Cosmology[1]

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Introduction

Cosmology is the study of the large-scale structure of the universe and its evolution. Since the ancient Greeks first proposed rational accounts of the origins and structure of the cosmos more than two millennia ago, philosophers, theologians, and scientists have pursued a variety of starkly different cosmologies. The twentieth century was a golden age of physical cosmology, with observational and theoretical advances leading to a cosmological Standard Model by the early 1970s. This model describes the universe as expanding from a hot, dense earlier state --- often referred to as the "big bang" --- with structures such as galaxies forming later due to gravitational clumping. Contemporary cosmology draws on virtually all fields of physics to give an account of the origin and development of the universe and structures within it. Since 1960 cosmology has developed into a mature scientific field, with substantial empirical support marshaled in favor of an impressively detailed history of the universe.

This substantial progress has not been accompanied by the resolution of basic questions about the appropriate aims and methods of cosmology. Does cosmology have a distinctive method, or limited aims, because it is the study of a unique object? Are there distinctive challenges to assessing cosmological theories? These questions have not been answered so much as set to one side. Cosmologists have justly celebrated the dawn of a new era of "precision cosmology" with rich data sets envied by their colleagues in experimental particle physics, and this success has led to a more ambitious agenda. On one front, cosmologists have claimed to resolve empirically long-standing questions regarding the origins of the universe. Although these claims are contentious, cosmology has clearly transformed traditional debates. Furthermore, cosmology now serves as the primary testing ground for many ideas in fundamental physics. Yet it is unclear whether cosmological observations can guide the development of theories as successfully as experimental research has guided other areas of physics.

This essay focuses on two central themes in philosophical reflections on cosmology – underdetermination and modalities. Kant argued that cosmological questions lead to antinomies because there cannot be an object of possible experience

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corresponding to the idea of the "universe." Treating the "universe" as an object of experience would require a completed synthesis of the infinite totality of everything in space and time, requiring an illegitimate extension of a concept of the understanding. Few would currently accept Kant's skepticism regarding the possibility of scientific cosmology, but it is common to argue that cosmology nevertheless faces unique evidential challenges. The first section below considers arguments to the effect that cosmology cannot discover new laws of nature, due to the difficulty with delineating law-like necessities from contingent facts. I then turn to two different senses of underdetermination in cosmology. First, due to the existence of a maximum signal speed, any observer will have access to only part of the spacetime she inhabits. As a consequence, the global properties of spacetime geometry cannot be conclusively established even by ideal observations. The second type of underdetermination is more closely tied to contemporary debates. Current conventional wisdom attributes 96% of the total mass-energy density to new *types* of matter. Yet inference to these new types of matter involve various assumptions and extrapolations of existing theories, raising the possibility that an alternative gravitational theory might save the phenomena without new types of matter. The final section takes up the most distinctive issue in philosophy of cosmology: how should we explain the origin of the universe? I briefly sketch three quite different approaches to this question.

The brief reviews of these topics should give some flavor of the debates within this field. I have focused on issues closely tied to topics familiar to philosophers of science, without pretending to provide a comprehensive survey. Furthermore, since cosmology draws on nearly every aspect of physics, it inherits related foundational problems. For example, the measurement problem of quantum mechanics resurfaces in the account of the origin of galaxies, which the Standard Model traces back to fluctuations in quantum fields in the early universe. The suggestions for further readings at the end of this chapter include more comprehensive surveys, as well as articles on topics not discussed below.

