Does inflation solve the hot big bang model's fine-tuning problems?

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Abstract

Cosmological inflation is widely considered an integral and empirically successful component of contemporary cosmology. It was originally motivated (and usually still is) by its solution of certain so-called fine-tuning problems of the hot big bang model, particularly what are known as the horizon problem and the flatness problem. Although the physics behind these problems is clear enough, the nature of the problems depends on the sense in which the hot big bang model is fine-tuned and how the alleged fine-tuning is problematic. Without clear explications of these, it remains unclear precisely what problems inflationary theory is meant to be solving and whether it does in fact solve them. I analyze the structure of these problems and consider various interpretations that may substantiate the alleged fine-tuning. On the basis of this analysis I argue that at present there is no unproblematic interpretation available for which it can be said that inflation solves the big bang model's alleged fine-tuning problems.

1. Introduction

Various fine-tuning problems are thought to beset the great triumph of 20th century cosmology, the hot big bang (HBB) model.[1] Chief among them are the so-called horizon and flatness problems. These problems were essential to the motivation of the idea of inflation in its original proposal (Guth, 1981), and their significance as fine-tuning problems was promoted immediately by subsequent proponents of inflation (Linde, 1982; Albrecht and Steinhardt, 1982), along with most of the discipline of cosmology soon thereafter.[2] These problems are still typically presented in modern treatments of cosmology to motivate the introduction of cosmological inflation as a solution thereto (Dodelson, 2003; Mukhanov, 2005; Weinberg, 2008; Baumann, 2009).

Standard presentations in the cosmological literature of the fine-tuning problems and their putative solutions through inflationary theory briefly relate the relevant physics, and then conclude with some vague statement, the content of which is essentially that the HBB explanation of a certain cosmological feature depends on fine-tuning and is therefore inadequate; inflationary theory is then claimed to address this fine-tuning by introducing new physics which obviates the problem. Precisely how the HBB model is fine-tuned and what makes the alleged fine-tuning problematic is invariably left unclear in such treatments. Without sufficiently clear answers to these questions, however, no rationally compelling case can be made that inflation truly addresses the HBB model's fine-tuning. Although it is widely thought that inflation indeed does so, these claims are based too much on imprecise intuitions. One would rather like these claims to be based on a sufficiently rigorous analysis of the fine-tuning problems, and on a clear demonstration that inflation solves these problems (so understood). Based on my own such analysis of the possible interpretations of the horizon and flatness problems, I ultimately argue that there is no unproblematic interpretation of either problem available for which it can be said that inflation solves the problem.

Philosophical analyses of the horizon and flatness problems with a similar motivation do exist (Earman, 1995; Earman and Mosterín, 1999; Smeenk, 2003; Maudlin, 2007). Yet the available analyses are either very limited in scope or are generally motivated by peculiar philosophical concerns distant from the kinds of concerns relevant to

[1] Often the terms "fine-tuning" and "special initial conditions" are used in intuitive and roughly overlapping ways, but there is some conceptual space between them should one like to look for it. Nevertheless the distinctions are unimportant to my account and I will use them essentially interchangeably.

[2] The history of these problems is interesting and worthy of study, but I will not engage directly with it for the most part. The interested reader is directed to the following sources: (Longair, 2006), a general history of astrophysics and cosmology in the 20th century; (Smeenk, 2005), a short history of the development of inflation; (Guth, 1997), a popular first-hand account by the father of inflation.

the practice of cosmology.[3] The present paper is an attempt to take a more physically motivated point of view, and therefore takes the concerns voiced by cosmologists as a starting point.

Although a clear account of the HBB model's fine-tuning problems and of how inflation is meant to solve them is of value in its own right, an analysis of this case has some significance to broader issues in the philosophy of science as well. I note one particular motivating line of thought here, and pick up on it again in the concluding remarks. It begins with remarks by Earman and Mosterín (1999), who emphasize that the HBB model's fine-tuning problems are not problems concerning the HBB model's consistency or empirical adequacy; rather the problems appear to raise concerns over the kind of explanation given by the model for certain physical features of the universe—namely features of the universe which are accessible to observation such as spatial uniformity and flatness. One might wonder though, "How can solving such mere explanatory problems represent progress towards an empirically successful theory?"

The context of inflationary cosmology provides a concrete case to investigate this question. At present the best argument for inflationary theory is not that it (allegedly) solves the HBB model's fine-tuning problems; instead it rests on the striking empirical confirmation of inflationary theory's predictions, specifically of a very precise spectrum of anisotropies of the cosmic microwave background (CMB) (White et al., 1994; Hu and Dodelson, 2002).[4] If this latter argument is successful—and it at least appears to be taken as such by most contemporary cosmologists—then inflationary theory is reasonably considered an empirically successful theory whose predictive successes go beyond the HBB model, and therefore represent progress over it.

Yet it is important to note that these predictions were unforeseen at the time of inflation's proposal. Insofar as scientific progress may be gauged by solving scientific problems (Kuhn, 1996; Laudan, 1978), one nevertheless has an explanatory story linking inflationary theory's putative success at solving the HBB model's fine-tuning problems with the later confirmation of its observational predictions. Roughly speaking, one might say that by solving the HBB model's conceptual problems, inflationary theory proves itself to be a progressive research program suitable for further development and empirical test. Although even so there is no guarantee that its predictions will be borne out, one's confidence in the theory is justified by its past problem-solving success. The viability of some such story depends however on whether inflation does in fact solve the HBB model's fine-tuning problems. If it does not, then the widespread adoption of inflationary theory well in advance of its striking empirical confirmation demands some other philosophical rationalization, else one is left to attribute this recent progress in cosmology on the irrational adoption of an ill-motivated idea—a collective decision which turned out to be implausibly lucky given the eventual empirical confirmation of the idea.

Although this line of thought gives one salient motivation for undertaking this investigation, the focus of the paper is on giving a thorough and philosophically rigorous analysis of the nature of fine-tuning in the HBB model, and determining whether inflationary theory addresses it in a satisfactory manner. It is not my brief to argue for or against inflationary theory; nor do I mean to argue that cosmologists are praise- or blameworthy for adopting the idea. My principal aim is only to investigate whether at the present time inflationary theory is justifiably motivated by its putative solutions to the HBB model's fine-tuning problems. I argue that it is not. There is no good reason, I claim, to think that inflationary theory solves these problems. But I emphasize that (some of) the interpretive problems which I point out plausibly can be solved; indeed I believe there are some philosophically interesting possibilities to investigate further—particularly in connection to the idea of dynamical stability and high degrees of symmetry.

