51
TIME IN COSMOLOGY

Craig Callender and C. D. McCoy

Readers familiar with the workhorse of cosmology, the hot big bang model, may think that cosmology raises little of interest about time. As cosmological models are just relativistic spacetimes, time is understood as it is in relativity theory, and all cosmology adds is a few bells and whistles such as inflation and the big bang and no more. The aim of this chapter is to show that this opinion is not completely right—and may well be dead wrong. In our survey, we show how the hot big bang model invites deep questions about the nature of time, how inflationary cosmology has led to interesting new perspectives on time, and how cosmological speculation continues to entertain dramatically different models of time altogether. Together these issues indicate that the philosopher interested in the nature of time would do well to know a little about modern cosmology.

Different claims about time have long been at the heart of cosmology.[1] Ancient creation myths disagree over whether time is finite or infinite, linear or circular. This speculation led to Kant complaining in his famous antinomies that metaphysical reasoning about the nature of time leads to a "euthanasia of reason." But neither Kant's worry nor cosmology becoming a modern science succeeded in ending the speculation. Einstein's first model of the universe portrays a temporally infinite universe, where space is edgeless and its material contents unchanging. One of the more popular versions of the big bang model is temporally finite: it begins with a bang and ends with a crunch. Later, Bondi and Gold's rival to the hot big bang, the steady-state theory, is, like Einstein's universe, premised on the idea that the large scale features of the universe don't change in space or time (the so-called "perfect cosmological principle"). Rather more exotic ideas followed: Milne, for example, abandoned relativity theory and posited *two* times nonlinearly related to one another (Kragh, 1996, 61ff.). Today the speculations continue. Often motivated by quantum considerations, one finds plenty of alternative cosmologies to the big bang model's contemporary successor, the ΛCDM model. These alternatives range from cyclic time universes, to string-theoretic "branes" colliding in a high-dimensional space, to eternally inflating multiverses chock full of bubble universes (Kragh, 2011).

The reason for so much variety in cosmological possibility is simple: the universe is really big and what we can see is really small. We are, in other words, faced with severe observational limitations in the context of cosmology (Ellis, 2007) and hence a severe underdetermination of cosmological modeling (Butterfield, 2014). According to relativity theory we can at best only detect signals from events within or on our past light cone—this is the "observable universe" in the maximal sense. According to the standard big bang model the observable universe is further limited physically by the existence of a surface of last scattering. Before the time of this event (decoupling) light was tightly coupled to matter such that it could not travel in space and time to our telescopes here and now. This essentially means that we don't have observational access to the very early universe. Since the entire universe is most likely much, much larger than the observable universe, what we can verify observationally gives us a relatively weak handle on the nature of the cosmos at large. Thus, many genuinely scientific models can plausibly fit the same observations, since the universe may well be very different outside the observational scope of our telescopes.

Furthermore, our astronomical and cosmological observations themselves are heavily theory- and model-laden. Astronomy reveals just how much our judgments of distances, angles, and even objects depend on background assumptions about the nature of astrophysical objects, the geometry of the universe, etc.[2] And a related additional consideration is that confidence in our own theories runs low in various cosmological regimes. For example, the big bang model posits that the universe began with an initial singularity. But should we trust general relativity at the high temperatures and energies of the big bang itself? And does the addition of inflation to the big bang model modify this expectation? How might the big bang story be modified by quantum effects from an expected future theory of quantum gravity? All this uncertainty about how to model the unobservable universe opens up space for cosmological models that feature different perspectives on time, which means that speculation about time in cosmology flourishes as much as—if not even more than—ever, despite the subject now having more and better empirical data than it has enjoyed before.

After a brief treatment of time in the standard model, we hope to give the reader a sense of some of the live options available for time in cosmology which are of philosophical interest. Although time may be infinite, space is not; as a result, our discussion necessarily will be abbreviated and selective.

51.1 Time in the Standard Model

The current standard model of cosmology, as mentioned, is usually called the ΛCDM model. It extends the classic hot big bang model, which includes only normal matter and radiation, by including exotic cold dark matter (CDM), the more exotic dark energy (Λ, the usual symbol for Einstein's cosmological constant), and a stage of inflation in the early universe that seeds the initial perturbations which give rise to structure in the universe.[3] The theoretical core of the standard model is the general theory of relativity, which models the universe as a four-dimensional spacetime manifold M endowed with a pseudo-Riemannian metric g and matter-energy distribution T.

Observations suggest that the universe looks pretty much the same in every direction. Supposing that the same holds at every other location in the universe leads one to posit the cosmological principle: the assumption that the universe is spatially homogeneous and isotropic (Beisbart and Jung, 2006). Applying this principle to general relativity requires presuming that there is a congruence of timelike curves in the spacetime manifold M which foliates it into a one-parameter (λ) family of spacelike hypersurfaces Σ_λ of constant intrinsic curvature κ (which can be positively curved like a sphere, flat like a plane, or negatively curved like a hyperbolic surface). The matter-energy distribution T in such a spacetime takes the form of a perfect fluid with constant density ρ and pressure p on the hypersurfaces of constant curvature. The collection of relativistic spacetimes that meet these conditions are usually known as the Friedman-Robertson-Walker (FRW) or Friedman-Lemaître-Robertson-Walker (FLRW) spacetimes.

