversibility are not the same but independent from each other and not necessarily correlated (following [3]). Time-reversal invariance is a property of dynamical equations and of the set of their solutions. Reversibility is a property of a single solution of such an equation. Dynamical equations are time-reversal invariant if they are invariant under the application of the time-reversal operator T, which performs the transformation $t \to -t$ and reverses all dynamical variables whose definitions as functions of t are not invariant under this transformation. If $f(t)$ is a solution of such an equation, then $Tf(t)$ is also a solution. These "time-symmetric twins" are temporal mirror images of each other and only conventionally different if no privileged direction of time is presupposed. A solution $f(t)$ is reversible if it does not reach an equilibrium state where the system remains forever. (In classical mechanics, for instance, a solution of a dynamical equation is reversible if it corresponds to a closed curve in phase space.) Time-symmetric laws are, in conclusion, perfectly compatible with asymmetric solutions (see [182]).

2 Ten Arrows of Time

Why do we remember the past, but not the future? For this asymmetry of our experience of time – an irreversibility of many processes and thus the direction of time – Arthur Stanley Eddington [41] coined the metaphorical expression "arrow of time".

It is an open and controversial issue whether there is a single arrow, including and perhaps "guiding" all physical processes, or whether some processes evolve in some sense independently of each other, instantiating their own arrows of time (detailed reviews and elaborations are given, e.g., by [35, 67, 131, 181]).

Conceptually, at least ten different arrows – categories of phenomena that have a direction in time – can be distinguished (see [148]):

- The psychological arrow of time: we remember the past, which seems immutable, but not the future, which isn't fixed for us yet. We experience a "stream" of time that doesn't turn back but moves us from birth to death. The psychological arrow is related to a computational arrow, if cognitive processes are computational – at least partly (omitting issues of phenomenal content aka qualia here).

- The causal arrow of time: effects never precede their causes, and these have coherent structures (at least in classical systems).
- The evolutionary arrow of time: complex natural but also cultural systems are based upon directed developments and often also upon differentiation. Exponential growth can only be observed in self-organizing systems.
- The radioactive arrow of time: exponential growth is confronted with exponential decay of radioactive elements which marks a direction in time as well.
- The radiative arrow of time: electromagnetic radiation diffuses concentrically from a point but never coincides at one point after moving in concentrically from all sides. (This is also true for sound waves, or for waves that result from a stone being thrown into water, or for the assumed gravitational waves emitted by rotating, collapsing, or colliding massive bodies.)
- The thermodynamic arrow of time: the entropy of a closed system maximises, so the system seems to strive for its thermodynamic equilibrium. For example, coffee cools down to ambient temperature and milk drops that have been poured into it don't stay together but disperse evenly.
- The particle physics arrow of time: the decays of certain particles, the neutral K mesons (kaons) and B mesons, and there antiparticles lead implicitly to the conclusion that there is an asymmetry of time because these decays break other symmetries. (More precisely, some processes governed by the weak interaction violate time reversal T, but can also be subsumed under time-reversal invariance nevertheless, because T-violation is compensated by an application of a unitary CP-transformation, and according to the CPT-theorem the combination of charge conjugation C, parity transformation P, and time reversal T is conserved.)
- The quantum arrow of time: measurements – or interactions with the environment (quantum decoherence) in general – interfere with a quantum system which realizes all possible states in superposition, and lead to only one classical state being observed. This so-called collapse of the wave function (if it really happens) describes, for example, why Erwin Schrödinger's infamous cat is not (observed as) dead and alive at the same time. Instead of collapsing, reality could also "split" into different parallel universes that would henceforth be independent of each other, so that all alternatives were simultaneously realized – in one world the cat is dead and in another one it is alive.
- The gravitational arrow of time: gravity forms structures, for example galaxies and stars, from tiny density fluctuations within the almost homogeneously distributed primordial plasma of the early universe (Fig. 1). Gravitational collapse can even create black holes. They are "one-way streets" of matter, places of highest entropy, and perhaps even irreversible annihilators of physical information. This arrow is also called (or subsumed under) the fluctuation arrow [70].
- The cosmological arrow of time: space has been expanding since the big bang.

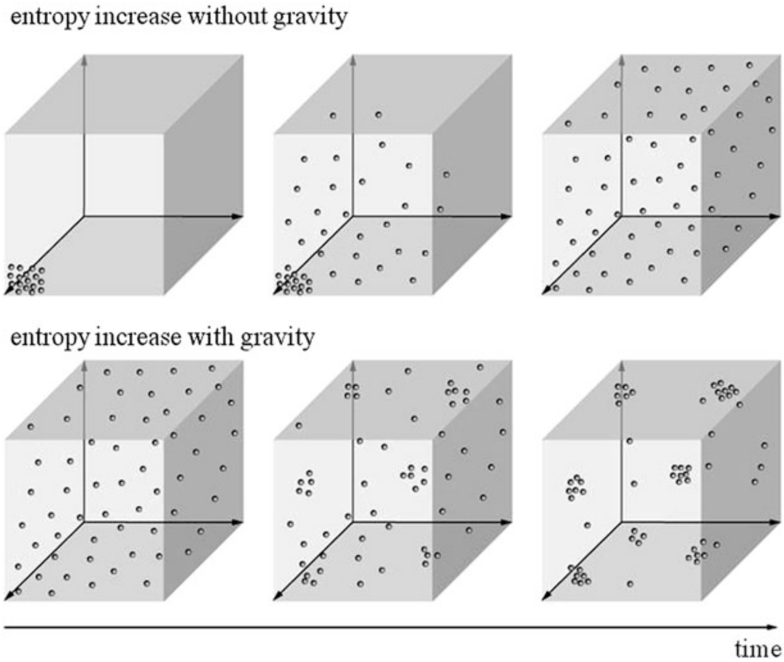

Fig. 1 Growing disorder. Entropy – the physical measure of a system's disorder – can only increase statistically in the course of time. For this reason it even defines in a way the direction ("arrow") of time. If a gas bottle is opened up in empty space, the gas molecules soon spread evenly throughout the entire volume – then, thermodynamic equilibrium is reached as a state of maximum entropy (top). Yet in a large space such as the early universe, gravity creates local concentrations of the originally almost homogeneously distributed gas (bottom) – and this was how stars and galaxies formed. An increase of entropy follows from this gravitational effect, which was not taken into consideration for a long time. There is still a debate about whether there can be a thermodynamic equilibrium, a "heat death", in an expanding space, and how the total entropy in the universe can be usefully defined at all.

These ten temporally directed processes seem more or less unrelated to each other at first glance. Yet given that at least today all arrows point in the same direction, it seems natural to search for a primordial, super, or master arrow of time that all the others could be ascribed to. The particle physics arrow of time, the cosmological arrow of time, and the thermodynamic arrow of time are likely candidates.

The thermodynamic arrow might be responsible for the psychological and the evolutionary arrow of time (cf. [68]; but see [94] for an argument against the correlation of thermodynamic and psychological or computational arrows, respectively). Entropy can also be defined for black holes and hence for gravitational processes (see [85, 113]). Causality is a difficult issue (see, e.g., [128, 129]) taken by some to be subjective or as a logical relation, ultimately, and thus reducible to other arrows (see [117]), but as the "cement of the universe" by others (see, e.g., [92]); thus perhaps causality is not only a pragmatic consideration but grounded in processes governed by conservation laws such as conservation of mass-energy, linear and angular momentum during transmissions of energy and momentum.

Still mysterious is the origin and implication of the particle physics arrow [15]. Joan A. Vaccaro [172] argued that processes which violate T-symmetry induce destructive interference between different paths that the universe can take through time. The interference eliminates most of the possible paths except for two that represent continuously forwards and continuously backwards progress in time. Data from accelerator experiments allow the distinction between the two time directions and indicate which path the universe is effectively following. Thus T-violation might have large-scale physical effects that underlie the unidirectionality of time.

There have also been controversial discussions about whether the arrow(s) of time in an evolving closed universe will reverse in the collapsing phase [35, 54, 55, 67, 71, 72, 82, 107, 112, 113, 181]. Perhaps the different arrows of time reduce to the cosmological arrow, so in some sense the direction of time would switch at the maximum size of the finite universe, when the expansion turns into contraction. Sometimes it has been argued that even the psychological and thermodynamic arrow of time would run backwards (from the perspective of the expanding stage), and observers would still believe they were living in an expanding phase. In a quantum cosmological framework, however, everything with classical properties is destroyed in the maximum stage, due to quantum interference, and the big bang and big crunch are ultimately the same, amusingly called the big brunch [82, 181].

3 Four Kinds of Answers

Where does the asymmetry of time – or at least the processes in time – originate if most laws of nature are time-reversal invariant and thus do not prefer a direction in time? Basically, four kinds of answers can be distinguished [148]:

- Irreducibility. The direction of time is not a derivable phenomenon but an essential attribute of time: then time simply passes and is independent, for example, of entropy. Many philosophers share this opinion. Tim Maudlin [98], for instance, defends it and accuses skeptics of only being able to argue for time symmetry because they already presuppose it. However, this objection might be reversed and Maudlin could be accused of not admitting the problem in the first place.
- Laws. Perhaps there is a fundamental, but still unknown law of nature that is time asymmetric. Accordingly, Roger Penrose [112] hopes that such an arrow of time follows from a theory of quantum gravity that unites quantum theory and the general theory of relativity. This might also explain the mysterious collapse of the wave function that many physicists assume. Therefore quantum theory would have to be modified in such a way that it contains a time asymmetry. Then the past could be calculated from a future perspective but not the other way round. This possibility would help historians to gain an advantage over physicists. Other

researchers, Ilya Prigogine [118] for instance, localize arrows of time in the peculiarities of complex systems far from thermodynamic equilibrium, which are postulated to have special laws.