The aim of the first half of this paper (§§2-3) is to formulate the HBB model's fine-tuning problems as clearly as possible in order to clarify their nature as scientific problems. Intuitions about the significance of the fine-tuning

[3]Earman (1995) makes a number of important points, but only considers that the problem might be a lack of a common cause, a failure of Machian intuitions, or that horizons make uniformity unlikely, none of which appear to be behind physicists' concerns. Smeenk (2003) also concentrates on common causes and probability concerns. Earman and Mosterín (1999) eschew any analysis of the nature of the problem, resting their further argumentation on empirical claims that are now known to be false. Maudlin (2007) argues that the lack of a dynamical explanation is what gives rise to the the problem, but there is no qualitative difference in the kind of explanations given by inflationary theory and the hot big bang model, so his diagnosis cannot be correct.

[4]Potentially the CMB's polarization could play a confirmatory role as well (Kosowsky, 1996). (Planck Collaboration, 2015) has the latest observational results for both the anisotropy and polarization spectrums. Although assessing the empirical confirmation of inflationary theory is an interesting project, it is beyond the scope of this paper. See (Ijjas et al., 2013; Guth et al., 2014; Ijjas et al., 2014) for recent discussion based on observational results from the Planck satellite, and (Smeenk, 2003, Ch. 7) for a philosophical assessment of the empirical confirmation of inflation which raises several concerns.

problems do vary somewhat among cosmologists (and the few philosophical commentators), so I will endeavor to "cast the net" somewhat widely by incorporating the comments of numerous expositors of the horizon and flatness problems. I find that cosmologists are best understood as holding that the initial physical conditions that give rise to the horizon and flatness problems are in some sense "unlikely" and that this improbability is problematic because the explanation of present conditions given by these unverifiable initial conditions is not robust—for all we know they could have been otherwise, in which case the HBB explanation would fail. The essential point made in these sections, however, is that none of the intuitive interpretations of the fine-tuning problems I survey are free of serious technical or conceptual difficulties.

The second half of the paper (§§4-5) then turns to the putative solution of the fine-tuning problems by inflation, supposing that the issues raised previously are soluble. Since inflation introduces fine-tuning problems of its own, it is important to understand what a solution to a fine-tuning problem actually accomplishes. I therefore argue for some reasonable success conditions on solving such fine-tuning problems. Based on these I evaluate the inflationary program's success at solving the fine-tuning problems understood according to the various interpretations investigated in the the first half of the paper. Under some interpretations inflation would indeed solve them, but since no interpretation is problem free, I suggest that there remains some important philosophical work in understanding the empirical successes of inflationary theory. I therefore conclude (§6) with comments on some of the philosophical ramifications of this investigation. The most salient point I wish to urge is that either some interpretation must be justified which shows how inflation solves the HBB model's fine-tuning problems, or else an alternate rationalization of inflationary theory's widespread adoption in advance of its later empirical successes, one not relying on problem solving, is needed.

2. Fine-Tuning Problems in Big Bang Cosmology

There are perhaps any number of aspects of big bang cosmology that one could find puzzling (Dicke and Peebles, 1979), but the two that (Guth, 1981) emphasizes as major motivations for introducing inflation are the high degree of uniformity of the cosmic microwave background (CMB) and the near spatial flatness of the universe, these being the features that lead respectively to the horizon problem and the flatness problem.[5] Besides being an important motivation for inflation, these problems remain the means of introduction to inflation in modern texts, lecture notes, and popular books on cosmology.[6]

In this section I give my own brief presentation of the two problems in order to introduce the relevant physics and highlight a few points that are regularly muddled or glossed over in standard presentations. It is worthwhile to go into the details in order to understand the conceptual significance of the problems, but the argument they are meant to support is simple. We assume the HBB model is correct and observe certain cosmological conditions (flatness and isotropy) consistent with the model. It is either the case that the HBB model explains these observed conditions by fixing certain initial conditions or that it is necessary to introduce some novel dynamical mechanism to the HBB model in order to explain the observed conditions. But the HBB model has particle horizons that preclude introducing some physically realistic dynamical mechanism which could explain the observed conditions. Therefore the HBB model can only explain the observed conditions by fixing initial conditions. These initial conditions are thought to be problematic, for which reason the HBB explanation is rejected.

This section explains the cosmological scenario that gives rise to the horizon problem (§2.1) and the flatness problem (§2.2). The next section (§3) then investigates what about this scenario could be seen as problematic. The reader well familiar with the nature of the horizon and flatness problems may therefore wish to skip to §3.

[5]Guth also emphasizes the "monopole problem" as a motivation for inflation, yet I agree with Penrose (1989) that problems like these are external problems (intuitively, and also in keeping with Laudan's sense of the term) to cosmology. The monopole problem arises because certain grand unified theories (GUTs) of particle physics predict the creation of magnetic monopoles in the early universe in such a quantity that they should have been observed by now. No monopoles have been observed. Either one takes this fact as suggesting a problem with cosmology or a problem with the GUT. GUTs remain speculative, so it is hard to see how a prediction of such a theory should constitute a significant problem for a highly confirmed model like the HBB model. (Linde, 1990) and (Linde, 1984) outline several other potential problems with HBB cosmology, many of which are external problems like the magnetic monopole problem or are equivalent to the horizon or flatness problems.

[6]In almost any text, set of lecture notes, etc. that treats inflation one will find a presentation of the horizon problem and the flatness problem. I recommend in particular the detailed lecture notes by Lesgourges (2006) for their treatment of these problems. Standard modern texts, to which the reader is invited to refer, include Liddle and Lyth (2000); Dodelson (2003); Mukhanov (2005); Weinberg (2008); Peter and Uzan (2009); Ellis et al. (2012).

2.1. The Horizon Problem

The basic empirical fact that suggests the horizon problem is the existence of background radiation with a high degree of isotropy (uniformity in all directions): the CMB.[7] In every direction we observe the CMB to have the spectrum of a thermal blackbody with a temperature T_0 of 2.725 Kelvin (2×10^{-4}eV), and departing from perfect isotropy only to one part in 100,000.

A fundamental assumption of the HBB model is the cosmological principle: the universe as a whole is (approximately) spatially homogeneous and isotropic.[8] Assuming the cosmological principle, the high degree of isotropy in the CMB is not just a fact about our particular observational situation; the CMB is isotropic for every fundamental observer in the universe;[9] in other words the present temperature of the CMB is inferred to be everywhere 2.725 Kelvin.

The HBB model in fact predicts the existence of this radiation, since it is released as a consequence of the universe's expansion and simultaneous cooling past the temperature where neutral hydrogen can form (an event known as recombination), which prompts radiation (photons) to decouple from matter and "free stream" throughout the universe. This radiation then cools with the expansion down to the presently observed temperature T_0. Thus, according to the empirically well-confirmed aspects of the HBB model, what essentially gives rise to this uniform background radiation is that the observable universe was highly uniform as a whole in its matter distribution at (and presumably well before) the time of recombination, and it then remained so afterwards.