One usually thinks of the members of the family of hypersurfaces Σ_λ as representing space and λ as representing time. Relativity, of course, permits the choice of another congruence of timelike curves which also foliate M into "spaces." So the sense in which λ represents time is relative to the choice of congruence that gives rise to it as a parameter. Under the assumption of the cosmological principle and choosing a foliation such that the corresponding spaces have constant curvature reduces Einstein's field equations to the following two, usually called the Friedman equations:

$$\dot{H} + \frac{4}{3}\pi(\rho + 3p) + H^2 = 0; \tag{51.1}$$

$$\dot{\rho} = -3H(\rho + p), \tag{51.2}$$

where H, the Hubble parameter, represents the expansion rate of space, and overdots represent time derivatives with respect to the chosen standard of time. Thus the first equation concerns the acceleration of the expansion of space ($\dot{H}$); the second is a continuity equation for the "cosmic fluid," which consists of radiation, dust, dark matter, dark energy, etc.

There is a natural standard of time to use in a non-vacuum FRW spacetime: the proper time of anything not moving with respect to the cosmic fluid. Hypothetical objects that are at rest with respect to it are called fundamental observers. Galaxies, for example, are approximately fundamental observers, since they do not move much with respect to the background fluid. The proper time of the cosmic fluid, which we will denote by t, is generally known as *cosmic time*.

Nevertheless, although the decomposition from above naturally picks out a particular time function (t), the theory is still entirely relativistic. We chose to foliate spacetime into slices of constant spatial curvature, but we could just as well have chosen an infinity of other foliations. It is therefore only when we choose the natural foliation and use cosmic time that one can claim that the universe is 13.8 billion years old—this duration is determined by the proper time of a hypothetical fundamental observer from the beginning of time until now. By contrast, to photons the world just began. Relativity doesn't choose sides over who is right about time, fundamental observers, arbitrarily moving observers, or photons. All are.

51.2 Breaking Up Spacetime

One of the central lessons of contemporary physics is that space and time, traditionally thought to be conceptually independent, are replaced by a unified spacetime. It may come as a surprise to many readers to discover that some physicists and philosophers want to use cosmology to undo this revolution and break up spacetime back into space and time. By "break up" we mean a genuine divorce, at the level of basic theory, and not merely a provisional separation for pragmatic calculational convenience (which is done all the time in numerical relativity). The thought behind the machinations is that cosmology actually justifies resurrecting a Newtonian-like absolute time.

Indeed, one finds the idea arising just after relativity was born and espoused by some of cosmology's biggest stars. For instance, just three years after general relativity was discovered and only one year after experimentally confirming it, Sir Arthur Eddington in 1920 wrote that "absolute space and time are restored for phenomena on a cosmical scale," hinting even that this cosmic time is God's time (Eddington, 1920 [1987], p. 168). Sir James Jeans writes:

> It was natural to try in the first instance to retain the symmetry between space and time which had figured so prominently in [special relativity], but this was soon found to be impossible. If the theory of relativity was to be enlarged so as to cover the facts of astronomy, then the symmetry between space and time which had hitherto prevailed must be discarded. Thus time regained a real objective existence, although only on the astronomical scale, and with reference to astronomical phenomena. (Jeans, 1935, p. 21)

That figures as significant as Eddington and Jeans suggest ditching the core postulates of relativity may be somewhat shocking. Both seemed to want to restore an "intuitive" notion of time, although admittedly Eddington gave off mixed signals on that matter (Canales, 2015).

Perhaps more isn't made of this rejection because it's not entirely clear whether either had a full rejection of relativity in mind. Eddington says that relativity is "reduced to a local phenomenon." Did he really want to abandon the core conceptual insights of a theory that he helped confirm in local physics (i.e., the solar system) when applied to the universe? Similarly, Jeans's talk of time regaining real objective existence *but only on the astronomical scale* sounds somewhat obscure conceptually: what exactly is "real" and "objective" about time on the astronomical scale and, more importantly, what does such a time have to do with the intuitive time of our experiences?

Today those desirous of a sundering of spacetime are somewhat clearer. Their motivations are diverse. Some file "philosophical" grounds for divorce, and others make their case for the sake of new physics. The first group, like Eddington and Jeans, wish to free "intuitive" metaphysical models of time from the clutches of relativity (Lucas and Hodgson, 1990; Crisp, 2008; Swinburne, 2008). The idea that the present is special, that it is what exists or what becomes, is famously threatened by relativity.[4] Finding a scientifically respectable absolute time according to which the world comes into being would give these prospective divorcees the "proof" that they need. The second group is instead worried about quantum mechanics and, more specifically, its famous measurement problem. Some solutions to this problem pick out a preferred foliation of spacetime. Some hope that cosmology reveals this preferred foliation in its choice of a natural time function (Roser and Valentini, 2014).

What is this special time function? Hawking proved that as long as a solution of Einstein's field equations is "causally stable" (loosely put, it doesn't permit time travel or anything close to time travel) the spacetime described possesses a global function whose value increases along every future directed timelike or null worldline (Hawking, 1969). These time functions are a dime a dozen however: typically there are an infinite number definable in any causally stable spacetime. Enter cosmology. The hope is that cosmological considerations will narrow down these time functions to a smaller set, or better, to something unique.