- Boundary conditions. Most physicists assume that the irreversibility of nature is not based upon time-asymmetric laws but is a result of specific, perhaps very improbable initial or boundary conditions (cf. [4, 131, 181]). The problem would thus be shifted to the origin of the universe and accordingly to models of quantum cosmology, though there is no consensus about the nature and form of these boundary conditions. A subset of such explanations are proposals of cyclicity. Here the universe oscillates through a series of expansions and contractions (e.g. [6, 27, 50, 140]) and/or evolves through a perhaps infinite series of big bangs (e.g. [113], see below). Real cyclic models, which do not shift the problem of time's arrow into the infinite past, have to show how the entropy created in each cycle is destroyed or diluted before or within the subsequent big bang, in order to reset the stage for the next oscillation. Therefore a decrease of entropy or entropy density must be explained.
- Illusion. If time is not objective – a property of the world or at least of some of its objects or their relations – but subjective, physicists are searching for an explanation in the wrong place. Immanuel Kant assumed time to be a pure form of intuition or perception, inherent in the human mind, a kind of transcendental requirement or pre-structure for the possibility of experience itself, hence nothing that belongs to the things in themselves. He claims that "time and space are only sensible forms of our intuition, but not determinations given for themselves or conditions of objects as things in themselves. To this idealism is opposed transcendental realism, which regards space and time as something given in themselves independent of our sensibility" ([80], A 369). Other philosophers suspect time of being a construct of consciousness or of the grammar of our language. There are also powerful, but controversial arguments from physics, especially relativity and quantum gravity, emphazising that there is no time independent from space, only a spacetime unity, or that a time parameter does not even appear in the fundamental equations of quantum gravity (such as loop quantum gravity) or quantum cosmology (especially the Wheeler–DeWitt equation) (see, e.g., [12, 84, 125, 181, 182]). So perhaps the arrows of time do not even exist in the world as such. If the entire history of the universe is there as a whole or unity, time would be a mere illusion in a certain sense.

Some of these accounts are mutually exclusive, others are not. For example time could be an illusion (or emergent), but an asymmetrical block universe (if, say, the big bang has much lower entropy than the big crunch) would still deserve an explanation, which might consist in a specific boundary condition or law. Or if time is fundamental (as, e.g., [31, 102] argue), this might be represented by a law too. Or perhaps specific boundary conditions are really an instantiation of a special law, as suggested by Stephen Hawking [74].

4 Fundamental Issues

It is a deep conceptual, physical, and even metaphysical question whether time is fundamental or not. What does this mean, and how can we know about it?

It is not clear from a conceptual point of view whether the direction of time is a necessary feature of time. If so, and if time is fundamental, then the arrow of time is fundamental too. In this case the chances of finding a deeper understanding, or at least a testable explanation in physics or cosmology, are slim. Time as a fundamental entity, as well as its arrow(s), could of course be represented as a fundamental parameter in a future fundamental theory, but this would be no derivation or explanation, just an assumption. Ultimately, time – and the arrow of time – would remain a mystery. This might very well be the case. However, methodologically, it can and should not be a premise or limit of research. On the contrary, scientists and philosophers alike should try to reduce and/or explain time – and proceed as far as they can get. Even wrong explanations are better than no explanation at all, because they can be revised and improved. And their errors may teach useful lessons nevertheless. If an explanation doesn't work, it could still tell us something new, if it is possible to understand why it doesn't work.

Note also that time could be fundamental whether or not it has a beginning. If time originated with the big bang, there was no "before". On the other hand time might be eternal, thus preceding the big bang, which is compatible with a multiverse scenario producing countless big bangs and, hence, universes. But the view that time is emergent is also consistent with either an absolute beginning or temporal eternity within or without a multiverse.

If time is fundamental, this doesn't imply logically that the arrow of time is also fundamental. Perhaps time's direction requires additional assumptions, such as causality or specific initial conditions, which might not be fundamental and could be explained (or they are purely accidental and therefore not further explainable).

For example, the fundamental theory might include a basic time parameter but still not tell us why the entropy of the universe is as low as it is, nor why time's direction could not change. The fundamental theory might be time-symmetric nevertheless – just as classical mechanics, the theory of electromagnetism, general relativity, quantum mechanics, and quantum field theory are. Alternatively, there could be a fundamental, even eternal time within a multiverse scenario where different universes or parts of the multiverse have different directions of time. Or microtime may be fundamental while macrotime (including an arrow, see [154,162], and below) is not; thus there may be places without local or even global arrows of time – as there could exist islands of reverse arrows (cf. [131–134], but against this [181]). Perhaps the far future empty universe will approximate to such a timeless place (cf. [170]), or there may already be localized regions somewhere within the universe, or there was such a state before the big bang, e.g., a quantum vacuum. Of course such conceptual possibilities are not solutions of the problem, just surveys, and conclusions must be supported by scientific arguments.

If there is no (or no non-reducible) time parameter in the fundamental theory, which is not known yet, one might argue that time is not fundamental – following the view that metaphysics should be determined or framed by our best scientific theory. This reasoning is controversial. But if one accepts the nature of time as a (at least partly) metaphysical issue at all, then attempts to understand it should be in accord with the best scientific theories. And if the fundamental theory contains no time, as some approaches in quantum gravity already suggest, time might be "emergent" or illusionary indeed. If so, ordinary time – or its many aspects – can (or must) be explained in a certain sense. And then there are good chances that the arrow of time can be explained too – at least approximately.

This explanation need not necessarily be a physical or cosmological one, by the way. Perhaps "time" has something to do with how we are practicing science, that is predict and retrodict events and facts. But this is based upon our everyday thinking, how we deal with our experiences and how we order sensations and intentions; it could have been simply advantageous in the evolution of our cognition and behavior (perhaps even a kind of useful illusion such as believing in free will or deities, see [149, 160]). Thus it might turn out that it is sufficient to take time as an ordinary-life concept, a way to describe and handle sensations and actions, to characterize it phenomenologically, and, perhaps, to search for a neuropsychological (or even neurophysiological) explanation. If so, the riddles of time would not be a genuine part of physics, only inherited by physics or transformed into it, but ultimately solved by cognitive neuroscience (see, e.g., [119, 120, 147]). In this respect, time might even be fundamental to us, together with space, that is "pure forms of sensible intuition, serving as principles of a priori knowledge", as Kant ([80], B 36) put it, and hence experimentally opaque, but for practical reasons transferred as a parameter into scientific theories. Thus time could be both fundamental (for observers) and an illusion (not existing mind-independently) – and even emergent (e.g., arising in complex neural networks of cognitive systems). To avoid conceptual confusion it is therefore important to clarify notions such as "fundamental", "emergent", "reducible", "illusionary", etc. in respect of the scope of application.

Though the concepts of time and its direction are indisputably important for our cognitive setting, it would require strong arguments assuming it is sufficient to reduce questions regarding the arrows of time in physics and cosmology simply to cognitive neuroscience or even philosophical phenomenology. It is trivial that science requires scientists, but it would be a non sequitur to claim because of this that there are no features independently from scientists or conscious states and events in general. It would be very surprising if scientific explanations end in or lead to scientific minds, rather than starting from them.

5 Gravity, Entropy, and Improbability

The second law of thermodynamics results – at least phenomenologically – from there always being more disordered states than ordered states. This can be illustrated by a box with many pieces of a puzzle. There is one and only one arrangement in which the pieces create a picture. Yet there is a high number of combinations in which the pieces are disordered and do not form a picture. This is similar to the molecules of stirred milk in a cup of coffee: theoretically they could agglutinate into a drop; in practice they never do because this is so improbable. The reason for such extremely low likelihoods is not represented by laws of nature, however, but by the boundary conditions, respectively the initial conditions. And it is these that pose a conundrum.

So one can argue like this (see [177]): Why does the thermodynamic arrow of time exist? Because the present entropy is so low! And why is it so low? Because it was even lower at earlier times!

This explanation is, however, as elegant as it is insufficient. Because it only shifts the problem, relocating it to the remote beginning of our universe. Yet the big bang 13.7 billion years ago lies in a dark past – and this is not just meant metaphorically. There was no light until 380,000 years after the big bang, when the universe had cooled down enough to release the cosmic microwave background radiation that we can measure today. Given that this radiation is extremely homogeneous – aside from tiny fluctuations in temperature on the order of a hundred thousandth of a degree – matter must have been extraordinarily uniformly distributed at this early epoch and in thermal equilibrium with the radiation. (Dark matter, if it exists, does not interact electromagnetically, and would have been 10 to 100 times more concentrated.)

The spectrum of the cosmic background radiation today almost perfectly resembles the electromagnetic radiation of an idealized black-body in thermal equilibrium with a temperature of 2.725 K (with an emission peak at 160.2 GHz). This might appear paradoxical at first, given that such an equilibrium is often assumed to be the maximum of entropy – like the heat death of the universe that physicists in the 19th century imagined to be the bleak end of the world, consisting ultimately only of heat and perhaps homogeneously distributed particles, if there are any that cannot decay.

Yet appearances are deceptive: the homogeneous fireball of the early universe did not have a high, but a very low entropy! Because in the balance gravity must not be ignored – something that was not recognized for a long time. And gravity is working in the opposite direction: clumping, not homogenizing. So at large scales homogeneity doesn't show a high entropy, but contrariwise a very low one, because gravity's part of the entire entropy here is very low. The strongest "concentrations" of gravity, black holes, are also the biggest accumulations of entropy. Physically speaking, gravitational collapse leads to the greatest possible amount of disorder. The entropy of a single black hole with the mass of a million suns (such as the one at the galactic centre, for example) is a 100 times higher than the entropy of all ordinary particles in the entire observable universe. Yet the homogeneous cosmic background radiation and further astronomical observations very clearly show that black holes did not dominate the very early universe, and this has remained so until today.