That is the basic HBB story, but some further details are needed to understand the horizon problem. Since observations indicate that the universe is expanding, one can parameterize this expansion by what is known as the scale factor a. The scale factor can be understood as a function of time that yields the ratio of (physical) distances between any two fundamental observers at the given time and some reference time. Often the scale factor itself can be used as a time parameter—one sets the scale factor at the present time to one (by making the reference time the present), and takes the big bang itself to "occur" at scale factor zero.[10]

The energy density of the CMB photons ρ_γ decreases with time (and thus with the scale factor when the universe is expanding): $\rho_\gamma \propto a^{-4}$ (faster than volumetrically). It follows, with some simplifying assumptions (Dodelson, 2003, 40-41), that

$$a(t) = \frac{T_0}{T}, \tag{1}$$

where $T_0 = 2.725K$ is the present temperature of the radiation background. Thus one sees that not only are early times characterized by higher energy densities, but high temperatures too.

Higher densities give rise to high reaction rates for the various particular constituents of the universe, and through these constant interactions the universe usually finds itself in a state of equilibrium.[11] When the expansion rate exceeds the reaction rate of some interaction, however, the particles participating in that reaction temporarily fall out of equilibrium. The reaction subsequently becomes "frozen out", i.e. essentially stops occurring, as temperature further decreases and a new equilibrium state is established.

Recombination is one such out-of-equilibrium event. It occurs when the temperature drops low enough ($T_* \sim .25$eV or at $a_* \sim 9 \times 10^{-4}$) such that neutral hydrogen can form from protons and electrons. The drop in free electrons

[7] The CMB is called "background radiation" because it originates from the cosmos and not from discrete sources (such as stars, quasars, etc.).

[8] Roughly speaking, spatial homogeneity means that space "looks the same everywhere" and spatial isotropy means that space "looks the same in every direction." More precisely we assume that spacetime can be decomposed as a warped product of time and space (McCabe, 2004); space is homogeneous and isotropic if the restriction of the spacetime metric to spatial hypersurfaces is maximally symmetric (Carroll, 2004, 329). If the universe is spatially homogeneous and spatially isotropic around one point, then it is spatially isotropic as a whole. Thus it is somewhat redundant to say "spatially homogeneous and isotropic." Nevertheless, doing so avoids any potential ambiguity. For a philosophical analysis of the cosmological principle see (Beisbart and Jung, 2006).

[9] Fundamental observers are those (not necessarily animate) cosmological objects which are at rest with respect to the universe's expansion, i.e. they follow (timelike) spacetime geodesics. For any geodesic there could have been an observer that followed it, so one permits oneself the use of the "fundamental observer" terminology for any such case.

[10] In the HBB model, the "big bang" refers to the model's past singularity. But singularities are not localized: indeed, there is no spacetime point that corresponds to the singularity (Earman, 1995). So there is no time when the big bang occurred, and the universe never had a scale factor of zero. If we suppose the HBB model of our universe is valid for all possible times, the scale factor ranges over the interval $(0, \infty)$. Nevertheless, so long as one keeps these things in mind, it is convenient to use locutions which mention the big bang, even though such locutions do not strictly speaking successfully refer to any real event.

[11] Expansion is important to maintain states of equilibrium in cosmology, since insufficient expansion would lead to gravitational collapse of the constituents of the universe (**?**).

during recombination leads to the rate of photon-electron (Compton) scattering to drop below the expansion rate, so that the photons decouple from matter. As the universe continues to expand, the rate of photon scattering only lessens. Thus the CMB photons have been traveling throughout the universe since decoupling essentially without interactions, i.e. they have been "free-streaming." Since the photons have been free-streaming since decoupling, the CMB provides a snapshot of "what the universe looked like" at the time of recombination—of an extremely uniform universe.

How did this uniform state of the universe at recombination come about? Assuming the HBB model is correct, either one extrapolates the uniform state of the universe back in time to some initial state of uniformity—back to the big bang itself (arbitrarily close to "$a = 0$") or as far back as one is willing to assume that the model remains accurate; else one supposes that some novel dynamical mechanism brings the universe to a state of spatial uniformity some time before recombination. In the first case, a uniform initial state plus the dynamical laws of the general theory of relativity (GTR) explain the uniform state of the universe during recombination, which explains the observed isotropy of the CMB. In the second case, the initial state of the universe is supposed to be other than uniform, yet some dynamical mechanism drove the universe to a uniform state before recombination, which state can then explain the observed isotropy of the CMB.

The second explanation, however, is precluded in the HBB cosmology (at least insofar as dynamical mechanisms are thought to operate "locally" or "causally"). The HBB model has causal features called particle horizons. A particular fundamental observer's particle horizon represents limits (given in distance at a time) on physically possible causal interactions that could have occurred between the observer and other co-moving objects in the universe. A co-moving object beyond the observer's particle horizon (at a given time) could never have been influenced causally by the observer, just as the observer could not have been causally influenced by that object. When one investigates the horizon structure of our universe (assuming it is modeled by the HBB cosmology), one sees that no such local and causal dynamical mechanism could be responsible for the observed isotropy of the CMB, since the horizon of any given fundamental observer at the time of recombination is smaller than the distance over which the universe is assumed to be homogeneous (I explain this further shortly). These horizons are for this reason the namesake of the "horizon" in "horizon problem", since their presence represents one essential challenge to explaining the particular, uniform state of the CMB dynamically.

The particle horizon of a given fundamental observer is traced out by the paths that all (non-interacting) photons and other massless particles could have traveled since the beginning of the universe from the initial point of the given fundamental observer's worldline (or since the time where the model is deemed valid).[12] Thus the particle horizon at a time separates co-moving objects into two sets: those that "could have been influenced by the fundamental observer" and those that "could not have been influenced by the fundamental observer." Cosmologies based on singular spacetimes, where the singular behavior occurs "in the past," will have a finite age, and therefore have particle horizons. Since the HBB model is singular in this way, it does in fact have particle horizons.

The CMB can be decomposed into an astronomical number of causally disconnected patches due to the existence of horizons in the HBB model.[13] Here is an explicit calculation that illustrates the magnitude of the causal disconnectedness of the HBB universe with presently observed conditions. The particle horizon of the observable universe at the present time (physical distance light could have traveled since the big bang) $\chi_{obs,0}$ is approximately 10^{28}cm (10^{10} light years). Since the universe has been expanding, the size of this observed homogeneous, isotropic domain at early times was smaller. At recombination the size $\chi_{obs,*}$ of the homogeneous, isotropic region that grew into the present one is equal to the size of the present horizon $\chi_{obs,0}$ times the ratio of scale factors:

$$\chi_{obs,*} = \frac{a_*}{a_0}\chi_{obs,0} \sim 10^{-3} \times 10^{28}\text{cm} = 10^{25}\text{cm} \tag{2}$$

Now we compare this to the size of the particle horizon at the time of recombination, $\chi_{cmb,*} \sim 10^{23}$cm. The ratio

[12]Some of the material on horizons is covered in (Earman, 1995). (Davis and Lineweaver, 2004) addresses these issues with remarkable clarity. (Ellis and Rothman, 1993) covers similar ground, but is targeted to an audience less familiar with relativity theory. The first significant discussion of horizons was (Rindler, 1956). There is an obvious relation between the light cone of a fundamental observer and the observer's particle horizons, most easily seen when displayed in a conformal spacetime diagram.