The key idea is to look at the (approximate) symmetries of the cosmological spacetimes. Observations of the 2.7K cosmic microwave background (CMB) radiation and galaxy counts support the claim that at a large scale the universe is amazingly spatially isotropic. Deviations exist, but they are slight. The inference to global homogeneity is more theoretical. If the universe were spatially inhomogeneous, then for it to look so isotropic to us would mean we are very specially placed. Since to us modern Copernicans it seems plausible that our location is not special, we assume spatial homogeneity too, i.e., we naturally assume the cosmological principle mentioned above. In the context of general relativity, that gives us the constant (spatial) curvature spacetimes of FRW, described above, and FRW's special time function t, the cosmic time.

However, we should surely not insist on perfect isotropy and homogeneity, since our universe is definitely not perfectly isotropic and homogeneous. So a time function somewhat less tailored to FRW is desirable. One especially popular geometrical choice is York or *constant mean curvature* time (York, 1972). To understand York time, consider the collection of relativistic spacetimes (M, g). Some of these spacetimes can be foliated by everywhere spacelike three-dimensional hypersurfaces. The four- dimensional geometry obviously constrains the geometry on these spatial leaves; in fact, it induces on each hypersurface Σ a spatial three-dimensional metric h (which determines the intrinsic curvature of Σ) and an "extrinsic curvature" K (which, roughly speaking, describes how Σ is embedded in the entire spacetime M). Thinking of these in dynamical terms, e.g. in the initial value formulation of general relativity, you can regard h as a configurational, position-like variable and K as its conjugate momentum (which therefore says something about h's time development). Now, on a select set of these spacetimes, we can find some that permit a foliation where the mean extrinsic curvature associated with each spatial slice is constant. The mean, or average, extrinsic curvature is given by the trace of K, $\mathrm{Tr}\, K$. For these spacetimes each leaf of the foliation is a hypersurface whose mean (extrinsic) curvature is equal to a constant, i.e., $\mathrm{Tr}\, K = n$. York time is then defined as a time function $t\colon M \to I \subset \mathbf{R}$ such that its level sets $t^{-1}(I)$ are the hypersurfaces with mean curvature equal to n, for every $n \in I$ (Andersson et al., 2012). In short, each "tick" of the York clock reads a value of constant mean curvature. (The global spatial homogeneity of FRW spatial hypersurfaces implies that they have constant mean curvature, so York time coincides with cosmic time in FRW spacetimes.)

Constant mean curvature is an interesting topic in differential geometry and has many physical applications. York time too has a number of virtues, especially when it comes to numerical relativity and actual calculation. But in the present context what makes constant mean curvature and York time attractive is that under certain conditions it is provably unique (Marsden and Tipler, 1980; Rendall, 1996). For instance, restrict attention to globally hyperbolic spacetimes with a compact Cauchy hypersurface, a vanishing cosmological constant, and satisfying the so-called strong energy condition. Then, except for some outlier cases ($\mathrm{Tr}\, K = 0$), the York time is provably unique. And as those three conditions are all geometrical in nature, one has a foliation that is in some sense geometrically unique (more below).

From a relativistic perspective, there is nothing surprising going on here. With York time one has just picked a special foliation tied to the curvature properties of certain spacetimes, and in some sufficiently special spacetimes this choice is natural. But one is no more forced to pick out a constant mean curvature foliation than to pick a different foliation, such as Misner's -log t, where t is the above FRW time (Misner, 1969). With York time in hand, however, those with the motivations described above now issue the divorce papers to spacetime. For tensers, no less than existence itself unfolds according to York time. And for those worried about quantum mechanics, the proposal is to identify the foliation quantum mechanics uses with York time. Physics or metaphysics marches to the beat of York. As for relativity, it can be abandoned. For the physics within the domain of special relativity, one sides with Lorentz over Einstein. For larger scales, one uses only the solutions of Einstein's equations that permit York time. The full possibilities allowed by general relativity are viewed as unnecessary extravagance.

Many commentators have questioned this identification of York time with metaphysical or quantum time. We cannot do justice to all the discussion here (see, for instance, Bourne, 2004; Callender, 2017). Perhaps the largest question that needs answering is simply: Why? Why think that metaphysical time or quantum time "cares" about constant mean curvature? Nothing in either metaphysics or (non-gravitational) quantum mechanics suggests any connection to curvature, let alone *constant mean curvature*. Why would metaphysical or quantum time care about maintaining an average? Here we will confine ourselves to just a couple of remarks.

First, the claims of the uniqueness of York time seem overblown—at least from the perspective of taking it seriously as a physically (as opposed to calculationally) preferred time. The uniqueness results occur only after quite a severe shrinking of the space of Einstein's solutions. The assumptions about a compact spatial slice, global hyperbolicity, the behavior of energy, and the cosmological constant may not hold. Probably they don't. But that is not all. Uniqueness is one thing, but existence is another. When does the York time exist? There are in fact many spacetimes that meet the above conditions but where York time does not exist. The "geometric invariance" of York time obtains only in a special class of spacetimes, one hardly demanded by observation.