Laws in Cosmology

Typically physics aims to describe isolated subsystems of the universe, and laws and initial conditions play different modal roles in this description. The laws capture relationships among quantities possessed by the system that hold by necessity, in some sense, whereas the initial conditions reflect contingent, accidental features. Operationally this distinction is manifest in an ensemble of similar systems: the laws hold for all of the members of the ensemble, whereas the initial conditions vary. An experimenter may create an ensemble in the lab by varying the starting set-up of a repeated experiment. An ensemble can also be studied observationally by finding common features of a class of objects --- as, e.g., in establishing that there is a law-like relationship between the shape of the light curve and intrinsic luminosity of a particular type of supernovae. Yet neither way of drawing the contrast applies to cosmology due to the uniqueness of the universe. Many conclude directly that there is no useful application of the concept of a "law of nature" in cosmology (see, e.g., Bondi 1948, Munitz 1962, Ellis 2007). Cosmology is then classified as a "historical" rather than "law-seeking" science, more akin to paleontology and evolutionary biology than to other areas of physics.

This argument is only as good as the starting assumption regarding how to draw the contrast between laws and initial conditions. This account, while quite intuitive, overlooks the possibility that the role of laws in giving successively more refined descriptions of a single system reflects their modal status. For example, the gravitational force law remained fixed in astronomers' models of the solar system for over two centuries. The continued success of these models arguably supports the claim that the gravitational force law should qualify as a law, without appeal to an ensemble of systems or experimental variation of initial conditions. This suggests that an analogous claim may play the epistemic role of a law, even in cosmology. The bearing of this point on ontic arguments against the applicability of the laws / initial conditions contrast to a single system depends on one's analysis of laws.

There is a further ambiguity regarding what kind of "law" is being considered. Nearly everything bearing the label "law" in a contemporary cosmology textbook is a local dynamical law, such as the field equations of general relativity, extrapolated to apply to the universe as a whole. Such laws do have the "multiplicity" this argument demands, in the sense that they apply to subregions of the universe, each treated as an individual system. There are candidates, however, for distinctively cosmological laws that cannot be regarded as extrapolations of local dynamics. A law stating, for example, that the universe is spatially bounded (as defined below) would apply to the universe as a whole but not subregions. Such laws do raise distinctive epistemic challenges, due to the inaccessibility of global properties of the universe.

Global Properties

Cosmologists face a distinctive challenge in establishing the global properties of spacetime. In theories such as Newtonian mechanics, spacetime geometry is postulated to have certain global properties. But the laws of general relativity permit a bewildering variety of spacetime geometries, with dramatically different global properties. Can the global spacetime geometry of the universe be determined by observation rather than postulation? The question is not whether the evidence dictates the appropriate theory to use in cosmology; instead, assuming the validity of the relevant theories – general relativity and other theories needed to interpret the data -- are observations sufficient to fix the best model, that is, the best spacetime geometry?

The answer is no, even for "ideal" observers who are able to learn as much as possible about spacetime geometry from observations. Two features of general relativity lead to this result. First, because there is a maximum signal speed, any point within spacetime can only receive signals from a limited region of the spacetime, namely, the past light cone for that point. Second, general relativity places very weak constraints on global spacetime geometry. The dynamical equations require that *locally* there is a specific relationship between spacetime geometry and the energy and matter present, but there are few *global* constraints.

As an example of a global property, consider whether the universe is spatially bounded --- roughly, whether there is a maximum spatial distance between any two points. (More precisely, we will take a spacetime that admits a preferred way of being sliced into three-dimensional surfaces ("space at a moment of time") to be bounded if and only if there is a maximum spatial distance between any two points lying within the same slice.) Whether spacetime is bounded depends on how matter is distributed throughout spacetime and how it moves, not just on the dynamics. The same is true for other global properties.

As a consequence of these two features, even an ideal observer, who can establish everything about the spacetime geometry of her past light cone, cannot determine the *global* properties of the entire spacetime. The idea behind the proof of this result (due to Manchak 2009, drawing on earlier work of Glymour and Malament), though not the proof itself, is simple. Consider a given spacetime with some specific global property, such as being spatially bounded, along with a collection of "pieces" consisting of the past light cone for every point in the spacetime. These pieces can be stitched together along with some other material, as in a patchwork quilt, to create a *different* spacetime that includes all the original pieces. Generally the constructed counterpart will not have the same global properties as the original spacetime --- continuing with the example, one can construct an unbounded spacetime from the pieces of a bounded spacetime (using multiple copies of some pieces). Yet every observer in the first spacetime will find an *exact copy* of her past light cone in the new spacetime, by construction. On what basis could our observer assert that she is in a bounded spacetime rather than its unbounded counterpart? And on what basis could she make any claims regarding the global properties of the spacetime she inhabits?