[13]Decomposing the CMB into causal patches involves partitioning the observable last scattering surface (space at the time of decoupling) into regions of space, each of which has all the other patches falling outside of its particle horizon at that time.

$\chi_{obs,*}/\chi_{cmb,*}$ is

$$\frac{\chi_{obs,*}}{\chi_{cmb,*}} \sim \frac{10^{25}\text{cm}}{10^{23}\text{cm}} \sim 10^2 \tag{3}$$

Thus the observed CMB can be divided into around 10^5 circular patches that were causally disconnected at the time of recombination. Since then a tiny number of the photons in adjacent patches have had time to interact with one another or with other matter, but for the most part they have not due to the low reaction rate at later times. It should be clear from the calculation that as one pushes the assumption of homogeneity farther back in time (to times much before recombination), the number of causally disconnected patches only increases.[14]

The local, causal dynamical explanation of a case of observed homogeneity and isotropy that one usually envisions in physics is a process of thermal equilibration. The CMB radiation has the spectrum of a near perfect black body (the spectrum one observes from a system in thermal equilibrium), so a seemingly natural explanation of this spectrum would be that the universe came to equilibrium at some early time. Statistical mechanical arguments are usually taken to show that interacting systems (like the universe) are expected to be found in a thermodynamic equilibrium given enough time. If the universe did not have particle horizons, then an explanation like this might well be expected to hold (since the universe is quite old, $\sim$ 14 Gyr). The presence of particle horizons makes it impossible for the observable universe as a whole to have equilibrated, since there has not even been enough time for the causally disconnected regions in the universe to interact at all by the time of recombination, much less come to an equilibrium.[15]

The upshot is that no realistic dynamical process could have coordinated the uniformity of the entire observable HBB universe, since it is usually assumed that any such realistic dynamical mechanism must act causally (the thought being that influences and signaling occur "locally" in GTR and quantum field theory—in an appropriate sense of "locally" (Maudlin, 2011)).[16]. Any given photon, and anything else for that matter, could only have interacted with a tiny fraction of the contents of the observable universe by the time of recombination, so the extent to which a dynamical process could drive the universe to uniformity is extremely limited. Thus it seems that this uniformity must depend on a "conspiracy of initial conditions;" in other words, each of the large number of causally disconnected patches had to have begun with similar initial conditions for the universe to be as uniform as it was by recombination. The only viable explanation of uniformity in the CMB in the HBB model, then, appears to be that the initial conditions of the universe, at some sufficiently early time, had to be quite nearly homogeneous and isotropic.

This discussion should make clear that the horizon problem (in this context) is really more of a "uniformity problem" (Earman and Mosterín, 1999, 18), since it is the empirical fact of CMB isotropy, and by extension homogeneity via the cosmological principle, that is "puzzling" or felt to be in need of explanation. If one considers the horizon problem as the problem that horizons simply *exist* in the universe, then likely the worry is not over horizons but the existence of a singularity in the past. While singularity avoidance remains a motivation in present theoretical research, it is not necessarily a motivation for inflation (since inflation is certainly possible in singular spacetimes).

The existence of particle horizons does play an important role in the generation of the problem discussed in this section, namely as a constraint on possible explanations of uniformity, so the terminology "horizon problem" is apt. In the following I will prefer referring to the general problem of explaining the uniformity of the universe as the uniformity problem (for the sake of conceptual clarity), but I will nevertheless occasionally use "horizon problem" ambiguously to refer to the horizon constraint and the uniformity problem (in keeping with general usage); I expect context makes clear which usage is operative.

2.2. *The Flatness Problem*

The basic fact inferred from observations which suggests the flatness problem is that the universe has a flat spatial geometry. The cosmological principle selects a set of highly symmetric spacetimes from the models of GTR, the Friedman-Robertson-Walker (FRW) models. These models have uniform spatial curvature k of three different kinds: positive like a sphere ($k = 1$), negative like a hyperboloid ($k = -1$), or flat like a plane ($k = 0$). Since there is a sense

[14]See, for example, Mukhanov (2005, 227) for similar calculations.

[15]Characterizing the horizon problem in terms of the failure of an equilibrium argument is somewhat misleading in any case—see (Carroll, forthcoming, §§3.2-3).

[16]But see (Wald, 1992) for a contrary view which discusses the possibility that quantum correlations beyond the horizon may play an important role in the early universe.

in general relativity in which "matter causes spacetime to curve," one can equivalently place a condition on the matter content of FRW models which determines the model's spatial geometry. If the energy density ρ is equal to the critical density ρ_{crit}, then the universe's spatial geometry is flat; if it is less than the critical density, then the spatial geometry is negatively-curved; if it is greater than the critical density, then the spatial geometry is positively-curved. Although we cannot directly observe the flatness of space, there is a variety of evidence, when interpreted in the context of the HBB model, that supports this conclusion. In particular, the spectrum of small anisotropies in the CMB strongly constrain the density parameter $\Omega = \rho/\rho_{crit}$ to very close to one: $\Omega = 1.000 \pm 0.005$ (Planck Collaboration, 2015, 38).

The flatness problem is often demonstrated by showing how flatness is an unstable condition in FRW dynamics. The Einstein field equations (EFE), the dynamical equations of general relativity, reduce to two equations in the highly symmetric FRW universes: the Friedman equation and the continuity equation are two typical expressions of these two equations. The Friedman equation can be written in terms of Ω:

$$1 - \Omega(a) = \frac{-k}{(aH)^2}, \tag{4}$$

where $H = \dot{a}/a$ is called the Hubble parameter. Since we are interested in departures from the critical density when considering instability, let us ignore the $k = 0$ case and whether the departures are positive or negative. Then we can rewrite the previous equation as

$$|1 - \Omega(a)| = \left(\frac{1}{aH}\right)^2. \tag{5}$$

From this equation we can infer that in the HBB universe the right hand side is always increasing (normal matter decelerates expansion), and therefore the energy density of the universe had to have been even closer to the critical density in the past—the earlier the time, the closer to the critical density. One may do various calculations to show that, given the accuracy to which the density is known today, the critical density at early times had to be constrained to an extraordinarily accurate value; some calculations indicate, for example, fine-tuning to one part in 10^{55} at the GUT scale (Baumann, 2009, 25).