Second, we suspect that many of the philosophical devotees of York time pick it simply because it seems to them to yield an attractive intuitive picture of cosmological evolution—that it is more or less like the familiar old absolute time of Newton or of their manifest *weltbild*. To chip away a little at this, we'll here note two relevant facts that we haven't seen in the philosophical literature. One, what makes York time great for numerical relativity but a bit weird for metaphysics is its avoidance of singularities. York time is definable in universes which, like ours (at least classically), contain black holes harboring singularities. The demand for constant mean curvature makes the foliation avoid these singularities, exponentially slowing York time to avoid them and lumping them all together at the "end of time." As a result, a singularity in a black hole born "today" (according to "intuitive" time) and one born a million years in your future (again, according to "intuitive" time) happen at the same moment of York time (Smarr and York, 1978) (see Figure 51.1). Two, during inflation the universe is said to enter into a de Sitter phase, that is, be describable by de Sitter spacetime. In the usual coordinates of de Sitter, all the $t =$ constant slices do indeed have constant curvature, which is nice; however, they all have the same value. The York clock seems to stop in the de Sitter phase!

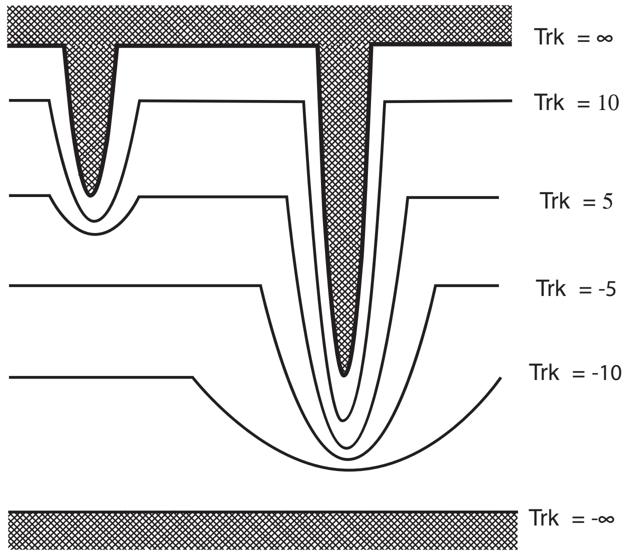

Figure 51.1 A depiction of York time in a spacetime with singularities. Adapted from similar figures in Qadir and Wheeler (1985)

None of these small observations constitute a knock-down objection to identifying York time with metaphysical or quantum time. But they should suggest to those hoping to rescue "intuitive time" that it's not really so much like our old friend absolute time as they might wish.

51.3 Cosmological Speculations

As we just saw, the use of distinguished foliations in cosmology invites deep questions about the nature of time and the significance of relativity. Putting those questions aside, the nature of time is pretty simple according to the standard big bang model: the universe began a finite amount of time to the past and will continue to expand indefinitely and ever faster to the future under the influence of dark energy; in addition, the entropy of its matter-energy distribution increases irresolutely toward this future; and, well, that's about it.

More specifically, due to the singularity theorems of Penrose, Hawking, and Geroch in the 1960s, the standard big bang model seems firmly committed to a past initial singularity (Smeenk, 2013). This basic consequence is intuitively suggested in typical expanding FRW universes since, assuming a positive cosmological constant and gravitating matter, the scale factor goes to zero and the matter density blows up as one goes back in time. The Hawking-Penrose singularity theorem makes the argument precise and therefore seems to provide an answer to the age old question about whether time is finite or infinite, the subject of Kant's famous first antinomy: time is finite toward the past but infinite toward the future (for flat and open cosmologies). Moreover, the geometrical modeling used in the big bang model allows one to skirt one of Kant's main worries, as the past is finite even though there is no "first" moment, just as there is no first positive real number.

That straightforward picture, however, is under threat from speculation hoping to address various outstanding theoretical problems. Modifications to the above picture—some quite dramatic—are frequently suggested based on cosmological applications of research programs in quantum gravity (e.g. superstring theory, loop quantum gravity) and from attempts to better understand inflation (e.g. eternal inflation). Indeed, despite its successes, inflation brings with it its own problems, and new developments of the general theory are regularly being proposed to escape these worries. These modifications essentially arise from what would be new physics. But modifications to the straightforward picture are often also connected to solutions of other perceived problems with the standard cosmological model. For instance, many physicists find the initial singularity predicted by the singularity theorems of general relativity to be a sign of the theory breaking down. They suspect that quantum effects will avoid these singularities. Similarly, many find the posit that the universe began in extremely low-entropy distasteful, or at least in need of explanation (Carroll, 2010). Can a cosmological model be devised that makes the past low-entropy a natural product of cosmological evolution as opposed to a special posit? Philosophers have debated whether these problems are really so dire.[5] Whether they are or not, eliminating one or both has led to the development of interesting new cosmological models that part ways in various respects with the standard picture of time. Here we briefly highlight some of the most prominent ideas that have gained currency.