Accepting the *cosmological principle* would allow the observer to draw such conclusions. This principle holds that spacetime geometry is maximally symmetric – more precisely, homogeneous and isotropic – such that any observer's view of the universe is equivalent to any other. Requiring this symmetry rules out the crazy-quilt constructions described above. Appealing as this principle may be, it is itself a *global* claim about spacetime geometry. So we have pushed our question back one step: what is the status of the cosmological principle? Cosmologists have taken a variety of positions on this question, treating the cosmological principle as (nearly) everything from a simplifying assumption to a necessary presupposition of cosmological theorizing (cf. Beisbart 2009). As an appealing alternative, one might hope that a stage of dynamical evolution in the early universe reliably leads to a "uniform" later state such that the cosmological principle (or something akin to it) holds (as discussed below). Confidence about extrapolations beyond our past light cone would then depend on the justification for such an account of the universe's history, and the cosmological principle would be rightly regarded as a factual claim regarding the universe rather than an *a priori* principle or convenient simplification.

This underdetermination of global properties of spacetime contrasts with a more threatening variety that has been a long-standing focus of philosophical debates. The validity of the various theories in play, from general relativity to other theories used to interpret the data, is not in dispute here. Manchak's theorem shows, rather, that the facts available to our ideal observer, in conjunction with the relevant theories, do not suffice to dictate a unique choice of global spacetime geometry. The best response is arguably to adopt a "resigned agnosticism" regarding global features of the universe (as Wilson 1980 puts it). Furthermore, remaining agnostic about whether the universe is bounded or unbounded, for example, has little if any direct relevance to empirical research in cosmology. By way of contrast, philosophers have often argued that evidence is not sufficient to decide between genuine rivals such as general relativity and alternative gravitational theories. Underdetermination in this second sense, illustrated in the next section, poses a direct threat to empirical research in cosmology, to the extent that inferences based on general relativity fail in rival theories.

Dark Matter and Dark Energy

According to contemporary cosmology, the ordinary matter of which mice and men are made contributes only approximately 4 % of the universe's total mass-energy. The rest comes in the form of distinctive *types* of matter that escape notice except by their gravitational effects, namely dark matter (22 %) and dark energy (74 %). Neither can be directly detected based on emitted radiation, unlike luminous matter such as stars. The presence of dark matter is arguably revealed by, for example, the motion of stars within galaxies as well as the motions of galaxies themselves, and that of dark energy is revealed by the accelerating expansion of the universe. Both dark matter and dark energy seem to play crucial roles in the formation of structures such as galaxies. These claims depend upon gravitational theory and other aspects of the Standard Model of cosmology.

In connection with our theme of underdetermination, it is natural to question the status of these inferences, which involve tremendous extrapolations of general relativity beyond the scales at which it has been successfully tested. Should the need for new types of matter be regarded as anomalies for the gravitational theory, an indication that the extrapolation is not correct, rather than striking discoveries?

How strong is the evidence in favor of dark matter and dark energy (hereafter, DME), given the possibility that there may be alternative theories that save the phenomena without needing them? (Using DME has the drawback, as with WMD for "weapons of mass destruction," of implying too much similarity between the items lumped together; the nature and status of dark matter and dark energy differ in important ways that we do not have the space to explore here.) This area of research is philosophically intriguing because it reveals a great deal about theory choice in the face of underdetermination.