This extreme uniformity of matter distribution and the "flatness" of our universe's spacetime geometry themselves appear almost as a miracle. Penrose [111, 112] was the first to recognize and even quantify this. Compared to all possible configurations of matter and energy in our universe, the actual state is extremely improbable.

Penrose estimated it to be a mere $1{:}10^{10^{123}}$, more recent data imply circa $1{:}10^{10^{122}}$ [85]. This double exponent is unimaginably huge. It has so many zeros that it would, if printed in the format of this book, amount to a stack that were considerably higher than the diameter of our observable universe. Thus a universe filled with black holes is much more likely than ours. Yet we don't observe such a black hole entropy dominated universe – and we couldn't even live in one. Viewed in this light, $1{:}10^{10^{122}}$ becomes a requirement for our existence.

One might argue therefore on the basis of the weak anthropic principle [13, 153] that we should not wonder about the low entropy, because if it were much higher, we could not exist and there would be no one to wonder about it. So low overall entropy is certainly a precondition for complex life. However, a much higher overall entropy would suffice, making such an argument very unconvincing. Therefore the anthropic principle is insufficient for a comprehension of time's direction, because the observable universe is much more ordered than would have been necessary for human existence. To be more accurate: the probability of our entire solar system including earth and all its life-forms popping out of coincidentally fittingly arranged particles might only be $1{:}10^{10^{85}}$ – but this is overwhelmingly more probable than the $1{:}10^{10^{122}}$ for the entire observable universe. So the anthropic principle is not helpful here: neither as a mere tautology stating a necessary condition for life nor as a selection criterion for a universe that makes life possible within a multiversal realm of possibilities, because even if there were $1{:}10^{10^{122}}$ universes differing in their initial conditions, this would not render the actual value of entropy in our universe plausible.

6 Beyond the Big Bang

We exist in a world full of order that is friendly to life in the thermodynamical sense because the big bang was supremely "orderly". And, as most scientists are convinced by now, this is exactly the reason why the universe runs like a clock – indicating a clear direction of time. But what was it that wound up the cosmic clockwork? How did this supremely special big bang come about? What caused the low entropy of the early universe?

Some 13.7 billion years ago the observable universe evolved from an extremely hot and dense region smaller than an atom which expanded enormously. While the aftermath of this big bang is both theoretically and empirically well established, and to a large extent understood, it is still a mystery as to how and why the big bang occurred at all. Was it the beginning of space and time, or only of matter? If it was a transition, what came before? If not, how could "everything" appear out of "nothing"? And was it a singular event or one of perhaps infinitely many. Do other universes also exist, and did they or will they interact with our own? These are difficult questions and controversial issues – but no longer beyond the scope of science. In modern quantum cosmology a lot of competing scenarios are being pursued [167]. They open up the exciting prospect of going "beyond" the big bang and even of finding a physical explanation for it.

"Ad fontes" ("to the sources") – this humanist slogan from the early modern period could be fitting for today's physicists too: in order to understand the direction of time, they also have to discover the origin of time. Yet the early days of the universe appear as incomplete, misleading, and dark, as historical sources often are. Considering the far longer periods of time, it is surprising that anything at all should still be preserved – and that cosmologists can partly decipher it. Indeed, the observable universe might have "forgotten" much of the information it held in its primordial times. This could be a result of cosmic inflation (insofar as it actually happened). The result of this huge expansion of space is that hardly anything remains in the observable universe from the time of inflation – if inflation had a beginning at all (and has not been going on since all eternity), something that most cosmologists presume indeed. But even in this case, our universe might have separated from the inflationary epoch at a randomly late point. Less than a hundred volume doublings would have been sufficient to cover all tracks from the time before inflation. Cosmic inflation has even been assumed to be the source of the low entropy of our universe [4]. Yet it seems that inflation alone could not have accomplished all of this (e.g., [100]). On the other hand, it might at least be the key to the door of such a deeper explanation that would have to make the initial conditions of inflation understandable – something that can be criticised as yet another shift of the problem however.

In the end, the breakthrough to a deeper understanding will be up to the theoreticians – in the form of a theory of quantum gravity that would have to be confirmed howsoever. The challenges are enormous, and the consequences are as yet unclear. Even our old companion time will probably not be left unblemished. It seems to dissolve entirely in the noise of the smallest scales of nature where there are no longer any clear, regular oscillations, and hence also no "clocks" (see [84]). The disturbing consequences of the theory of relativity – which reduced time to a "fourth dimension" and merged it with space into a unity [115] – cannot be reversed in a quantum theory of gravity, but are here to stay. General relativity implies that there is no background spacetime – no stage where things move autonomically, without affecting spacetime. Hence, there is no "time" that everything could flow along. This seems to be even more true for a theory of quantum gravity. Here the notion of a spacetime continuum breaks down at the Planck scale, turning lengths and time intervals into quasi-discrete entities. Perhaps the world must be described without a concept of time on its fundamental level [83, 123].

Nevertheless the big bang still appears special, and the arrows of time, whether fundamental or not, deserve an explanation. This might even reach beyond the big bang. Actually the big bang was not necessarily the absolute beginning of everything. Whether it was or whether it happened, on the contrary, as a phase transition – for example a "bounce" of an earlier, contracting universe or an accidental fluctuation within a quantum vacuum – is an open and very controversial issue (see below). But in principle the fluctuation or bounce scenario is a promising candidate for a dynamic origin and, thus, explanation, of the arrow of time.

Furthermore, if the big bang was not the beginning of everything but a phase transition, one need not ask how something came out of nothing (which is of course a different question than why there is something rather than nothing): the big bang then was not something that sprang into existence ex nihilo, and nor did spacetime or energy or the laws of nature. It is also meaningless to ask why the entropy was so small at the beginning, if there was no ultimate beginning at all. Nevertheless this question reappears in a modified form: Why was the entropy so small at the bounce or at the beginning of the fluctuation? If it had been large, the big bang would not have produced the smooth, low-entropy universe which is still observed today, but a chaotic mess.

7 Big Fluctuation

If the big bang was a fluctuation, the special low entropy of the universe could have originated as a pure accident (and therefore could be explained away).

But even if our observable universe were only a coincidentally developed island of order in a much greater ocean of chaos – a statistical fluctuation, as Ludwig Boltzmann deliberated as early as 1895 – then it would still be incomprehensible why this fluctuation is so persistent (Fig. 2). After all, about 13.7 billion years have passed since the big bang. But it appears to be much more probable for the spontaneous fluctuation to have arisen only last Thursday or a few seconds before this very moment right now – with all the pseudo-traces of an alleged past: the memories of earlier tax declarations and children's birthdays, the fossils of dinosaurs, the meteorites from the beginning of the solar system and the cosmic background radiation from the aftermath of the big bang itself. In a nutshell: such a bogus-universe – or only a single brain in which such a pseudo-world manifests itself – should arise overwhelmingly more frequently simply by chance than a highly structured, ordered space of at least 100 billion light years in diameter. This often disregarded objection was already made (roughly) by Carl Friedrich von Weizsäcker [176] in 1939 and reappeared in modern dark energy cosmology as the problem of the Boltzmann brains [39, 90, 161]. To give some thermodynamical numbers of entropy fluctuations in a de Sitter background, the probability of our observable universe, $1{:}10^{10^{122}}$, is extremely tiny in contrast to a spontaneous ex nihilo origination of a freak observer, perhaps $1{:}10^{10^{21}}$ for the smallest possible conscious computer, and between $1{:}10^{10^{51}}$ and $1{:}10^{10^{70}}$ for a "Boltzmann brain" [36]. (Thus, there is a controversial discussion going on about wrong assumptions underlying those kinds of estimates – not because many scientists believe that such a solipsistic illusion is true, but because these probabilities indicate possible errors in cosmological reasoning and deep difficulties of multiverse models, especially the measure problem in inflationary cosmology.)

Of course, a virtue can be made out of necessity. Sean Carroll and Jennifer Chen [30] did just that. They argue that our universe really is a mere fluctuation

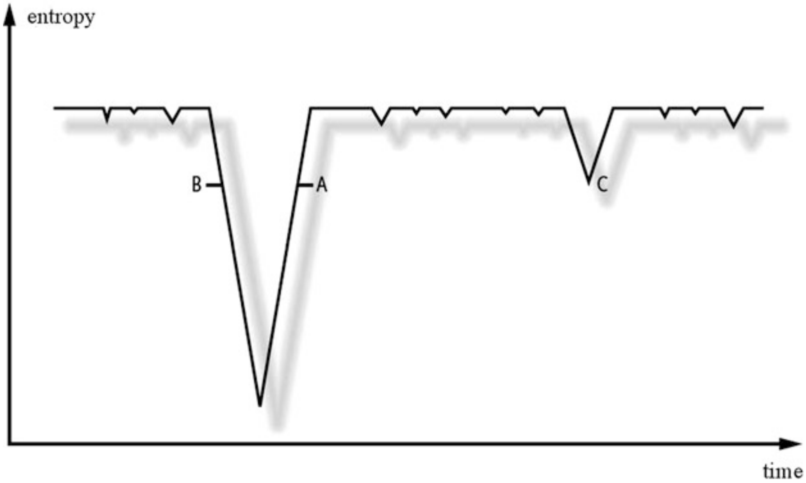

Fig. 2 Order from chaos: When a system is in a state of maximum disorder – i.e., entropy – then temporary "islands of order" and thus local directions of time (point C) develop by means of chance processes over long periods of time. That's why there have been recurring speculations about the entire observable universe being such an island in the midst of chaos. Intelligent observers could only live within one of these "entropy gradients" (point A). Yet there are two fundamental difficulties with such a viewpoint. First, it would be much more likely for everything around A to have originated out of chaos only very recently (as in the case of C) – but then most of what seems to have happened in the past would be a mere illusion. Second, life-forms in the vicinity of B would experience the direction of time exactly in reverse to A.