51.3.1 Multiverses and the Past

One major development is the concept of a multiverse. This idea, that the universe given in the standard model is just one of a plurality of different universes, has become mainstream in cosmology and theoretical physics more generally. Interest in the multiverse derives from influential arguments that claim that the multiverse is a natural consequence of inflationary (Steinhardt, 1983; Vilenkin, 1983; Linde, 1986) and string-theoretic scenarios (Susskind, 2007). On the scenario known as eternal inflation, for example, a physical mechanism creates "bubble universes"—causally disconnected "pocket" universes—out of an inflating background spacetime. Insofar as one takes inflation to be an important part of the contemporary standard model of cosmology (the ΛCDM model), as cosmologists do, one has at least some reason to take the multiverse seriously. And clearly the idea of a multiverse opens up some intriguing new possibilities for the nature of time, possibilities that have only recently been explored.

The basic picture in eternal inflation is that the universe does not "enter into a de Sitter phase," as said above. Instead, the universe *is* essentially de Sitter space. The de Sitter universe is the relativistic spacetime analog of a sphere, just as Minkowski space is the relativistic spacetime analog of a plane. As such, it is the maximally symmetric spacetime with positive curvature (although it can be given a flat spatial slicing like the $k = 0$ FRW spacetime). In cosmology the accelerated expansion of de Sitter space is driven by a cosmological constant-like "inflaton" field in some appropriate potential. If spacetime were merely de Sitter, then nothing much would happen of course, apart from continuous exponential expansion. Quantum fluctuations of the inflaton field, however, can lead patches of spacetime to tunnel to another state and cease inflating, in such a way that a bubble universe may be born in a hot, dense big bang-like state. As bubble universes are continuously born, the space in between the universes continues to expand (although there is generally some probability that bubble universes may collide; these collisions may even leave a detectable footprint in, for example, the CMB). Thus one has an eternally inflating (toward the future) background spacetime which spawns a multiverse of big-bang-universe-like bubble universes, each of which has its own arrow of time, beginning, and (potentially, if it recollapses) ending.[6]

While many questions and concerns arise about the universe, let's focus on the traditional one about whether time is finite or infinite. Singularity theorems à la Penrose, Hawking, and Geroch do not obtain in eternally inflating spacetimes. These theorems make assumptions, typically about the behavior of matter-energy, that are not true in eternal inflation. So we don't have the same assurance that the world begins with a bang in an inflationary scenario as we do in a classical non-inflationary spacetime. Nonetheless, many cosmologists believe that the world still begins with a past singularity. They appeal to influential arguments by Vilenkin, Borde, and Guth that show that the geodesics of the inflationary multiverse scenario (eternal inflation) are past-incomplete, and hence that the inflationary multiverse had a beginning (Farhi and Guth, 1987; Borde and Vilenkin, 1996; Borde et al., 2003). These arguments have been called "singularity theorems" in analogy with the original classical singularity theorems. On the basis of these theorems, it would seem that the fundamental picture of time in the multiverse remains substantively the same as in the standard model, namely, finite to the past and infinite to the future (although of course there is the novelty associated with the birthing of pocket universes, which introduces times local to each universe).

But is that judgment correct? The eternal inflation "singularity theorems" are of quite a different character from those of Penrose, Hawking, and Geroch. They do not, for instance, make any assumptions about the behavior of energy, making them surprisingly general, nor do they apply to all past directed geodesics (past comoving geodesics are allowed to escape to past infinity). The main difference is that the geodesic incompleteness of eternally inflating spacetimes is not due to spacetime singularities but rather due to the spacetime being "incomplete," i.e., extendible. This observation and the physical plausibility of a steady-state-like eternal inflation have led Aguirre and Gratton, for example, to propose an extension which would make eternal inflation "two-sided" and geodesically complete. In their model eternal inflation proceeds in opposite temporal directions from a null boundary between the two regions, each causally-disconnected half of the entire spacetime birthing bubble universes to their respective futures (Aguirre and Gratton, 2002, 2003). Nonetheless, there is a clear sense in which time is infinite in both directions, since the arrows are connected at the boundary. Thus Aguirre and Gratton's clever maneuver would seem to partially restore Kant's old antinomy about the age of the universe, at least for eternally inflating spacetimes, since such spacetimes may seemingly be either finite or infinite toward the past.

51.3.2 Bouncing Through the Big Bang

Dissatisfaction with inflationary theory, a distaste for singularities, or an aversion to multiverses has led many to desire an alternative to the mainstream views in cosmology. Some propose that a big bang singularity can be avoided by a physical mechanism which causes a "bounce" before a singularity is reached. Thereby an old, collapsing (epoch of the) universe leads to a new (epoch of the) universe, one which looks just like the beginning of a classical big bang universe. Although the proposals flowing from the aforementioned motivations differ, they often have similar ideas so it is common to lump them together as the class of "bouncing" or "cyclical" cosmological models.[7] On some models this "bounce" happens only once; on other models it repeats and the universe's growing and shrinking resembles that of a linked set of sausages. In either case, what we thought of as the past-finite universe is only one epoch of a past-infinite universe of multiple epochs.

There are even more exotic possibilities though. Penrose proposes a model he calls the conformal cyclic cosmology: he glues together the "end" of what we thought was our universe, namely the stretched out accelerated infinite expansion, with the beginning of what we thought was our universe, the big bang. He is able to make this identification due to a conjecture that both the beginning and the end are conformally invariant. That is, despite appearing counterintuitive because of their size differences, the metrics describing the beginning and the end are conjectured to be the same except for scale—distances are different but angles are the same. In this theory, what one takes to be inflation is actually the *end* of a previous universe. This process repeats in a cycle and hence is an example of an infinitely recurring universe. Unlike in the "sausage link" model, where contracted big bangs are glued together, the conformal rescaling allows Penrose to glue together large expanded regions with small contracted regions (Figure 51.2).