Most cosmologists have accepted DME, and the following three considerations are crucial. First, the relevant inferences involve weak gravitational fields at large length scales. No one expects general relativity to be preserved by subsequent theories in some domains, for example at sufficiently short length scales or in the presence of strong gravitational fields, due to the need to include quantum effects. A failure of general relativity in the regime relevant to the inferences regarding DME, by contrast, would be surprising; the failure of *Newtonian* gravity at low accelerations (regarded as a limit of general relativity), needed to avoid dark matter, would be shocking. Aside from confidence in current theories in the relevant domain, DME are supported by a variety of evidence. Several lines of evidence with different theoretical underpinnings and sources of systematic error yield compatible estimates of the amount of DME. Finally, the mainstream position converts observational discrepancies in cosmology into problems in particle physics: to provide physical accounts of these new types of matter. These are significant challenges. But these new types of matter are not clearly ruled out by current theories; instead, there are a variety of ways to account for DME.

Critics of DME regard the flexibility of current theories as a liability, perhaps too readily exploited to avoid anomalies. Rather than reconsidering the gravitational theory or cosmological model, the mainstream cosmologist adds new types of matter *ad hoc* as needed to save the phenomena. The alternative is to modify the gravitational theory or cosmological model. A theory called modified Newtonian dynamics (MOND) appears to capture various aspects of galaxy phenomenology without dark matter by changing the Newtonian gravitational force law. Some of the evidence for dark energy can be accommodated without modifying the gravitational theory, but instead adopting a cosmological model that places our galaxy at the center of an enormous bubble of lower density. The accelerated expansion typically taken as a dynamical consequence of dark energy would then be a consequence of our special position in a non-uniform distribution of matter. These are two interesting proposals (out of several) that eschew DME, and neither is as fully developed and comprehensive as the Standard Model. Yet, if these proposals do lead to consistent theories (certainly a big "if"), they pose an important challenge: perhaps all available evidence will not be sufficient to decide between modifying the matter distribution or gravitational theory. (Albeit there is not always a clear contrast between the two.)

This debate functions at two levels, with detailed evaluations of particular proposals considered alongside more general questions regarding appropriate criteria for theory choice. With regard to evaluating specific proposals, underdetermination may prove to be transient. There are appealing prospects for new sources of evidence regarding dark matter, actively being pursued at the time of writing. Experimental direct detection of a dark matter candidate would be particularly convincing. Experiments currently underway use cryogenically cooled solid state detectors, which (roughly) register the scattering of dark matter particles off of nuclei. A successful test of this sort would be almost entirely independent of gravity and cosmology.

Yet it is clear that, even without such decisive new results, scientists do not assign equal degrees of confidence to the various proposals. How to assign degrees of confidence rationally is the focus of the more general debate. For many scientists, proper assessment of the competitors depends on issues such as the expected domains of applicability of a given theory and its relationship to other theories. Critics of MOND, for example, emphasize that it is hard to reconcile with the insights of general relativity. There are also debates regarding the appropriate goals of the competing theories: MOND arguably accounts for various aspects of galactic phenomenology more successfully than the Standard Model, whereas the Standard Model fares better than MOND in account for large-scale structure. The computational complexity of the Standard Model's account of structure formation has made it difficult to assess whether it can account for smaller scale structures, with newer simulations producing structures that look more like real galaxies. Even if this remains a legitimate criticism of the Standard Model, one is left with comparing the successes of two competing theories in different regimes. Finally, whether the pessimist is right to claim that underdetermination will persist depends upon how one characterizes empirical success. There are many ways in which DME are revealed, each depending on different aspects of the cosmological model and gravitational theory. More carefully tracking these dependencies allows one to assess the degree to which different measurements rest on independent assumptions. This is important if one characterizes the success of a theory (as defended by Harper 2011) in terms of the degree to which a variety of independent sources of evidence constrain the parameters appearing in the theory. (In this case, the "parameters" characterize the quantity and distribution of DME.) The Standard Model with DME may fare better on this account than its competitors, even if it is not vindicated via new experiments or observations.