For further illustration, let us assume that matter obeys a simple equation of state during the various epochs of the universe, namely the pressure $p = w\rho$ for some number w. Differentiating the Friedman equation with which we started and using the continuity equation, one can derive the following equation:

$$\frac{\mathrm{d}\Omega}{\mathrm{d}\ln a} = \Omega(\Omega - 1)(1 + 3w). \tag{6}$$

We wish to see how Ω behaves under slight perturbations from the critical density, so assume that $\Omega = 1 \pm \epsilon$ at the present time, with ϵ small. At other times we assume $\Omega = 1 \pm \delta(a)$. We can integrate the previous equation easily, yielding

$$\delta(a) = \epsilon a^{(1+3w)}. \tag{7}$$

Thus flatness is unstable under small perturbations so long as $(1 + 3w)$ is positive, i.e. the strong energy condition is satisfied. Since the strong energy condition is indeed assumed to hold in the HBB model at early times, we conclude that flatness is dynamically unstable. This suggests that the initial conditions of the universe had to be very special—only a narrow range of initial densities of matter could have resulted in the universe we observe. If the initial density had been much different, the universe would have collapsed by now (for $\Omega > 1$) or would have already cooled rapidly (for $\Omega < 1$). The current density parameter is bounded between $\Omega_+ = 1.005$ and $\Omega_- = 0.995$. So, according to the previous equation, at recombination ($w = 0$ and $a_* = 9 \times 10^{-4}$) the density parameter Ω must have been $\sim 1 \pm 1 \times 10^{-6}$; at the GUT scale the flatness was even more extreme: $\Omega = 1 \pm 1 \times 10^{-40}$.

Why is the universe so close to the critical density? I can afford to be brief, as the argument is parallel to the explanation of uniformity above. One explanation is just that the universe is in fact that flat and indeed was even flatter at early times. One might even assume that k is exactly zero, which is certainly attractive due to its simplicity (Dicke and Peebles, 1979, 507). It is also conceivable that some dynamical mechanism drove the universe to a flat geometry at some early time. However, just as in the case of the uniformity problem, horizons represent an obstacle to any such dynamical explanation, so one must conclude that very particular initial conditions (extremely close to flatness) are necessary in order for the HBB model to explain the presently observed flatness of the universe. Thus (although it is not usually pointed out or recognized) the horizon problem represents a constraint on both the uniformity problem and the flatness problem.

3. Fine-Tuning as a Scientific Problem

The previous section exhibited two cases where an explanation is sought for observed cosmological conditions. In the first case the explanandum is the remarkable uniformity of the CMB; in the second it is the remarkable flatness of the universe's spatial curvature. The existence of horizons in the HBB model precludes the possibility of some dynamical mechanism bringing these conditions about. Instead one is forced (in the context of the HBB model) to assume particular initial conditions which give rise to the presently observed conditions.

Thus, although one sometimes encounters comments to the contrary, the HBB model certainly has the resources to provide explanations of these features. That is, it is not at all the case that the HBB model is somehow empirically (or descriptively) inadequate (Earman and Mosterín, 1999, 19). The model simply requires that the universe has always been remarkably uniform and flat (up to the limits of its range of applicability). This is completely in accord with familiar theories of explanation. According to Hempel's deductive-nomological theory of explanation, for example, uniform and flat initial conditions plus the dynamical laws of the general theory of relativity provide a sufficient explanans to account for the observed uniformity and flatness (Earman, 1995, 139). More sophisticated theories naturally acknowledge such explanations (initial conditions plus dynamical laws) as well, since they are paradigmatic of most familiar and accepted physical explanations.

Cosmologists find the HBB model's explanation of uniformity and flatness unsatisfying. This dissatisfaction is exemplified through the identification of the uniformity problem and the flatness problem as problems, and is primarily directed toward the initial conditions that must be assumed. But what makes the HBB explanation problematic, such that an alternate explanation is desirable or even demanded? That is the question to be addressed in this section. I claim that there is presently no good answer, for all of the intuitive answers given by cosmologists (and philosophers) are on analysis beset with significant technical or conceptual difficulties.

To try to get a handle on what the nature of the problems is, let us first see what cosmologists explicitly say about the initial conditions that figure into the uniformity and flatness problems. Usually one finds a presentation, similar to the one I have given in the previous section, in cosmological texts, but, as I mentioned already, little discussion of what makes the stated facts precisely problematic. One only finds appended to the statement of the relevant facts, e.g. that the density parameter Ω must have been $\sim 1 \pm 10^{-6}$ at recombination, a comment suggesting that such facts are "puzzling" and yield "impressive numbers" (Guth, 1981), are "fantastic" and yield "large numbers" (Linde, 1990), are "profound" and "disturbing" (Dodelson, 2003), and even are "contradictory" (Weinberg, 2008); the HBB explanations by way of initial conditions are said to be "unpalatable" (Rees, 1972)"unnatural" (Wald, 1984; Olive, 1990; Goldwirth and Piran, 1992; Mukhanov, 2005), "unlikely" (Liddle and Lyth, 2000), "special" (Riotto, 2002), or improbable (Linde, 1990). Although examples could be easily multiplied further, these remarks essentially cover what one finds in the literature.[17]

Few authors note that the HBB model is empirically adequate with respect to the observed uniformity, but some do. Among the remarks of those who do, one can find some suggestions of what problem might be behind the horizon problem. For example Baumann (2009) remarks that the HBB model has "shortcomings in predictive power" and Misner (1969) states that such models "give no insight" into the uniformity of the CMB.

The trend in these comments suggests that the initial conditions of the HBB model are thought to be special in some respect, from which one infers that this specialness is somehow the cause of concern. Certainly philosophers have made claims that fit this general pattern (Munitz, 1986; Earman, 1995; Earman and Mosterín, 1999; Maudlin, 2007).[18] But in most cases these available analyses misdiagnose cosmologists' concerns, replacing them with the

[17] Also one finds a complaint about the initial condition's lack of explanation itself. As Hawking points out in the introduction to the proceedings of the first workshop primarily focused on inflationary theory, "the [HBB] model does not explain why the universe was as it was at one second. It is simply assumed as an initial condition" (Gibbons et al., 1983, 2). Guth also remarks that "in the standard model this incredibly precise initial relationship [to insure flatness] must be assumed without explanation" (Guth, 1981, 347). Since the HBB explanations appear to be of the sort found in classical, relativistic, and quantum mechanics, where there is usually no further need to explain these initial conditions in practice, the observation that the initial conditions are not explained by the model does not seem to be especially significant. Is cosmology somehow different? Indeed, there are some distinct explanatory considerations in cosmology, which will are discussed at the end of this section. Some cosmologists also have expect initial conditions to be eventually eliminated from physics. The relevance of this attitude to inflationary cosmology is discussed in §5.