It should be noted that bouncing and cyclical models do have a long history in cosmological thought, and indeed they have periodically appeared as scientific proposals in the 20th century.[8] Thus the recent spate of them is not entirely a novelty. What is novel is the ever- increasing breadth of these proposals and the ingenious application of theoretical resources. What makes these models more than just an exercise in pure reasoning is that they can be used to make predictions about (what in the standard model would be called) the early universe, in particular the primordial spectrum of

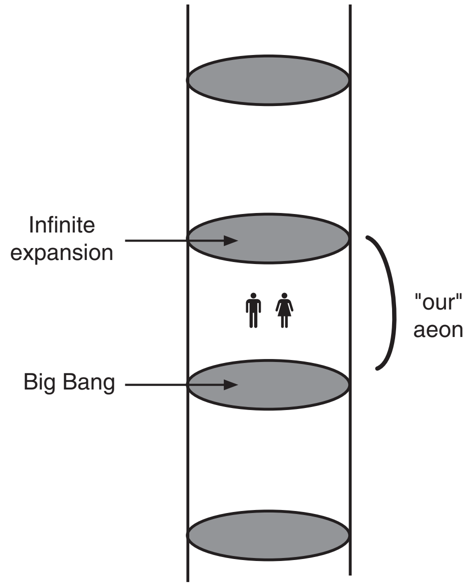

Figure 51.2 Aeons of time in a conformal cyclic universe

inhomogeneities that gave rise to the formation of stars and galaxies. Whether any of the predictions of these higher speculations will be confirmed (or are even confirmable) of course remains to be seen. But for philosophers of time, at least, it is worth noting that for now many of these remarkable proposals provide viable alternatives to the default view that time is finite to the past.

51.3.3 Eliminating the Past Hypothesis

To explain the thermodynamic arrow of time, most physicists and philosophers feel that one must, in some sense or other, assume that the early universe began in a state of extremely low-entropy. Making this assumption, typical initial states will then be overwhelmingly likely to evolve toward higher entropy states. Distinguished physicists such as Boltzmann and Feynman saw the need for such an initial posit and subsequent philosophers have generally agreed with it. Following Albert (2000), this assumption is often dubbed the "past hypothesis."[9]

As noted already, several physicists and philosophers feel that explaining the low-entropy state of the very early universe is one of the great mysteries still remaining in physics. The goal is to find a dynamical origin of the past hypothesis. If one can show that dynamical laws necessitate a low-entropy state in our local past, then we can get rid of the otherwise ad hoc past hypothesis. To this end, several physicists have in recent years proposed cosmological models that do not require the invocation of the past hypothesis (Aguirre and Gratton, 2003; Carroll and Chen, 2004; Barbour et al., 2014; Goldstein et al., 2016). Some of these approaches are closely connected to the topics of the previous subsections: the Carroll and Chen (2004) model, like the Aguirre and Gratton (2003) model,[10] is an eternally inflating multiverse with dual arrows of time, while the Barbour et al. (2014) model is a version of a "one bounce" cosmology driven by gravity.

Cosmological considerations of course have always been at the heart of discussions of time's arrow. Boltzmann's famous cosmological story was in fact not entirely unlike the bouncing universe scenarios. Thermal fluctuations to states of low-entropy are in effect past boundaries for two "universes," each with an oppositely directed arrow of time, pointed in the direction of increasing entropy (Figure 51.3). Later, approximately 30 years after the Hubble expansion of the universe was discovered, the cosmologist Thomas Gold suggested that expansion caused the thermodynamic arrow

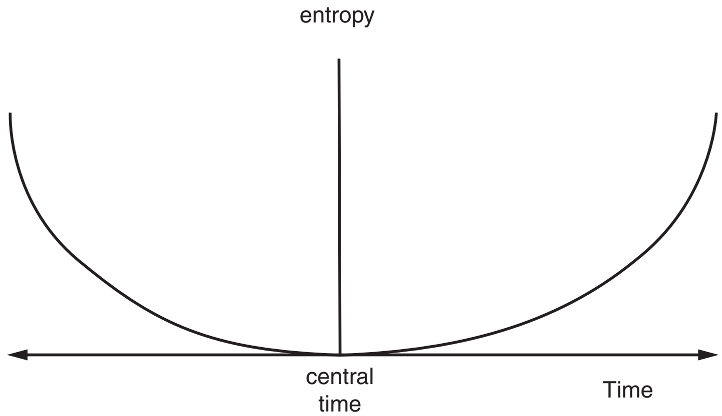

Figure 51.3 The arrow of time aligning with increasing entropy in "two-sided" universes

of time (Gold, 1962). Boltzmann's theory was roundly dismissed when he proposed it, as he wrote well before the advent of modern cosmology. And Gold's idea was criticized by many, as the link between expansion and thermodynamic entropy wasn't as tight as Gold hoped.