Origins

The most significant and distinctive question in philosophy of cosmology concerns the origin of the universe. Why does the universe exist, and how should its origin be explained? If the universe is eternal, as in many cosmologies of past eras, there is no “creation” to be explained, although one may still ask why one eternal cosmos rather than another is actual. According to the Standard Model, time is finite to the past. Extrapolating backwards from the observed universe, matter in the early universe was in a hot, dense state. There are a variety of ways in which this initial state seems quite “improbable.” How should we understand or explain this starting point for the Standard Model?

But, first, in what sense does the Standard Model require an “initial state” at all? Time is finite to the past in the sense that a particular class of curves, representing possible trajectories of freely falling observers, must have finite length. This length represents time elapsed along the trajectory “since the big bang,” where the “bang” is an initial singularity. This singularity was initially regarded as an artifact of the idealizations employed in the simplest cosmological models, but the singularity theorems established in the 1960s showed that the existence of an initial singularity follows from much more general assumptions. The initial state is not specified “at the singularity” itself because the singularity is not a region within spacetime – it is an ideal point. Physicists usually take the initial state to be specified at the limits of applicability of general relativity, where we can still make sense of spacetime geometry. Describing earlier times presumably requires insights from a theory of quantum gravity. Quantum gravity may also revive the possibility of a “cyclic” cosmology by allowing an extension through the initial singularity, in which case the “initial” state would register the impact of an earlier phase of the universe’s history.

Physicists routinely reject one way of explaining the initial state. In many other areas of physics, the state of a given system at an arbitrary time can be used, in conjunction with the laws, to explain the state of the system at other times (giving a Hempelian D-N explanation). Why the state at that time obtained is treated as a contingent fact. As such it is not usually the target of why questions, although one may be able to answer such questions by appealing to the larger environment of which the system is a part. By way of contrast, most cosmologists are not content to explain the early state of the universe as simply the one required to evolve into what we now happen to see. There is a strong rationalist impulse to explain why this state must have obtained, or to shift the explanatory burden to the dynamics.

The demand for a deeper explanation is motivated in part by the striking “improbability” of the initial state required by the Standard Model. Several features of the early universe appear to be finely-tuned, in the sense that they must be almost precisely as they are to yield a universe as complex, and suitable for life, as our own. To take two prominent examples, observations of the background radiation left over from the early universe indicate that distant regions were at very nearly the same temperature. This uniform temperature cannot be explained in the same way as the uniform temperature of, say, the coffee in my cup, because the distant regions cannot causally interact; instead, this striking uniformity has to be posited as a feature of the initial state. Second, the observed rate of expansion of the universe is close to the critical rate separating contraction back into a "Big Crunch" from never-ending expansion. This is striking because if the expansion rate is not exactly critical, the difference between the expansion rate and the critical rate increases with time as a result of the dynamics. Finding a system close to such a dynamically unstable state is like finding a needle balanced on its point. The universe must have been *incredibly* close to the critical rate initially for it to be as close to the critical rate now as observations indicate. This is usually called the *flatness problem* because the model with critical expansion rate has a flat spatial geometry. These two features, and others, raise explanatory challenges: why does the early universe exhibit such glorious pre-established harmony between distant regions? How was the initial expansion rate so delicately chosen?

There are three main lines of response to these challenges:

1. *New Physics*

   By far the most influential response to these challenges is to supplement the Standard Model with a new account of dynamical evolution in the early universe, such that the dependence on a finely-tuned initial state is reduced. Guth (1981) made a persuasive case for inflationary cosmology along these lines. His proposal replaced the normal expansion supposed to hold in the Standard Model in the very early universe (at roughly 10^{-35} seconds) with a brief burst of exponential expansion. This growth spurt resolves both problems noted above (as well as other fine-tuning problems): inflation stretches and flattens the universe, and causal interactions among distant regions we observe are possible since these regions all originate from a small pre-inflationary patch. This answers the explanatory challenge as follows: a "generic" initial state chosen *before* inflation evolves into a uniform, flat state that is an appropriate starting point for the Standard Model. This reflects a preference for explanations that are "robust" in the sense that they do not depend on a quite specific initial state.