[18] For example, Smeenk identifies cosmologists' complaint as being that "[the HBB model] is explanatorily deficient, because it requires an 'improbable' initial state" (Smeenk, 2013, 632). My analysis is in agreement with Smeenk's statement, but fills in the details for why explanatory deficiencies are problematic in the context of cosmology, details missing in his analysis.

kinds of concerns that would occur only to philosophers, e.g. a failure of the principle of the common cause or of sufficient reason. Little attention is paid to what cosmologists actually say about these problems (to be fair, they do say little!) or what physical or methodological grounds there might be to cause them concern. The goal of my subsequent analysis, then, is to be somewhat more systematic in surveying various ways that these initial conditions are physically special, and why special initial conditions of these kinds are problematic, based on the complaints that cosmologists actually make.

Recall that the argument underlying the uniformity and flatness problems from the previous section is as follows:

1. The present universe is observed to be spatially flat and uniform.
2. Either the HBB model explains these conditions by fixing an initial condition or by a novel dynamical mechanism that brings them about.
3. The HBB model's particle horizons preclude such a dynamical mechanism.
4. Therefore spatially flat and uniform initial conditions are required to explain the presently observed flatness and uniformity.

Cosmologists reject the conclusion of this argument as an adequate explanation roughly according to the following argument sketch:

1. Uniformity and flatness are special initial conditions.
2. Special initial conditions are problematic.
3. Therefore, uniformity and flatness are problematic initial conditions (give inadequate explanations).

For the sketch to be a full and rationally compelling argument, one requires grounds for the two premisses, i.e. one requires answers to the following questions: "Why are uniformity and flatness special?" and "Why are these special initial conditions problematic?"

Both Guth and Linde draw attention (in the remarks quoted above) to the size and accuracy of the numbers that fall out of the calculations involved in the horizon and flatness problems. There is certainly nothing special, mathematically-speaking, about large numbers in themselves; such numbers moreover appear ubiquitously in physics. Nor is there anything particularly problematic about them on the face of it. They are, after all, just numbers. Incredible accuracies also do not seem intrinsically suspicious. When explicitly represented by numbers, initial conditions and parameters have to take some such (precise) value presumably. Why not one with a large exponent? It is thus hard to take seriously the idea that such calculated numbers are by themselves indicative of a problem.

If the concern of cosmologists is simply the numbers involved in their calculations, it would appear to be easy to adopt a skeptical position and reject that the horizon and flatness problems are truly problems. This appears, in any case, to be the attitude adopted in (Earman, 1995; Earman and Mosterín, 1999). Regarding such large numbers, for example, Earman and Mosterín draw attention to a quotation by Guth in (Lightman and Brawer, 1990, 475):

> In an interview Guth said that initially he was less impressed by the horizon problem than by the flatness problem because the latter but not the former involves a 'colossal number' that must be explained. (This fascination with colossal numbers is something that seems to infect many inflationary theorists.) Is there really a substantive difference here? (Earman and Mosterín, 1999, 23, fn. 17)

Clearly, the tone of this footnote leaves little doubt that the authors believe there is no such substantive difference. If one takes Guth's comments merely at face value, then it is indeed hard to take seriously that there is any substantive difference. But a thorough analysis should go beyond comments taken at face value. Indeed there are plainly substantial differences between the two problems. For example, uniformity may be dynamically unstable in (some) expanding FRW models (when we consider small perturbations), but flatness is demonstrably unstable within the context of FRW models that satisfy the strong energy condition (it was demonstrated in the previous section). So it is at least plausible that the numbers to which Guth refers do arguably have a significance beyond their mere size or accuracy when suitably interpreted. This difference may not simply be in terms of "colossal" numbers, but in real features of the cosmology in question.

Thus whether cosmologists have a "fascination" or any other psychological reaction to such numbers is (from the point of view of philosophy anyway) simply beside the point. Although cosmologists certainly do use subjective psychological language to describe their reactions to the problems—puzzling, impressive, fantastic, profound, disturbing, unpalatable, etc.—what makes a problem a scientific problem is not these reactions alone. Science does indeed aim to explain things that are puzzling and profound, but it plainly does not aim to explain all such things.[19] As Nickles observes, "scientists know that some problems are more interesting than others" (Nickles, 1981, 87)—certain problems attract attention, others do not. The interesting question is why the former do and the latter do not.

That a large or accurate number is suggestive of a problem therefore reasonably depends on more than just the number itself—but on what? The underlying mathematics of a theory cares little for particular numbers (apart from identities, etc.). For a number to be suggestive of a problem, it must be substantially linked to some theoretical expectation, otherwise it at best amounts to an uninteresting "oddity."[20,21] Theoretical expectations of a future theory are no sure guide to a correct future theory, but they do often derive from "positive heuristics" (Lakatos, 1970) rather than being mere guesses. To understand how large numbers may be suggestive of a scientific problem, one should therefore understand the operative heuristics.[22]

One of course does not have to look far to find such heuristics guiding problem statements and solutions in theoretical physics. Behind expectations in fine-tuning cases in particle physics, for example, is the concept of naturalness. The notion of naturalness applied in particle physics has a precise sense (which I will not be discussing), but it is roughly similar to the intuitive notion one might have of simplicity in parameters and initial conditions. However, uniformity and flatness are clearly simple conditions (spatial homogeneity and isotropy, and $\Omega = 1$, respectively) so a lack of simplicity does not at least appear to be at work in problematizing the HBB model.

Perhaps instead it is precisely the simplicity of the initial conditions that is cause for concern. Spatial uniformity is certainly a special condition on models in GTR in a precise sense—indeed, spatial uniformity is the greatest amount of spatial symmetry a spacetime can have. Flatness is special as well insofar as it is precisely a point of dynamical metastability in FRW models. In a sense that can be made precise, then, almost all other models of GTR do not have so many symmetries as the spatially uniform FRW models, and there are no other metastable FRW models besides the one with flat geometry.

It is therefore possible to identify the HBB model's initial conditions as special in a clear sense, i.e. to ground the first premiss in the argument sketch. This in part supports a heuristic such that a maximal degree of symmetry is deemed unphysical, or one which holds that cosmological models should not exhibit dynamical instabilities. But one should be able to explain why high degrees of symmetry and dynamical instability are problematic as well (at least in cosmology), i.e. to ground the second premiss. There are some reasons to doubt that this can be complellingly done.

In the first place, symmetry considerations play a central role in contemporary theoretical research, so it cannot be that there is something problematic about a physical model simply possessing symmetries. There are certainly questions one can raise over their ontological and epistemological significance (Brading and Castellani, 2003), but it does not seem to be the case that models with high degrees of symmetry necessarily lack, e.g., predictive or explanatory power. Is there something problematic specifically about cosmologies with high degrees of symmetry? There is some evidence (Isenberg and Marsden, 1982) that symmetric spacetimes are exceedingly rare in the space of solutions of

[19]Cf. Callender's discussion of the flatness problem and the example of a surprising hand of cards in a card game (Callender, 2004, 202). "Surprisingness is of course a psychological notion, and we do not ordinarily demand that science explain away surprising events."