In the model of Goldstein et al. (2016), we see something like Boltzmann's original idea being floated again, possibly also connected to something like Gold's original idea. They examine a toy model, a large classical gas of non-interacting particles in Euclidean space. Measuring the size of 3d space occupied by the gas, they find that normal evolution takes the gas to a central time where the gas occupies a uniquely minimum size. They further show that the entropy associated with this measure of system size grows in both temporal directions away from this central time. Each solution comes with its own past hypothesis, if you like, at its central time. No special additional posit is necessary. Interestingly, this is compatible with a Boltzmannian picture of statistical mechanics, one where most microstates realizing low-entropy macrostates evolve into states realizing higher entropy macrostates. This picture is a lot like Boltzmann's original idea, except that the matter and size of the space it occupies grows without bound and hence "bounces" once, unlike in Boltzmann's model. Insofar as the model is connected to expansion, there is also an echo of Gold's idea here too. Gold's idea faltered because there was no necessary link between expansion and entropy increase. Expansion can be an isentropic process, so it is hard to see how it could cause the thermodynamic arrow. Whether the present idea suffers a similar fate, however, remains to be seen.

Notes

1. (Dainton 2010) is a good philosophical introduction to the philosophy of space and time. (Smeenk 2013) provides an accessible review on the topic of time in cosmology. (Harrison 2000) is a classic physics text on cosmology that is more oriented toward history and philosophy than usual. (Kragh 1996) and (Longair 2006) are useful historical references for 20th century cosmology.
2. See Anderl's contribution to this volume for more details on issues with astrophysical evidence.
3. For more on dark energy and dark matter, see Jacquart's contribution to this volume. For more on inflation, see Ijjas's contribution to this volume.
4. See Eagle's contribution to this volume for more on this threat.
5. See, e.g., (Earman 1995) for discussion of singularities and (Callender 2004) and (Price 2004) on the low-entropy posit.
6. See Ijjas's contribution to this volume for more on eternal inflation.
7. Prominent examples include those discussed in (Khoury et al. 2001); Steinhardt and (Turok 2007); (Ashtekar 2009); (Penrose 2010). A recent review of bouncing models is (Battefeld and Peter 2014).
8. A fine survey of this history can be found in (Kragh 2011, Ch. 8).
9. See Shahvisi's contribution to this volume for more on the past hypothesis and entropy increase.
10. See (Vilenkin 2013) for discussion of these models in relation to the arrow of time.

References

Aguirre, A. and Gratton, S. (2002). Steady-state eternal inflation. *Physical Review D*, 65: 083507.

Aguirre, A. and Gratton, S. (2003). Inflation without a beginning: A null boundary proposal. *Physical Review D*, 67: 083515.

Albert, D. (2000). *Time and Chance*. Cambridge, MA: Harvard University Press.

Andersson, L., Barbot, T., Béguin, F. and Zeghib, A. (2012). Cosmological time versus CMC time in spacetimes of constant curvature. *Asian Journal of Mathematics*, 16(1): 37–88. http://projecteuclid.org/euclid.ajm/1331663451.

Ashtekar, A. (2009). Loop quantum cosmology: An overview. *General Relativity and Gravitation*, 41: 707–741.

Barbour, J., Koslowski, T. and Mercati, F. (2014) Identification of a gravitational arrow of time. *Physical Review Letters*, 113: 181101.

Battefeld, D. and Peter, P. (2015). A critical review of classical bouncing cosmologies. *Physics Reports*, 571: 1–66.

Beisbart, C. and Jung, T. (2006). Privileged, typical, or not even that?—Our place in the world according to the Copernican and the cosmological principles. *Journal for General Philosophy of Science*, 37: 225–256.

Borde, A., Guth, A. and Vilenkin, A. (2003). Inflationary spacetimes are incomplete in past direction. *Physical Review Letters*, 90: 151301.

Borde, A. and Vilenkin, A. (1996). Singularities in inflationary cosmology: A review. *International Journal of Modern Physics D*, 5: 813–824.

Bourne, C. (2004). Becoming inflated. *British Journal for the Philosophy of Science*, 55: 107–119.

Butterfield, J. (2014). On under-determination in cosmology. *Studies in History and Philosophy of Modern Physics*, 46: 57–69.

Callender, C. (2004). There is no puzzle about the low-entropy past. In C. Hitchcock (ed.), *Contemporary Debates in the Philosophy of Science*. Hoboken: Wiley-Blackwell, chapter 12, pp. 240–255.

Callender, C. (2017). *What Makes Time Special?* Oxford: Oxford University Press.

Canales, J. (2015). *The Physicist & the Philosopher*. Princeton, NJ: Princeton University Press.

Carroll, S. (2010). *From Eternity to Here*. New York: Plume.

Carroll, S. and Chen, J. (2004). *Spontaneous inflation and the origin of the arrow of time*. ArXiv Eprint. http://arxiv.org/abs/hep-th/0410270.

Crisp, T. (2008). Presentism, eternalism, and relativity physics. In W.L. Craig and Q. Smith (eds.), *Einstein, Relativity and Absolute Simultaneity*. New York: Routledge, pp. 262–278.

Dainton, B. (2010). *Time and Space* (2nd edition). Durham: Acumen Press.

Earman, J. (1995). *Bangs, Crunches, Whimpers, and Shrieks*. Oxford: Oxford University Press.

Eddington, A. (1920 [1987]). *Space, Time and Gravitation*. Cambridge: Cambridge University Press.