among myriads. This is possible if the entirety of empty space, taken as a quantum vacuum, contains even more entropy than isolated black holes that only have the maximum entropy within a specific volume. Such an (eternal) accelerating expansion of space, driven by the still mysterious dark energy, could indeed entail an even higher entropy than black holes. Yet such a vacuum must produce random quantum fluctuations again and again. Some of them become huge because of inflation, until they deflate entirely due to the perpetual expansion caused by dark energy. And such cycles, according to Carroll and Chen, are more likely than random fluctuations of dinosaurs and bogus-universes. Thus, in an infinite future, time might not be a problem. Eventually, anything could spontaneously pop into existence due to quantum fluctuations if spacetime is eternal. They would mostly result in meaningless garbage, but a vanishingly small proportion would contain people, planets, and parades of galaxies. This book will also reappear again (a modern version of the well-known philosophy of eternal recurrence, which has many other versions in current cosmology too, see [168]). And this kind of quantum resurrection might even spark a new big bang. According to Carroll and Chen, one must be patient, however, and wait some $10^{10^{56}}$ years for another recurrence of our observable universe (if a de Sitter vacuum with a positive cosmological constant Λ is the "natural ground state"). Our whole universe might be such an island in a Λ-sea, i.e., a dark energy dominated vacuum (see also [37, 38] for a different, but related scenario). Still, there is no preferred direction of time in this scenario, because in both directions of time, baby universes emerge by means of fluctuations, empty out, and beget babies of their own. On an extremely large scale, such a multiverse looks time-symmetric on average – in the "past" as well as in the "future", new universes come into existence and reproduce without limit. An arrow of time appertains to each one of them, yet in half of the cases it points oppositely to the others.

If it is believed that such cycles are bogus as well, one has to look somewhere else for an explanation of the low initial entropy of space. In other words, if the stream of time is not a coincidence, then it must flow from a source. And this might provide a selection of initial conditions. Perhaps our universe is indeed the result of a natural selection process within a multiverse, such as the string landscape [142], if many newborn universes rapidly vanish. Laura Mersini-Houghton [102] proposes that the out-of-equilibrium quantum dynamics of the landscape of the initial patches may have provided such a selection mechanism. The tendency of any system is to reach equilibrium by maximizing entropy. But as matter degrees of freedom tend to equilibrium by trying to pull the initial patch to a black hole crunch, the gravitational degrees of freedom contained in the vacuum energy tend towards equilibrium by trying to expand that initial patch to infinity. These opposing tendencies in this tug-of-war on the initial patch guarantee that this system is far from equilibrium, and that its dynamics selects the initial conditions of the universe. If the vacuum energy wins over matter, the initial patch grows, giving rise to an inflating survivor universe. But if the pull of matter is stronger, then the initial patch cannot grow and contracts, resulting in a terminal universe. Therefore, in the ensemble of all possible initial conditions and energies on the string landscape multiverse, where every vacuum hosts a potential birthplace for a universe, only a fraction of them are selected as survivor universes, namely initial states with high vacuum energies. Although an ensemble of all possible initial states has shrunk to a subset by being wiped clean of the low energy patches, it still contains a whole multiverse of survivor universes. Such a selection process might also be a key to understanding the arrow of time because survivor universes start at high energies and therefore low entropies. Thus the direction of time would have a dynamical origin. And if the ergodicity of the phase space is broken, a universe cannot fluctuate back close enough to its previous state. If so, dynamics would not allow temporary or eternal duplications. According to Mersini-Houghton our cosmic domain is connected with everything else in the multiverse through nonlocal quantum entanglement, inherited from the entanglement of the initial patches, which cannot be lost. And these superhorizon-sized connections left imprints on the cosmic microwave background and large scale structure. Actually she predicted the existence of two giant voids (one might have been detected already [97, 127, 159]), a dark flow of galaxies (some indications of which have also been discovered [81, 165]), a higher supersymmetry breaking scale (which could be tested by particle colliders like the Large Hadron collider) if our universe acquired its initial vacuum energy by breaking supersymmetry, and certain cosmic microwave background features (a suppressed amplitude of perturbations but an enhanced power with distinct signatures at higher multipoles in the power spectrum, which is in agreement with recent measurements).

8 Big Bounce

Another possibility is that the big bang originated out of a big bounce, a collapse of a precursor universe or spacetime [104]. To explain the arrow of time, the bounce had to be special. There are basically two possibilities: either entropy rises forever, constituting a persistent arrow of time through all eternity, or entropy decreases during the contracting phase before the bounce and increases after it.

If entropy rises forever and the bounce is the end of an infinitely long contraction, from eternal past to the moment of the bounce, the entropy somehow stayed quite low, or else it was reduced at the bounce at least in a region that became the observable part of the universe. Perhaps there was a "cosmic forgetfullness" at work, destroying entropy and/or information from the precursor universe (see [17, 19, 20]).

It is also possible that, while global entropy increases, the entropy density within local horizons or Hubble volumes decreases from one cycle to the next due to the dark-energy-driven exponential expansion (see [87, 88, 140]). Furthermore, there are scenarios – relying on a strange form of dark energy called phantom energy – that describe entropy decrease before/during the bounce [27, 50]. Whether our universe has such subtle properties is, however, questionable and awaits substantiation.

Alternatively, entropy must have had a minimum value at the bounce and was in fact higher on the other "side", whence it increased both in the contracting phase before the bounce and the expanding phase after it. If so, the evolution of the universe, both in size and in entropy, would be symmetric in time. The time-reversal symmetry of the laws of physics would be accompanied by the large-scale behavior of the universe. And the pitfall of temporal chauvinism [116] – the temptation to treat the "initial" state of the universe differently from the "final" state – would also have been avoided. Very recently indeed some bounce models came up with higher entropy and thus opposite thermodynamic arrows of time on either side of the bounce: both in Euclidean quantum gravity ([69, 70, 108]; see also [169]) and in loop quantum gravity [19, 20] (for opposite arrows in an inflationary scenario see [1, 2]).

The cost of this advantage is a new problem however: Why was the entropy so low at the bounce? So in a time-symmetric scenario the mystery lies not in the infinite or most distant past beyond the big bang, but right in the temporal "center" of the universe (assuming it will expand forever). Is the fine-tuning problem therefore just shifted again – shifted back to the big bang, even if it were not an inexplicable singularity? And if entropy is increasing away from the bounce in both directions, one can argue that there are two opposite arrows of time which prevent a causal explanation of the bounce. Instead, the bounce can then be understood as the (uncaused?) origin of two unrelated universes. This would explain away the problem of time's direction, because both directions are realized; thus globally there is no fundamental asymmetry. But the mystery of the low entropy at the beginning of the universe(s) would still remain.

9 A Fundamental Asymmetry?

A straightforward explanation for the arrow(s) of time would be a fundamental derivation of a law or genuine property of nature for understanding the low entropy as an initial condition with a fundamental origin, not a dynamic one. This basic asymmetry might be encoded within the spacetime structure itself, i.e., the arrow of time would be an intrinsic property of spacetime and does not need to be reduced to non-temporal features [40].

Matias Aiello, Mario Castagnino and Olimpia Lombardi [3] for instance argue that the subset of time-symmetric spacetimes has measure zero in (or is a proper subspace of) the set of all possible spacetimes admissible in general relativity, because symmetry is a very specific property, whereas asymmetry is highly generic. Therefore, in the collection of all physically possible spacetimes (if it exists!), those endowed with a global and non-entropic arrow of time should be overwhelmingly probable, whereas non-existence of the arrow of time would require an extraordinarily fine-tuning of all the variables of the universe. Furthermore, the global time-asymmetry could be transferred to local contexts as an energy flow pointing to the same temporal direction over the whole of its spacetime. Thus in this approach the arrow of time is defined by the time-asymmetry of spacetime and expressed by the energy flow.

Brett McInnes [99, 100] speculates about a geometrical explanation. Due to the homogeneity of the cosmic microwave background, low entropy is more precisely low gravitational entropy and should be based upon spatial uniformity. Thus it has an intrinsically geometric form and root. McInnes therefore argues that the initial geometry must have been smooth (a perfectly flat spacelike surface, which was exactly locally isotropic around each point) and that there was a beginning of time, because something which has no past cannot be distorted by any "prior" conditions. Furthermore, baby universes can only have an arrow of time if they inherit one; if so, the problem of explaining the arrow is reduced to its explanation in the case of the "first" universe which would have come out of "nothing". If it originated along a spacelike surface with the topology of a torus, recent results in global differential geometry suggest that the geometry of this surface had to be non-generic. This geometric specialness would be communicated then to matter through the inflaton. The first universe inflated and gave birth to baby universes which inherited the arrow of time.

John Richard Gott III and Li-Xin Li [57, 58], cf. [166]) suggested another explanation for the arrow of time. Their model of a self-creating universe assumes a cold, low entropy time loop at the onset of the multiverse, a curled-up small time dimension, comparable to the compactified extra dimensions in string theory. In this model a region of a closed timelike curve allows the universe to be its own "mother". Thus the universe would not have been created out of nothing but out of something – itself. This also avoids the problems associated with both an eternal spacetime and an absolute beginning. Although it is sometimes said that asking what happened before the big bang is meaningless, like asking what is south of the South Pole, by supposing the universe (or the first of a multiverse) broke out of a time loop, asking what was the earliest point might be like asking what is the easternmost point on the Earth: one can keep going east around and around the Earth – there is no easternmost point. For every event in the very early universe there would have been events that preceded it, and yet the universe would not have existed eternally in the past. This also offers a new kind of cosmology in respect to time as the class of pseudo-beginning models do (see below).