   A very different approach that also involves new physics draws inspiration from the problems of time's arrow in thermodynamics. Almost all fundamental laws of physics are time-reversal invariant in the sense that, for any given sequence of states that is allowed by the laws, the "time-reversal" is also allowed. This lack of a preferred directionality conflicts with processes we see everyday that do have a preferred direction, such as an egg falling to the floor and cracking, as opposed to an egg re-assembling and flying back onto the counter. The laws of thermodynamics capture this lack of reversibility, yet apparently conflict with the time-reversal invariant laws of mechanics presumably governing the egg. In the 1870s Boltzmann speculated that the answer lies in a posit regarding the initial state: although the time-reverse of an egg cracking is possible, it is extremely unlikely given that the universe began in a particular (low entropy) initial state (cf. Albert 2000). Neo-Boltzmannians in cosmology (notably Penrose 1979) also explain several features of the Standard Model as reflecting a particular choice of the initial state. This approach is diametrically opposed to the dynamical approach discussed above, in which the imprint of a "generic" initial state is washed away by subsequent dynamics. Instead, an apparently quite special initial state is posited, much as Boltzmann suggested.

Advocates of this "theory of initial conditions" approach further propose new physical laws that constrain the allowed initial states to explain why such a state obtained. The proposed laws directly apply to the initial state, rather than, like inflation, the subsequent dynamical evolution. Different philosophical accounts of laws render conflicting verdicts regarding whether a global constraint on the initial state should be regarded as a law. On a Mill-Ramsey-Lewis approach to laws, for example, a constraint on the initial state will quite plausibly be one of the axioms in best system (see "Laws of Nature") and hence qualify as a law. On the other hand, views that treat laws as a special type of causal relationship will lead to the opposite conclusion. Yet in either case it seems that the constraint on the initial state will have a special explanatory role.

2. *Anthropic Explanation*

What kind of universe could lead to creatures like us? The carbon that proves to be so useful in building complex molecules originates in the death throes of stars. There must then be a first generation of stars to produce carbon and other heavy elements and scatter them into the interstellar medium, along with a second generation of stars heating and illuminating planets rich in these heavy elements, providing evolution time to explore design space. A universe with an expansion rate much lower than the critical rate would recollapse too quickly for this to occur, whereas a universe with an expansion rate much higher than the critical rate would expand too quickly for galaxies, and stars, to form at all. Pursuing this line of thought leads to a different assessment of the delicate choice of an initial expansion rate: it is a necessary condition for our existence. A similar argument led Collins and Hawking (1973) to explain the uniformity of the universe as a consequence of our existence. If we consider an ensemble of universes generated by varying the initial state, they proposed, we would naturally find ourselves in a universe with an initial state that is compatible with our existence. The response has come to be called an "anthropic explanation" (see, e.g., Earman 1986, McMullin 1993 and Roush 2003 for general discussions).

Recent developments within string theory and inflationary cosmology provide speculative mechanisms for generating such an ensemble, often called a *Multiverse*. Roughly put, these ideas suggest that at the largest scales the Multiverse consists of worlds within worlds, each with different physical features (such as, but not limited to, different values of the initial expansion rate). These scenarios have been extensively studied recently as a way of accounting for dark energy. Attempts to calculate the amount of dark energy based on quantum field theory lead to wildly inaccurate results. But if the Multiverse generator leads to an ensemble of worlds with different values of dark energy, we can reason (as above) that only a value close to the observed value is compatible with our existence. The Multiverse picture makes it possible to explain various features of our universe as consequences of a selection effect. Just as we find ourselves in the habitable zone of the solar system, we also find ourselves in a habitable region of the Multiverse. Whether this provides a successful response to the explanatory challenge is quite contentious. Discovering that feature *X* of the initial state is a necessary pre-condition of our existence may reduce our surprise at seeing *X*. But does the original challenge demand a deeper explanation than this?