Ellis, G. (2007). Issues in the philosophy of cosmology. In J. Earman and J. Butterfield (eds.), *Philosophy of Physics*, Vol. B of *Handbook of the Philosophy of Science*. Amsterdam: Elsevier, pp. 1183–1285.

Farhi, E. and Guth, A. (1987). An obstacle to creating a universe in a laboratory. *Physics Letters B*, 183: 149–155.

Gold, T. (1962). The arrow of time. *American Journal of Physics*, 30: 403–410.

Goldstein, S. Tumulka, R. and ZanghÌ, N. (2016). Is the hypothesis about a low entropy initial state of the Universe necessary for explaining the arrow of time? *Physical Review D*, 94: 023520.

Harrison, E. (2000). *Cosmology: The Science of the Universe* (2nd edition). Cambridge: Cambridge University Press.

Hawking, S. (1969). The existence of cosmic time functions. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science*, 308: 433–435.

Jeans, J. (1935). Man and the universe. In J. Jeans (ed.), *Scientific Progress*. London: Allen & Unwin, pp. 1–12.

Khoury, J., Ovrut, B., Steinhardt, P. and Turok, N. (2001). Ekpyrotic universe: Colliding branes and the origin of the hot big bang. *Physical Review D*, 64: 123522.

Kragh, H. (1996). *Cosmology and Controversy*. Princeton, NJ: Princeton University Press.

Kragh, H. (2011). *Higher Speculations*. Oxford: Oxford University Press.

Linde, A. (1986). Eternally existing self-reproducing chaotic inflationary universes. *Physics Letters B*, 175: 395–400.

Longair, M. (2006). *The Cosmic Century*. Cambridge: Cambridge University Press.

Lucas, J. and Hodgson, P. (1990). *Spacetime and Electromagnetism*. Oxford: Oxford University Press.

Marsden, J. and Tipler, F. (1980). Maximal hypersurfaces and foliations of constant mean curvature in general relativity. *Physics Reports*, 66: 109–139.

Misner, C. (1969). Absolute zero of time. *Physical Review*, 186: 1328–1333.

Penrose, R. (2010). *Cycles of Time*. London: Bodley Head.

Price, H. (2004). On the origins of the arrow of time: Why there is still a puzzle about the low-entropy past. In C. Hitchcock (ed.), *Contemporary Debates in the Philosophy of Science*. Hoboken, NJ: Wiley-Blackwell, pp. 219–239.

Qadir, A. and Wheeler, J.A. (1985). York's cosmic time versus proper time as relevant to changes in the dimensionless "constants", K-meson decay, and the unity of black holes and big crunch. In E. Gotsman and G. Tauber (eds.), *From SU(3) to Gravity*. Cambridge: Cambridge University Press, pp. 383–394.

Rendall, A. (1996). Constant mean curvature foliations in cosmological spacetimes. *Helvetica Physica Acta*, 69: 490–500.

Roser, P. and Valentini, A. (2014). Classical and quantum cosmology with York time. *Classical and Quantum Gravity*, 31: 245001.

Smarr, L. and York, J. (1978). Kinematic conditions on the construction of spacetime. *Physical Review D*, 17: 2529–2551.

Smeenk, C. (2013). Time in cosmology. In A. Bardon and H. Dyke (eds.), *A Companion to the Philosophy of Time*. Oxford: Wiley-Blackwell, pp. 201–219.

Steinhardt, P. (1983). Natural inflation. In G. Gibbons, S. Hawking and S. Siklos (eds.), *The Very Early Universe*. Cambridge: Cambridge University Press, pp. 251–266.

Steinhardt, P. and Turok, N. (2007). *Endless Universe*. New York: Doubleday.

Susskind, L. (2007). The anthropic landscape of string theory. In B. Carr (ed.), *Universe or Multiverse*. Cambridge: Cambridge University Press, pp. 247–266.

Swinburne, R. (2008). Cosmic simultaneity. In W.L. Craig and Q. Smith (eds.), *Einstein, Relativity and Absolute Simultaneity*. New York: Routledge, pp. 244–261.

Vilenkin, A. (1983). The birth of inflationary universes. *Physical Review D*, 27: 2848–2855.

Vilenkin, A. (2013). Arrow of time and the beginning of the universe. *Physihcal Review D*, 88: 043516.

York, J. (1972). Role of conformal three-geometry in the dynamics of gravitation. *Physical Review Letters*, 28: 1082–1085.

Further Reading from the Editors

In this volume, Chapter 25 by N. Huggett on time as emergent and Chapter 26 by K. Thébault on the problem of time are both relevant here. C. Smeenk, "Time in Cosmology", in A. Bardon and H. Dyke (eds.), *The Blackwell Companion to the Philosophy of Time* (Oxford: Blackwell, 2013): pp. 201–219 is an additional general survey of the present topic. J. Earman, *Bangs, Crunches, Whimpers and Shrieks* (New York: Oxford University Press, 1995) provides a review of relevant technical material. C. Callender, *What Makes Time Special?*. (Oxford: Oxford University Press, 2017) explores the question of what distinguishes time from other physical dimensions. S. Carroll, *From Eternity to Here* (New York: Plume, 2010) is a big-picture overview directed at a popular audience.