10 A Universe With or Without a Beginning

Did the universe have a beginning or does it exist forever, i.e., is it eternal at least in relation to the past? This fundamental question was a major topic in ancient philosophy of nature and the Middle Ages. Philosophically, it was then more or less banished by Immanuel Kant's "Critique of Pure Reason" [80]. He argued that it is possible to prove both that the world has a beginning and that it is eternal (first antinomy of pure reason, A 426f/B 454f). Kant believed he could overcome this "self-contradiction of reason" ("Widerspruch der Vernunft mit ihr selbst", A 740) by what he called "transcendental idealism". After that the question as to whether the cosmos exists forever went out of fashion in philosophical discussions. This is somewhat surprising, because Kant's argument is quite problematic (see, e.g., [48, 75, 79, 93, 130, 135, 178, 179]). In the 20th century, however, the question once again became vital in the context of natural science, culminating in the controversy between big bang and steady state models in modern physical cosmology ([86]). In recent years, it has reappeared in the framework of quantum cosmology [147, 148], where, on the one hand, there are models that assume an absolute beginning of time while other scenarios suppose that the big bang of our universe was only a transition from an earlier state, and that there are perhaps infinitely many such events.

General relativity breaks down at very small spatiotemporal scales and high energy densities, leading to singularities. This is why quantum cosmology is needed. But in contrast to the framework of general relativity, which is theoretically well understood and has been marvelously confirmed by observation and experiment, the current approaches in quantum cosmology are still quite speculative, controversial, and almost without any empirical footing as yet. Nevertheless they offer promising new prospects – not only for explaining the big bang, but also for solving the problems of time.

Note that "big bang" is an ambiguous term which has led to some misunderstandings and prejudices. One should draw a distinction between at least four logically different meanings [154, 163]:

(1) the hot, dense early phase of our universe where the light elements were formed,
(2) the initial singularity,
(3) an absolute beginning of space, time, and energy, and
(4) only the beginning of our universe, i.e., its elementary particles, energy, vacuum state, and perhaps its (local) spacetime, its arrow of time, its invariants (described by its laws and constants of nature).

That our universe originated from a big bang in the meaning of (1) is almost uncontroversial, while (2) is relativistic cosmology's limit of backward extrapolation where the known laws of physics break down. Different models of quantum and string cosmology try to overcome this limit, and (3) and (4) are two distinct possibilities, broadly classifying many different competing models. Those characterized by (3) are initial cosmologies. They postulate a very first moment (see [59], [136]) or a limit or boundary of the past. Those characterized by (4) are eternal cosmologies. There are different kinds of them, in both ancient and modern cosmology: static ones (without irreversible changes on a coarse-grained level), evolutionary ones (with cumulative change), and revolutionary ones (with sharp phase transitions). They could have either a linear or a cyclic time. Option (4) also allows the possibility that there are other universes (for different notions of "universe" and "multiverse" see, e.g., [154, 163]) and that our universe neither exists eternally, nor came into being out of nothing or out of a timeless state, but that space and time are not fundamental and irreducible at all, or that there was a time "before" the big bang – "big bang" in the sense of (1). Such pseudo-beginning models offer (as time-loop models do) a third option between initial and eternal cosmologies. Thus, although there is already an overwhelming plentitude of cosmological models [167], from a conceptual point of view there are not many options. Insofar as they try to explain the big bang they can be classified roughly into just four types with respect to time (Table 1). Most of them might be realized either uniquely as one universe, or as a multiverse, especially if "spatial branching" is possible – as, for instance, in eternal inflation.

Both initial and eternal cosmologies involve severe explanatory problems, so it is useful to search for alternatives.

Eternal cosmologies need not assume a first cause or accident, but they shift the burden of explanation into the infinite past. Although every event might be explicable by earlier events and causal laws, eternal cosmologies cannot even address the questions as to why a temporally infinite cosmos exists and why it is the way it is. And there might be even deeper problems. Since we are able to assign a symbol to represent "infinity" and can manipulate such a symbol according to specified rules, one might assume that corresponding infinite entities (e.g., number of particles or universes) might exist. But the actual (i.e., realized in contrast to potential or conceptual) physical (in contrast to mathematical) infinity has been vehemently criticized as not being constructible, implying contradictions (see [76]

Table 1 Big bang cosmologies with respect to time

types of cosmology	sub-types	universal	multiversal
initial: absolute beginning		yes	yes
eternal: no beginning	• steady state	yes	no
	• quasi-steady state	yes	yes
	• bounce (with/out arrow of time reversal)	yes	perhaps
	• oscillation (cyclic)	yes	yes
time-loop	• at the beginning	yes	yes
	• the universe as a whole	yes	yes
pseudo-beginning	• from a static state	yes	perhaps
	• from a fluctuating vacuum	no	yes

and [141], ch. 5). If this were correct, it should also apply to an infinite past. (A future-eternal cosmos might be less problematic, if it is viewed as an unfolding, unbounded, i.e., only potential one.) This is a controversial issue, but it might be seen at least as another motivation to search for alternatives to past-eternal cosmologies.

Initial cosmologies, on the other hand, run into deep metaphysical troubles to explain how something could come out of nothing and why is there something rather than nothing at all (see [105, 157]). Even the theological doctrine of creatio ex nihilo does not start with nothing at all but with something, that is God, so the principle "ex nihilo nihil fit" still holds. And contemporary secularized ex-nihilo initial cosmologies usually claim, as Alexander Vilenkin has said (quoted in [150] (p. 45); cf. [175] (p. 205)), that there were at least the laws of physics, even if there was nothing else. (Concerning his own model, Vilenkin [174] (p. 26) admitted that "the concept of the universe being created from nothing is a crazy one", and an analogy with particle pair creation only deepens the problem, because matter-antimatter particles do not pop out of nothing, but are transformations of energy which is already there.) Similarly, Heinz Pagels [109] (p. 347) subscribed to some kind of platonism with respect to physical laws: "This unthinkable void converts itself into the plenum of existence – a necessary consequence of physical laws. Where are these laws written into that void? What "tells" the void that it is pregnant with a possible universe? It would seem that even the void is subject to law, a logic that exists prior to space and time." And Stephen Hawking [73] (p. 174) asked: "Even if there is only one possible unified theory, it is just a set of rules and equations. What is it that breathes fire into the equations and makes a universe for them to describe? The usual approach of science of constructing a mathematical model cannot answer the question of why there should be a universe for the model to describe. Why does the universe go to all the bother of existing?" But if one does not subscribe to an origin of something (or everything) from what is really nothing, one need not accept platonism with respect to the ontological status of physical laws [150]. They might simply be seen as the outcome of invariant properties of nature. If so, they do not govern nature but are instantiated from it. They are abstract descriptions – just as a model or theory of reality is not to be confused with reality itself.

So from what has been sketched here, it is helpful to search for a “third way” between initial and eternal cosmologies to explain more than the latter but not fall into the problems of the former. Pseudo-beginning cosmologies, as they can be called, might offer such a middle course [154, 156, 162]. Based on a distinction between two kinds of time scale, microscopic and macroscopic, these models also offer a conceptual and perhaps physical solution of the temporal aspect of Kant’s “first antinomy of pure reason”, i.e., showing how our universe could in some sense have both a beginning and an eternal existence.

11 Microtime, Macrotime and the Pseudo-Beginning Proposal

Kant’s first antinomy makes the error of the excluded third option, i.e., it is not impossible that the universe could have both a beginning and an eternal past. If some kind of metaphysical realism is true, including an observer-independent and relational time, then a solution of the antinomy is conceivable [154]. It is based on the conceptual distinction between a microscopic and a macroscopic time scale.

Only the macroscopic scale is characterized by an asymmetry of nature under a reversal of time, i.e., the property of having a global or at least wide-ranging evolution – an arrow of time – or many arrows, if they are independent from each other. Thus, the macroscopic (coarse-grained) scale, or macrotime for short, is by definition temporally directed – otherwise it would not exist. (It shall not be discussed here whether such an arrow must be observable in principle, which would raise difficult questions, e.g., in relation to an empty, but globally expanding universe.)

On the microscopic scale, however, there exist only local, randomly distributed events without dynamical trends, i.e., without a wide-ranging time-evolution or an increase of entropy density. This time symmetry occurs if one or both of the following conditions are satisfied: first, if the system is in thermodynamic equilibrium (e.g., if there is a huge number – or degeneracy – of microscopic states identifiable with the same coarse-grained macroscopic state); and/or, second, if the system is in an extremely simple ground state or metastable state. (Metastable states are local, but not global minima of a potential landscape and hence can decay; ground states might also change due to quantum uncertainty, i.e., due to local tunneling events or fluctuations.) Thus, while microtime always exists, provided there are at least some quantum fluctuations, macrotime could vanish or may be absent altogether. In conclusion, conceptually there are two kinds of timelessness: genuine timelessness, which means the absence of both micro- and macrotime; and effective timelessness, in which only macrotime is absent.

Distinguishing between micro- and macrotime does not rely on whether – and in which sense – time is real or not. It is therefore advantageous or effective to use temporal concepts even if time is ultimately taken to be an illusion (for example because only spacetime is real, because time is not fundamental, or because it emerges only within consciousness or as a fiction of language). Hence the distinction of micro- and macrotime remains helpful and is largely independent of ontological considerations.

A system with microtime but no macrotime does not need to have massive particles; events of any kind, e.g. quantum fluctuations or gravitational wave interference would suffice. One might argue that for any kind of time there must be at least some processes which could, in principle, serve as a clock. If so, then any kind of microscopic oscillation would be enough for the persistence of microtime. If photons are exchanged or scattered, for instance, then there is clearly change – at least conceptually. This is sufficient for the existence of microtime – although not for a sophisticated clock, which would not only depend on periodic processes but would also need to be able to track and record them. Such storage ability, or "memory", requires a (local) thermodynamic non-equilibrium and thus macrotime.