A very different kind of anthropic explanation appeals to an intentional or goal-directed Creation, with the initial state chosen so that intelligent life will eventually arise. This theistic explanation does not directly address the physical concerns that raised the original explanatory challenge, because the mechanism for choosing the initial state does not fall within the domain of physics. Advocates of this approach will insist on a change of venue: having reached the limits of explanation within physics, we should consider an alternative explanatory framework that can address further questions. There are currently lively debates among philosophers and cosmologists comparing the explanatory virtues and vices of Multiverse and theistic approaches (the essays in Carr 2007 provide a recent overview).

Finally, there are separate questions regarding how to precisely characterize anthropic reasoning. Some physicists (notably Weinberg 2007) have argued that anthropic reasoning is a crucial new aspect of theory assessment that has to be confronted in cosmology. Yet there is little agreement regarding the details of anthropic reasoning, including on basic questions such as whether new “anthropic” principles are needed to supplement standard inductive methodology.

3. *Reject Explanatory Demand*

Perhaps the problem lies not with the finely-tuned initial state itself but with the demand for an “explanation” of it. Empiricists have often objected to overuse of the Principle of Sufficient Reason, and press shop-worn criticisms of the traditional argument from design back into use here (see, in particular, Callender 2004). The initial state seems as good a candidate as any for a brute fact, or appropriate explanatory stopping point. To make a compelling case, the empiricist needs to distinguish between the inappropriate rationalist demands for explanation and the legitimate problems with contemporary theory. The Standard Model is clearly not a complete, flawless cosmological theory, and there are good reasons to expect that it should be supplemented. What the empiricist rejects, more precisely, is the claim that an otherwise empirically adequate theory should be regarded as unsatisfactory insofar as it requires a "finely-tuned" initial state.

The empiricist reply can be further defended with a critical assessment of the arguments regarding the "improbability" of the initial state. The sheen of quantitative precision rubs off the fine-tuning arguments once one asks how these probabilities are assessed, for there is little agreement on how to define a measure on the space of possible cosmological models or on what such a measure might mean. Should these probabilities be regarded as the objective chance that a universe with a particular initial state is "actualized," perhaps by the Creator hitting it with a dart thrown at the space of possible models? And which dartboard is chosen as the target? In the absence of a more secure theoretical description of the physics of the very early universe, it is not clear what space of models should be considered.

The assessment of these responses touches on central topics in general philosophy of science, such as scientific explanation, laws, and confirmation theory, along with more technical issues.

References

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

Beisbart, Claus (2009). "Can we justifiably assume the cosmological principle in order to break model underdetermination in cosmology?" *Journal for General Philosophy of Science* **40**: 175-205.

Bondi, Herman (1948). "Review of Cosmology," *Monthly Notices of the Royal Astronomical Society* **108**: 104 – 120.

Callender, Craig (2004). "Measures, explanations and the past: Should special initial conditions be explained?" *The British Journal for the Philosophy of Science* **55**: 195–217.

Carr, Bernard, ed. (2007). *Universe or Multiverse?* Cambridge: Cambridge University Press.