[20]Before the advent of inflation many prominent cosmologists felt that the horizon and flatness problems were puzzling, but did not represent real problems (see the interviews by Lightman and Brawer (1990) and (Brawer, 1995)). Once Guth clearly articulated the problems and a potential solution (which depended on relaxing the horizon constraint on dynamical solution), the community took them much more seriously. Laudan (1978) in particular comments on this frequent phenomenon, namely that problems often appear only after their solution. This is in keeping with the view of scientific problems defended in, e.g. (Nickles, 1981), that "a problem consists of all the conditions or constraints on the solution plus the demand that the solution (an object satisfying the constraints) be found." In a slogan: "Knowing what counts as an answer is equivalent to knowing the question" (Hamblin, 1958).

[21]Fine-tuning problems are often described by physicists as "aesthetic" problems, by which they mean that these problems are problematic only because of certain theoretical expectations that may not be satisfied: "There does not have to be a resolution to the aesthetic questions – if there is no dynamical solution to the fine-tuning of the electroweak scale, it would puzzle us, but would not upset anything within the fundamental theory. We would just have to live with the existence of fine-tuning" (Donoghue, 2007, 232).

[22]Laudan remarks that "anything about the natural world which strikes us as odd, or otherwise in need of explanation, constitutes an empirical problem" (Laudan, 1978, 15). A statement like this may make it seem, at least for Laudan, that our proclivities to find something odd or in need of explanation are indeed grounds for raising scientific problems of the kind explored in this paper. Yet these proclivities are based on something more objective—as Nickles proclaims, "problems are entities which have 'objective' existence" (Nickles, 1981, 111)—than mere subjective prejudice. Laudan agrees: "Our theoretical presuppositions about the natural order tell us what to expect and what seems peculiar, problematic or questionable" (Laudan, 1978, 15). The operative heuristics or theoretical presuppositions thus are precisely the appropriate objects of philosophical investigation—at least from this point of view in the philosophy of science.

GTR. To turn this into argument that disfavors the possibility of symmetric spacetimes, however, requires additional considerations beyond the observation that symmetric spacetimes are special (in this sense). These considerations are usually advanced in the guise of probability theory (although measures and topologies can be used to this purpose as well)—so in this case it is improbability (or unlikelihood) that is essentially problematic, not symmetries in and of themselves.

There is a suggestion of another potential explanation of why symmetries are problematic in cosmology when one recognizes that cosmological models are highly idealized, coarse-grained representations of the actual universe. The actual universe is clearly not perfectly spatially homogeneous and isotropic, nor is it even a linearly perturbed version of such FRW models (gravitational collapse is much evident in the universe and is a non-linear process). Such cosmologies may be good "high-level", coarse-grained approximations of the actual universe, but if the dynamics of the "low-level", finer-grained model does not keep it in the neighborhood of the idealized, symmetric, high-level model, then one has the start of an argument to disfavor it as a reliable model.[23] This line of thought, however, again leads us away from the idea that symmetries are problematic to other considerations, in this case to considerations of dynamical instability.

With respect to dynamical instability, one might first observe that the very notion, standardly used in investigating dynamical stability, of a perturbation is absurdly unphysical in the context of cosmology, as there is no external perturbing agent to be found "outside of the universe." Since perturbations evidently require some perturbing agent, it may seem that dynamical instability is not problematic in cosmology in the same way that it is in physical systems which are in environments where small perturbing agents are ubiquitous, in which case it is to be expected that one never finds a dynamically unstable system in a metastable state.

The famous case of Einstein's static universe being unstable under various perturbations (Earman, 2001, 195), as shown by Eddington, is however an example where instability was and is widely thought to be problematic.[24] Eddington claimed that "the initial disturbance can happen without supernatural interference" (Eddington, 1930, 670), i.e. the perturbation could come from within the universe rather than without. Although he gave suggestions, he did not give an explicit account. Subsequent work (Harrison, 1967; Gibbons, 1987; Barrow et al., 2003) has clarified under what conditions the Einstein universe is stable (and similarly for other cosmologies as well). But the necessity or even preference for stability in cosmology should not be assumed without argument. This is especially so since there are arguments from dynamical systems theory that might be taken to suggest that cosmological dynamics should in fact be expected to exhibit instabilities (Tavakol and Ellis, 1988; Tavakol, 1991; Coley and Tavakol, 1992).

Although my cursory comments above cannot be said to adjudicate the issue definitively, I believe the considerations raised should be enough to cast doubt on there being a strong and obvious case to be made for simplicity being problematic in cosmology. In particular the case has not been explicitly made by inflationary cosmologists when explicating the horizon and flatness problems. Without such an explication, it simply cannot then be said that simplicity is at the heart of the HBB model's fine-tuning problems.[25]

In any case, the kinds of arguments centered on simplicity appeared to lead directly to likelihood considerations, and indeed cosmologists do say frequently that uniformity and flatness are "unlikely" or "improbable."[26] Indeed the other complaints mentioned previously (simplicity, large numbers and accuracies) can be made to fit under the broad umbrella of "probabilistic" reasoning. For example, the high degree of symmetry exhibited by uniformity can be intuitively described as improbable (since there are so many ways that it could have lacked those symmetries), and that our universe is close to a metastable spacetime can be said to be unlikely (since it could have been curved in so many ways). It is therefore tempting to interpret the uniformity and flatness problems as problems based on the improbability of the observed conditions in the context of HBB theory. It captures most of their complaints in a common framework. Perhaps for these reasons one finds philosophers generally concluding that special initial conditions are special because improbable (Earman, 1995; Earman and Mosterín, 1999; Price, 2002, 1996; Smeenk, 2003, 2013).

[23] See (Wainright and Ellis, 1997) for an introduction, relevant to this line of thought, to the application of dynamical systems theory to cosmology.

[24] The argument convinced Einstein himself that his model was unphysical (Nussbaumer, 2014).

[25] Nevertheless I do think the issue is of some importance and interest, and deserves an independent philosophical investigation that goes beyond my treatment here. There is a rich physics literature on stability and symmetries in GTR and cosmology, but as yet very little philosophical attention has been paid to it.

[26] "The [FRW] models are clearly very special within the class of all cosmological models, and so a priori are highly unlikely" (Wainright and Ellis, 1997, 3).

There are, however, significant challenges to adopting improbability as the explication of specialness in this context which have not been adequately addressed. Whether such descriptions can be substantiated objectively remains an open question, despite many earnest attempts to do so (Gibbons et al., 1987; Coule, 1995; Gibbons and Turok, 2008; Carroll and Tam, 2010). The technical problems with defining a natural probability measure on the space of possible cosmologies are well-detailed in Schiffrin and Wald (2012); Curiel (2014). Curiel relates the difficulties of constructing suitable likelihood measures on the infinite-dimensional space of relativistic spacetimes; even restricting attention to minisuperspace, the finite-dimensional space of FRW models with a scalar field to drive inflation, Schiffrin and Wald show that a probability measure cannot be defined without some arbitrary choice of regularization of divergent integrals, since the natural Lebesgue measure gives the total space infinite measure. Although arguments for particular regularizations have been made (Carroll and Tam, 2010; Gibbons and Turok, 2008), Schiffrin and Wald (2012) and Curiel (2014) give compelling reasons to doubt whether such choices have any physical significance.