If macrotime is not fundamental, the arrow(s) of time could have a beginning – and therefore an explanation. Some still speculative theories of quantum gravity permit the possibility of a global, macroscopically timeless ground state (e.g., quantum or string vacuum, spin networks, twistors). Due to accidental fluctuations, which exceed a certain threshold value, universes might emerge out of that state. Due to some also speculative physical mechanism (like cosmic inflation) they acquire – and thus are characterized by – directed non-equilibrium dynamics, specific initial conditions, and hence an arrow of time. (It could be defined, for instance, by the cosmic expansion parameter or by the increase of entropy.) Note that, strictly speaking, such universes are not "inside" or "embedded in" the vacuum ground state, but cut their cords and exist in some respects "somewhere else".

Systems with an arrow of time undergo a directed development. This is manifest only on a macroscopic scale. Such a macroscopic time, or macrotime for short, comes along with an increase of entropy. This macroscopic global time-direction is the main ingredient of Kant's first antinomy, for the question is whether this arrow has a beginning or not. To get a simplified idea of macro- and microtime, classical thermodynamics and statistical mechanics can serve as an analogy (Figs. 3 and 4, see [4]).

For example molecules in a closed box (Fig. 3) spread from a corner (1) – if they were released there, for instance, from a gas cylinder – in every direction and eventually occupy the whole space (3). Then a state of equilibrium is reached which has no directed development anymore and thus no macrotime. Coarse-grained "low-resolution snapshots" of the whole system or sufficiently large parts of it show no difference (3 and 4). On a fine-grained level there are still changes (3 versus 4). Thus, a microtime always remains. Due to accidental, sufficiently large fluctuations – which happen statistically even in a state of equilibrium if there is enough microtime

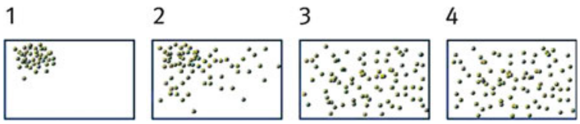

Fig. 3 Micro- and macrotime in a closed system.

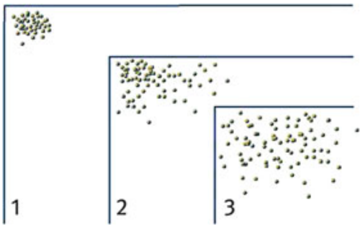

Fig. 4 Micro- and macrotime in an open system.

available – local structures can arise (from 3 to 1) and a macrotime temporarily comes into being again.

If the system is not closed but open (Fig. 4), a state of equilibrium does not necessarily develop, and macrotime does not vanish. For instance, in the universe this is the case because space expands. Whether there were specific, improbable initial conditions at the big bang (1) or whether order and a directed development could have come out of quite different initial configurations is controversial. Possibly the whole universe is an accidental fluctuation in a macrotimeless quantum vacuum.

In conclusion, and contrary to Kant's thoughts, there are reasons to believe that it is possible, at least conceptually, that time both has a beginning – in the macroscopic sense with an arrow – and is eternal – in the microscopic notion of a steady state with statistical fluctuations.

Is there also some physical support for this proposal?

Surprisingly, quantum cosmology offers a possibility that the arrow has a beginning and that it nevertheless emerged out of an eternal state without any macroscopic direction of time. So this possible overcoming of the first antinomy is not only philosophically conceivable but is already motivated by modern physics. At least some scenarios of quantum cosmology, loop quantum gravity (quantum geometry), and string cosmology can be interpreted as examples for such a local beginning of our macroscopic time out of a state with microscopic time, but with a quasi-eternal, global macroscopic timelessness.

To put it in a more general, but abstract framework and get a sketchy illustration, consider Fig. 5. Physical dynamics can be described using "potential landscapes" of fields. For simplicity, only the variable potential (or energy density) of a single field is shown here. To illustrate the dynamics, one can imagine a ball moving along the potential landscape. Depressions stand for states which are stable, at least temporarily. Due to quantum effects, the ball can "jump over" or "tunnel through" the hills. The deepest depression represents the ground state.

Usually it is assumed that the state of the universe – the product of all its matter and energy fields, roughly speaking – evolves out of a metastable "false vacuum" (Fig. 5, top left) into a "true vacuum" (maybe the "ground state") which has a state of lower energy (potential). There might exist many (perhaps even infinitely many) true vacua that would correspond to universes with different constants or laws of

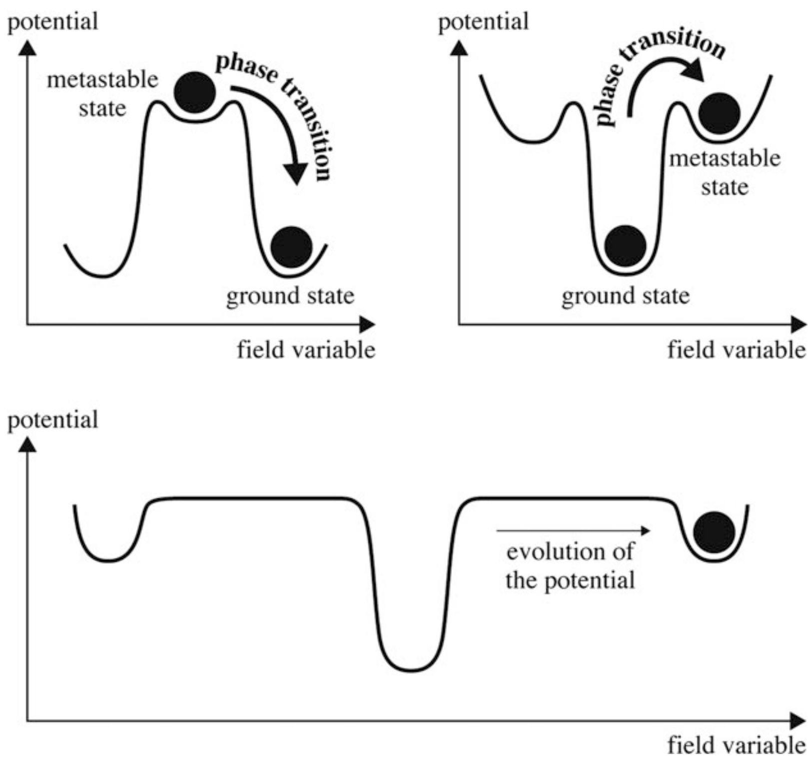

Fig. 5 Something out of almost nothing.

nature (imagine the graph in Fig. 5 not as a line but as a three-dimensional object shaped like a sombrero, where every spot on its brim corresponds to a different universe with a different set of physical laws and constants). The initial condition of this scenario, however, remains unexplainable and unlikely.

It is more plausible to start with a ground state that is the minimum of what can exist physically (Fig. 5, top right). According to this view, an absolute nothingness is impossible. There is something rather than nothing, because something cannot come out of absolutely nothing, and something does obviously exist. Thus, something can only change, and this change might be described by physical laws. Hence, the ground state is almost "nothing", but can become thoroughly "something" (more). (Therefore, it is only marginally, but qualitatively incorrect to say that there is something rather than nothing because nothingness is unstable – a difference which makes all the difference in the world and, in fact, makes the whole world.) Possibly, our universe – and, independent from this, many others, probably most of them having different physical properties – arose from such a phase transition out of a quasi-atemporal quantum vacuum (and perhaps got completely disconnected). Tunneling back might be prevented by a deformation of the potential (sketched in Fig. 5, bottom). For example this might happen due to the exponential expansion of this brand new space. Because of this cosmic inflation the universe may have become gigantic, while the potential hill may simultaneously have broadened enormously and become (almost) impassable. This preserves the universe from relapsing into non-existence. On the other hand, if there is no physical mechanism to prevent the tunneling-back or make it at least very improbable, there is still another option: if infinitely many universes originated, some of them could be long-lived only for statistical reasons. But this possibility seems to be less predictive and therefore an inferior kind of explanation for not tunneling back.

An example of such a dynamical resolution of the arrow of time problem was recently sketched by Raphael Bousso [24] (see also [143]). He has shown how, in principle, the string theory landscape can give rise to an arrow of time, independently of the initial entropy and without creating a Boltzmann brain problem. If certain assumptions hold, upward fluctuations spontaneously create metastable vacua in which the expected number of ordinary observers is greater than that of Boltzmann brains. If this proposal is correct, or an analogous one within a different theoretical framework, low-entropy boundary conditions are neither necessary nor sufficient for macrotime to arise.

The micro-/macrotime distinction is neutral in respect of whether opposite arrows of time could emerge from a bouncing region or a fluctuating vacuum. This issue is model-dependent (provided that time's direction is not fundamental). No temporal chauvinism should be assumed a priori, but this only poses the question and does not answer it. Nor does it solve the problem whether and how one can know about a global time-symmetric cosmos. Opposite arrows arising from a bounce at least were in some contact, though it is doubtful how influences could propagate to the other "side" of time, if the causal arrow comes along with the other arrows. Opposite arrows arising from a huge vacuum, however, could be arbitrarily far from each other. Perhaps quantum entanglements left their mark, but how might they keep track of time's direction in other universes?

Another crucial question remains even if universes could come into being out of fluctuations of (or in) a primitive substrate, i.e., some patterns of superposition of fields with local overdensities of energy: Is spacetime part of this primordial stuff or is it also a product of it? Or, more specifically, does such a primordial quantum vacuum have a semi-classical spacetime structure or is it made up of more fundamental entities?