Collins, C. B. and Hawking, Stephen (1973). "Why is the universe isotropic?" *Astrophysical Journal* **180**: 317–334.
Earman, John (1986). "The SAP also Rises: A critical examination of the anthropic principle." *American Philosophical Quarterly* **24**: 307–317.
Ellis, George (2007). "Issues in the philosophy of cosmology." In *Handbook for the Philosophy of Physics*, J. Earman and J. Butterfield, eds., vol. Part B. Elsevier, 1183–1286.
Guth, Alan (1981). "Inflationary universe: A possible solution for the horizon and flatness problems." *Physical Review* **D 23**: 347–56.
Harper, William (2011). *Isaac Newton's Scientific Method: Turning Data into Evidence about Gravity & Cosmology*. Oxford: Oxford University Press.
Manchak, John (2009). "Can we know the global structure of spacetime?" *Studies In History and Philosophy of Modern Physics* **40**: 53–56.
McMullin, Ernan (1993). "Indifference principle and anthropic principle in cosmology." *Studies in the History and Philosophy of Science* **24**: 359–389.
Munitz, Milton (1962). "The logic of cosmology." *British Journal for the Philosophy of Science* **13**: 34–50.
Penrose, Roger (1979). "Singularities and time-asymmetry." In *General Relativity: An Einstein Centenary Survey*, ed. by Hawking and Israel. Cambridge: Cambridge University Press, 581–638.
Roush, S. (2003). "Copernicus, Kant, and the anthropic cosmological principles." *Studies In History and Philosophy of Modern Physics* **34**: 5–35.
Weinberg, Steven (2007). "Living in the multiverse." In *Universe or multiverse*, ed. by B. Carr. Cambridge: Cambridge University Press, 29–42.
Wilson, Mark (1980). "On the Observational Uniqueness of some Theories," *Journal of Philosophy* **77**: 207-233.

Further Reading

Ellis (2007) provides the most comprehensive recent survey of issues in philosophy of cosmology; see also my survey, "Philosophy of Cosmology," in *The Oxford Handbook of the Philosophy of Physics*, ed. by Robert Batterman (Oxford: Oxford University Press, 2012). *Modern Cosmology and Philosophy*, ed. by John Leslie (Amherst, NY: Prometheus, 1998) includes a number of articles by physicists and philosophers. An exemplary introductory text covering the basics of modern cosmology, at the level of advanced undergraduate physics courses, is Barbara Ryden, *Introduction to Cosmology* (New York: Benjamin Cummings, 2002). Methodological debates have been an important part of the historical development of cosmology: see George Gale's entry in the Stanford encyclopedia (http://plato.stanford.edu/entries/cosmology-30s/) on debates in the 1930s, and for debates related to the Steady State Theory see Balashov, "Laws of Physics and the

Universe," in *Einstein Studies in Russia*, ed. by Balashov and Vizgin (Boston, Basel: Birkhäuser, pp. 107-148). For more thorough discussions of the historical development of cosmology, see the work of Helge Kragh; in particular, *Cosmology and Controversy* (Princeton: Princeton University Press, 1996), and *Higher Speculations* (Oxford: Oxford University Press, 2011). Roberto Torretti's "Spacetime Models of the World," in *Studies in History and Philosophy of Modern Physics* **31** (2000): 171-186, gives an overview of the first steps in relativistic cosmology. John Earman's *Bang, Crunches, Whimpers and Shrieks* (Oxford: Oxford University Press, 1995) is a technically challenging study of philosophical issues related to singularities and acausalities in general relativity, including a critical assessment of debates regarding initial conditions. More recent papers by Earman touch on a number of the topics discussed above. See Pooley's chapter on "Space and Time" (in this volume) for references to recent work regarding the problem of time's arrow. Finally, two research groups have recently begun active work in philosophy of cosmology and have websites with blogs and other content: http://philocosmology.rutgers.edu/, and http://philcosmo.physics.ox.ac.uk/.

Biographical Sketch

Chris Smeenk is Associate Professor in the Department of Philosophy, Western University, and the Interim Director of the Rotman Institute of Philosophy. His primary areas of research are philosophy of physics, primarily spacetime theories and cosmology, and seventeenth century natural philosophy, focusing on Newton.