Both alternatives have already been investigated in some respect. Unique-universe accounts, especially the modified Eddington models – the soft bang/emergent universe – presuppose a kind of semi-classical spacetime [14, 43, 44, 121]. The same is true for some multiverse accounts describing our universe (and others) as a fluctuation or collapse/tunnel event – e.g., the models explained in [11, 25, 26, 30, 37, 38, 49, 56, 77, 138, 146] – where Minkowski space, a tiny closed, finite space or the infinite de Sitter space is assumed. The same goes for string theory inspired models like the pre-big bang scenario of [53, 151, 173], because string and M-theory is still formulated in a background-dependent way, i.e., requires the existence of a semi-classical spacetime (for some speculative ideas in string theory that go beyond this, i.e., treating spacetime as emergent, see, e.g., [34]).

A different approach is the assumption of “building blocks” of spacetime, a kind of pregeometry [110], and also the twistor approach (see [74], ch. 6), and the cellular automata approach [180]. The most elaborated accounts in this line of reasoning are loop quantum gravity ([7, 10, 19, 123, 124, 126]; see also [152], and for comparisons with string theory [68, 110, 126]) and its relatives such as spin foams or dynamical triangulation [5]. Here, “atoms of space and time” underlie everything. According to the theory of loop quantum gravity, for example, spin networks made out of one-dimensional structures are the “building blocks” of reality [10]. Their connections and excited states define matter and forces, but also lead to the emergence of spacetime in the first place. Thus, spacetime would not be a foundation of nature but a subordinate product – in the end an illusion, “albeit a very stubborn illusion”, as Albert Einstein already assumed in the context of relativity. Abhay Ashtekar likes to quote Vladimir Nabokov in this context: “Space is a swarming in the eyes, and Time a singing in the ears”. Carlo Rovelli [123, 125] also assumes time to be a phantasmagoria.

Though the question whether semiclassical spacetime is fundamental or not is crucial, an answer might nonetheless be neutral with respect to the micro-/macrotime distinction. In both kinds of conceptualizations of the quantum vacuum, the macroscopic time scale is not present. And the microscopic time scale has to be there in some respect, because fluctuations represent change (or are manifestations of change). This change, reversible and relationally conceived, does not occur “within” microtime, but actually constitutes it. Out of a total stasis (even on the microscopic level) nothing new and different can emerge, because an uncertainty principle – fundamental for all quantum fluctuations – would not be realized. In an almost, but not completely static quantum vacuum, however, nothing changes macroscopically either, but there are microscopic fluctuations.

Surely a background-independent approach is more promising philosophically, for it is simpler and more fundamental and takes the lesson of general relativity more seriously. The concept of microtime can nevertheless be applied to such a “spacetime dust”. A good illustration (or candidate) is the spin foam approach in loop quantum gravity (see [9, 106, 114]), but in principle spin networks would also suffice (see [123, 124]), and some versions of loop quantum cosmology are indeed related to a pseudo-beginning [8, 18, 19].

To summarize, the concept of a pseudo-beginning of our universe (and probably of infinitely many others) is a viable alternative to both initial and past-eternal cosmologies. Note that this kind of solution bears some resemblance to a possibility of avoiding the spatial part of Kant’s first antinomy, i.e., his claimed proof of both an infinite space without limits and a finite, limited space: the theory of general relativity describes what was considered logically inconceivable before, namely that there could be universes with finite, but unbounded space [42], i.e., this part of the antinomy also makes the error of the excluded third option. Thus, the pseudo-beginning proposal offers a way of steering a middle course between the Scylla of a mysterious, secularized creatio ex nihilo, and the Charybdis of an equally inexplicable eternity of the world.

If our universe has a beginning within the multiverse, one could object that it was only shown that certain parts of the world had a beginning, but not the world as a whole, i.e., the sum of all its parts. Thus, the question would repeat itself, although in a larger context. And, indeed, this is already an issue of contemporary cosmology.

For example Alvin Borde, Alan Guth and Alexander Vilenkin [22] argued that, within the framework of a future-eternal inflationary multiverse, as well as some more speculative string cosmologies, all worldlines are geodesically incomplete and, thus, the inflationary multiverse has to have a beginning. Unfortunately, if future-eternal inflation is true, all "hypotheses about the ultimate beginning of the universe would become totally divorced from any observable consequences. Since our own pocket universe would be equally likely to lie anywhere on the infinite tree of universes produced by eternal inflation, we would expect to find ourselves arbitrarily far from the beginning. The infinite inflating network would presumably approach some kind of steady state, losing all memory of how it started [...]. Thus, there would be no way of relating the properties of the ultimate origin to anything that we might observe in today's universe" ([63], p. 78). (However, there is some discussion whether early inflationary traces could remain nevertheless, and thus a cosmic persistence of memory, see, e.g., [51, 52]. It is also controversial whether eternal inflation happened at all, see [101, 139] for crucial problems.)

On the other hand, Andrei Linde and – at least for the sake of argument – Anthony Aguirre and Steven Gratton argued that the multiverse could be past-eternal nevertheless, because either all single world lines would have to start somewhere, but not the whole bundle of them [89], or there could exist some (albeit strange) spacetimes with single past-eternal world lines [1, 2].

This issue is not settled, and even in those scenarios a global arrow of time may not necessarily exist. However, other frameworks are possible – and they have already been developed to some extent – where a future-eternal inflationary multiverse is both not past-eternal and beginningless, but arises from some primordial vacuum that is macroscopically timeless. Thus, again, the beginning of some classical spacetimes is not equivalent to the beginning of everything.

One can also imagine that there is no multiverse, but that the whole (perhaps finite) universe – ours – was once in a steady state without any macroscopic arrows of time but, due to a statistical fluctuation above a certain threshold value, started to expand ([121] and, independently, [14, 43–45]) – or to contract, bounce, and expand – as a whole, and acquired an arrow of time. In such a case the above-mentioned reply, which was based on the spatial distinction of a beginning of some parts of the world and the eternity of the world as a whole, would collapse.

Nevertheless, it is necessary to distinguish between the different notions and extensions of the term "universe". In the simplest case, Kant's antinomy might be based on an ambiguity of the term "world" (i.e., the difference between "universe" and "multiverse"), but it does not need to be; and it was not assumed here that it necessarily was.

The temporal part of Kant's first antinomy was purely about the question whether the macroscopic arrow of time is past-eternal or not. And if it is not past-eternal this does not mean that time and hence the world has an absolute beginning in every respect – it is still possible that there was or is a world with some underlying microscopic time. Thus the pseudo-beginning proposal at least shows that there is a promising third option besides Kant's dichotomy and antinomy, but of course this proves neither that such a possibility is the only consistent one nor that, as a matter of fact, our universe arose from such a time before time.

12 Conformal Cyclic Cosmology

According to the conformal cyclic cosmology developed by Roger Penrose [113], the history of the universe consists of a (perhaps endless) succession of aeons, where the indefinitely expanding remote future of each aeon is in some sense identical with the big bang of the next aeon, and the entropy of the universe of the remote future seems to return to the small value that it had at the big bang. This is conceptualized as the conformal continuation of the remote future of a previous aeon of the universe; the future infinity of our universe precedes the big bang of another aeon; and this succession continues indefinitely. So the entire succession of aeons taken together provides a conformal manifold which is non-singular in the past direction.

Penrose's proposal is promising because, with spacetime conformal rescalings, the spacetime metric can be changed without affecting the light cones and thus causal relations. This is a consequence of general relativity. Nine of the ten independent components of the metric tensor $g_{\mu\nu}$ at any one point in spacetime determine where the light cone is at this point. The remaining independent component provides the scale of the metric at that point. It fixes the actual passage of time, once the causal spacetime structure has been determined, since the metric tensor is basically a measure of clock rates. The causal structure can be understood as more fundamental than the time rates because various parts of physics – for example James Clerk Maxwell's conformally invariant theory of electromagnetism – depend only on this causal or conformal aspect of $g_{\mu\nu}$, not on the scaling. This allows a kind of circumvention of the big bang singularity.

Mathematically, a cosmological singularity can be represented as a conformal boundary (hypersurface) to a spacetime, where an infinite conformal expansion is applied; and vice versa the asymptotic infinite future spacetime can be represented as a hypersurface involving an infinite conformal contraction. Furthermore, the conformal geometry of the spacetime manifold can be extended in a smooth way to a region preceding the big bang or to a region extending smoothly to beyond the future infinity. These boundaries were introduced merely as a mathematical convenience in the first place. But the conformal cyclic cosmology demands that both extended regions represent real spacetime regions. Here a past-spacelike hypersurface boundary is adjoined to a spacetime in which the conformal geometry can be mathematically extended smoothly through it, to the past side of this boundary, i.e., to a pre-big bang Lorentzian manifold. Thus the big bang singularity is expanded out infinitely into what can be described as a smooth past boundary – a spacelike hypersurface instead of a singularity, such that the conformal metric of spactime extends across that hypersurface. This transformation preserves the causal structure of the original spacetime, although it does not preserve lengths and times.

It seems confusing that the vanishing density and temperature in the infinite future can somehow be equated with an initial state with the seemingly opposite properties of an almost infinite density and temperature. And this would indeed be physically meaningless if the metric geometries of the two regions were to match. But temperature and mass density depend on the metric structure of spacetime, and cannot be determined merely from the causal (conformal) spacetime structure. In other words, matter is sensitive only to the nine components per point provided by the conformal structure of the universe, the light cones, but is blind to the single remaining component that provides the scale of the metric which would determine clock rates and distance measures.

Any particle of mass m can be seen as a "clock" which ticks away with a frequency ν that is proportional to this mass: $\nu = mc^2/h$, where h is Planck's constant. But because of the high temperature in the very early universe, the particles were effectively massless (they exceeded the Higgs mass), satisfying conformally invariant equations. If it is further assumed that their interactions are also described by such equations, no "clocks" existed immediately after the big bang, because according to relativity theory there is no passage of time for massless particles. Constructing a clock out of photons and gravitons alone is not possible, because they are conformally or effectively conformally invariant, respectively. Thus the early universe loses track of the scaling which determines the full spactime metric, while retaining its conformal geometry (rather than the slightly more restrictive metric geometry) – one might even claim that, near the big bang, no conception of the passage of time should be applied.

Similar conjectures about the distant future of the universe are reasonable too, but in a mathematically reverse sense: while a conformal factor becomes infinite at the big bang, it goes to zero at the future boundary, which is spacelike if there is a positive cosmological constant. So in the very remote future there are also no clocks in principle, and the universe "forgets" time. With conformal invariance both in the distant future and at the big bang, Penrose argues that the two situations are physically identical, so that the furthest future of one phase of the universe becomes the big bang of the next. Although temperature undergoes an enormous change at the crossover surface – approaching zero just before it and infinity immediately beyond it – the frequencies and thus energies of photons are completely rescaled. So without massive particles, there is no way of defining lengths or times, whence the only physically meaningful structure is the conformal structure, i.e., the causal structure. By compressing the conformal factor towards the far future, and expanding it towards the beginning, the geometry of the future conformal boundary can be joined seamlessly to the initial conformal boundary.

It is also crucial that the Weyl curvature should be zero on both the future boundary and the past boundary, so that the big bang is still well-defined in the model as the unique hypersurface on which the Weyl curvature vanishes. However, there are black hole spacetime regions of divergent Weyl curvature that are singularities in the conformal geometry, and these can be encountered as future endpoints of particles' timelike world lines. According to the Weyl curvature hypothesis, they indicate an asymmetry between past and future, just as a big crunch singularity does. This would be inconsistent with the conformal cyclic cosmology. Therefore the Weyl-divergent future-type singularities must have dissappeared by the time the future hypersurface is reached, in order not to violate the conformal smoothness. This seems possible indeed, because in the far future all black holes will eventually disappear due to the quantum effect of Hawking evaporation, which brings the Weyl curvature back to zero.

Penrose postulates that information is lost in this process and standard quantum theory is violated. Thereby entropy is also claimed to be effectively renormalized, decreasing significantly before crossing the hypersurface, which reproduces the enormous specialness of the big bang. This real information loss during or after black hole evaporation is in disagreement with other accounts [166], and it remains unclear and controversial whether the effective reduction of phase space volume violates the second law of thermodynamics, or even what this means.

The conformal cyclic cosmology is based on some other debatable assumptions. As in the pre-big bang scenario [53, 173] and in the cyclic universe scenario [140], there is no inflationary epoch – exponential expansion did not take place after the big bang but before it, and this generated the scale-invariant spectrum of density perturbations for the post-big bang universe. At the change-over from one aeon to the next, scalar fields might be produced, or simply remain; these would create dark matter after the big bang (which must eventually decay into massless particles in the remote future). And gravity is considered to be infinitely large at the big bang (which is why its degrees of freedom are zero, i.e., gravitational entropy is low), but gets smaller with time and eventually falls to zero at the final boundary. Furthermore, in the remote future there must be only electromagnetic and gravitational radiation, but no massive fermions and charged particles. This implies that protons will decay, neutrinos will become massless (or decay too), and electric charge is not exactly conserved (or electrons will also decay) – requiring an as yet unknown physical process. Only then does the conformal geometry become the relevant spacetime structure again. And quantum fluctuations, which are inevitable in a vacuum with positive energy density, must not spontaneously create anything from massive particles to black holes, which is expected on very large time-scales; otherwise they would prevent the universe from ever reaching an exact state of conformal invariance in the far future.

So conformal cyclic cosmology seems quite speculative. But it should be testable. For example, gravitational wave bursts arising from close encounters between black holes might leave their mark on the future boundary, influence its conformal geometry, and generate spatial variations in the matter density just after the next big bang. Such bursts of gravitational radiation would cause a superposition of circular patterns on the celestial cosmic microwave background sphere, similar to the appearance of ripples on a pond following a sustained period of rain (whether there are already hints for this is controversial, see [46, 47, 60–62, 64, 103, 145]).

In the conformal cyclic cosmology there is neither a multiversal "surface" of pseudo-beginning, in contrast to some quantum and string cosmological models of the emergent universe, nor is there a "branching" of universes in contrast to models such as eternal inflation, the recycling universe, or cosmological natural selection. The conformal cyclic cosmology represents a linear succession of universes (or one endlessly repeating kind of universe).

Penrose's model can also be interpreted as a kind of pseudo-beginning (and pseudo-ending) cosmology. It does not represent an absolute beginning because even when (macro)time disappears, space remains (at least if it is assumed that the big bang curvature singularities are overcome). Time, or macrotime, is not eternal, strictly speaking. The (thermodynamic) arrow of time vanishes, along with a supposed effective decrease of entropy – or phase space reduction –, if this really accompanies black hole evaporation. Therefore gaps in macrotime exist in the conformal cyclic cosmology, namely when there are no longer any massive particles around (in the remote future of each aeon) or when particles are effectively massless (in the very early phase of each aeon). But microtime continues. Causality remains, and there is not nothing – there are still lonely photons and spreading gravitational waves which may even influence the subsequent aeon.

Thus conformal cyclic cosmology can be categorized as lying between initial and eternal cosmologies – like some other models, but in a different way. There is a big bang beginning, in fact there are arbitrarily many, but it is not the beginning of everything, and it may even bear signs of the preceding aeon in the form of gravitational wave imprints. The succession of aeons seems to be eternal (if it is stable, which has not yet been shown), and may never vanish. But there are "chasms" in macrotime, i.e., recurrent disappearances of the thermodynamic arrow of time and other arrows – excepting the causal arrow, at least (con)formally. So there are "periods" where no clocks of any sort could be built and no passage of time could be observed in principle. In this scenario time ends temporarily, paradoxically speaking, at least if time is relational. (It may still be claimed, however, that there is a kind of fundamental, global time, pervading all the aeons, and at least conceptually this is somewhat presupposed by referring to an infinite succession of aeons.)

13 The End of Time

Whether time has a beginning or not and whether it ends at some point remains puzzling [170, 171].

If time is emergent, either created by fundamental physical entities or by our consciousness, it would ultimately be an illusion. And the end of time would have essentially arrived as soon as this illusion is debunked or explained (or as soon as consciousness comes to an end). Physicists like Julian Barbour [12] and Carlo Rovelli [125] advocate this idea and call it "the end of time". It is, strictly speaking, an epistemological or conceptual issue.

If time is fundamental, however, it remains an open question whether it is finite or not. This is a matter of physics and/or metaphysics.

An end of fundamental (and also emergent) time is equivalent to a classic global singularity – for example in the big crunch [16, 122] or in a sudden "freezing" of all dynamics, including cosmic expansion [23]. There would no longer be any classical time.

From the perspective of quantum mechanics, however, a wild superposition of states without any quasi-classical phenomena is more plausible [78]. This would be the end of the world as we know it, but not the end of everything.

Future singularities such as the global one in the big crunch or local ones in black holes might be avoided by means of quantum gravitational effects. Instead there would be a bounce in which time continues or in which it is reborn.

And there are other doomsday scenarios about how time could end. One is called big snap [144]. Here it is argued that – just like a rubber band, which cannot be stretched indefinitely because of its finite number of atoms – the granular nature of spacetime implies destructive events to come if space has a finite number of degrees of freedom and expands too much. Equally devastating would be a signature change [95, 96]. Here the time dimension turns to a fourth spatial dimension if the universe is a four-dimensional brane, moving through a higher-dimensional bulk, and approaches the velocity of light. This would cause a big freeze within the brane – though time would still continue within the bulk.

Another kind of dissolution of classical time could be classified as a pseudo-ending. It wouldn't have to be the end of everything, but it could lead to a quantum vacuum in which there would no longer exist a macrotime albeit there would still be a microtime – a structureless, reversible state of equilibrium. (Whether "existence" necessarily takes place "in time" or independently of time is a difficult terminological and philosophical question, but maybe not a scientific one.) So it seems possible that the arrows of time end – but not time itself. In other words: macrotime stops, but microtime goes on. This would be a pseudo-ending analogous to a pseudo-beginning of the universe. Here the end of time would mean the end of macrotime. This could happen if the future of space becomes an empty but eternally expanding de Sitter universe. (Only if it is fundamental would time remain, displaying itself in the expansion, although the latter cannot be measured.) Then there wouldn't be any more (irreversible) events, at least not locally, because there would be nothing left to change (neglecting virtual quantum processes).

Paradoxically, the end of (macro)time could be a temporary one if a vacuum is left. If random fluctuations above some threshold value arise, which in the long term are unavoidable in quantum systems, an arrow of time can develop again. This is somewhat similar to Boltzmann's [21] original fluctuation hypothesis, but it is based upon different physical conditions (quantum processes in a dynamical spacetime instead of mechanistically conceived atoms and radiation in an infinite static space; cf. [33]). In a quantum mechanical de Sitter universe, it is even possible for new big bangs to arise from the vacuum, which is not entirely empty due to quantum fluctuations (see [30, 37, 38, 113, 164]). Then new arrows of time emerge, and there is a time after time, a succession of "interrupted" macrotimes.

"There is a theory which states that if ever anybody discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory which states that this has already happened", Douglas Adams once joked. Modern cosmology has come up with many strange models and possibilities. Issues of time are central here. Although it is too early to decide between the competing approaches, it seems quite probable that the universe is bizarre and perhaps even inexplicable and absurd to some extent [158]. But one thing seems to be certain already: time is not what it used to be.

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