One may also raise various conceptual problems with making sense of probability in cosmology that cast doubt on interpreting specialness as improbability in the context of these problems (Ellis, 2007; Smeenk, 2013). Briefly, here are two simply stated issues. First of all, it is unclear what the appropriate reference class for cosmological probabilities is. How can we even know what the space of possible cosmologies is when there is just one universe? Is it all relativistic spacetimes? Just FRW models? Secondly, it is not apparent what the empirical significance of such probabilities is, since we observe a single universe evolving deterministically. The probabilities of statistical physics, for example, can be empirically confirmed since one generally has a multiplicity of identically-prepared systems for which one can obtain statistics and verify the theory's probabilistic assumptions. The usual interpretation of cosmological probabilities then is that they are just probabilities of initial conditions. But if they are, then how can such probabilities be justified? Is one to imagine some creator picking one of the possible universes as Penrose (1979) vividly illustrates? It is important to recognize that the success of problematizing uniformity and flatness in terms of likelihood depends crucially on successfully meeting these difficult conceptual challenges. Although a fuller exposition of the challenges facing cosmological probabilities and other measures of likelihood would be able to drive the point in more definitively, an honest assessment of the prospects of meeting these challenges, even just on the basis of the papers mentioned here, appears to be rather dim.

Nevertheless, if these problems are surmountable such that one can say that uniformity and flatness are indeed improbable in a sufficiently rigorous sense, then it is, I claim, at least possible to explain why they are problematic—intuitively it is because improbable initial conditions lack explanatory power (and predictive power). Improbable initial conditions might be seen as problematic because the probabilities tell us that those conditions probably do not obtain. But confidence in our observations and models transfers to the initial conditions, i.e. our present observations are relevant to our credences. Nevertheless, in the cosmological case there is little hope of verifying the conditions of the universe before recombination since radiation cannot travel freely to our telescopes from those times. The real worry then is that the initial conditions of the universe might easily have been otherwise (for all we can ascertain from observational evidence) than what the HBB model tells us; if they were indeed different, even slightly, then our HBB explanation of the present conditions fails (catastrophically—the universe collapses before we're around or stars never form). The problem is not that the HBB model cannot explain and predict phenomena, it is that the explanations and predictions it provides are not robust. A theory which provides a robust explanation of some phenomenon is better—has a stronger explanation I would say—than one which depends on improbable initial conditions to explain the same phenomenon.[27]

Some, in agreement with Earman (1995, 146) and Smeenk (2003, 239), may not be convinced that lacking explanatory power is all that problematic for a theory (exhibiting as evidence various examples from elsewhere in physics). Surely, at least when all other things are equal, a theory is preferable to another when the former explains more or better or more robustly than the latter. But when they are not, it is not so clear that the more powerful explanatory theory is always the better. For example, a cheap way to increase the explanatory power of a theory is to limit the space of possible models of the theory, say by assuming an additional constraint (Maudlin, 2007, 44). If one assumes the strong energy condition, then the only permissible expanding FRW models are decelerating. Hypothetical observations that suggest that the universe's expansion is decelerating would in this case be explained by the nature of matter in such a model, namely by the strong energy condition holding.[28] But adding additional constraints

[27] There are surely many dimensions of explanatory power; I only claim that robustness of explanation is one of them.

[28] It may be objected that assuming a constraint does not make a theory more explanatory. Why, after all, is the strong energy condition true?

on a theory limits the descriptive possibilities of that theory, so increasing explanatory power in this way is usually not desirable. When those descriptive possibilities are not thought to obtain, however, there appears to be no loss by excluding them. Still, even in this case, it should be recognized that there are general costs to excluding descriptive possibilities (less unification of phenomena, lack of simplicity, etc.) which presumably must be balanced them against the benefit of increasing the theory's explanatory power.

In cosmology the uniqueness of the universe changes the calculus of balancing explanatory and descriptive power. There are no other observable universes, and therefore no empirical motivations to preserve descriptive power in cosmological models. It thus appears always favorable to pursue cosmologies with greater explanatory power.[29] Indeed one occasionally hears expressed the idea that the perfect cosmology would include no free parameters, would leave no cosmological feature accidental, etc.[30] A cosmological theory that severely lacks explanatory power by depending on special initial conditions for crucial explanations, especially one that is thought to be correct only at certain averaging scales and in certain energy regimes, can therefore legitimately be seen as problematic, in the sense that it is plausible to think that more powerful theories exist which maintain the empirical adequacy of the prior theory.

It may be useful to recap the foregoing argument. I claimed that the most intuitive analysis of the uniformity and flatness problems (as understood by cosmologists who have commented on them) depends on the initial conditions being special because they are improbable or unlikely; I argued furthermore that improbable and unlikely initial conditions are problematic because models with such conditions lack explanatory power. While this may not seem much about which to make ado—it could be said of nearly any theory that requires initial conditions—I have argued that there is a strong inclination in cosmology towards theories with greater explanatory power, more so than elsewhere in physics. Empirical considerations do not pull so strongly against explanatory power and towards the preservation of descriptive power in cosmological theory due to the uniqueness of the universe.

Now, the fact that these improbable initial conditions are also observationally unverifiable represents a significant theoretical risk to the HBB model, making the aforementioned inclination considerably stronger. As a matter of risk reduction in theory construction, theorists would much prefer to hedge their bets on a theory with greater explanatory resources (by introducing, say, some dynamical mechanism that drives the universe towards the observed conditions) and to reject the HBB explanation of uniformity and flatness. Yet, as shown in §2, particle horizons represent an obstacle to devising a cosmology with greater explanatory power, since the HBB's particle horizons preclude the dynamical explanations that would come with it. Thus one has the horizon problem, and its two manifestations: the uniformity problem and the flatness problem.

This particular argument hinges on the success of substantiating the attributions of probability in cosmology, a task that faces many seemingly insuperable challenges as noted in this section. Other explications of specialness in cosmological fine-tuning problems, such as a high degree of symmetry or dynamical instability, could perhaps be substituted, but they do not clearly problematize the HBB model's explanations of these problems alone. Thus I conclude that there is at present no problem free interpretation of the HBB model's fine-tuning.

4. Inflation and the Fine-Tuning Problems

Inflationary theory, in its basic version, suggests that the universe underwent a phase of accelerated expansion in its very early in its history. The crucial realization, made originally by Guth, is that this one simple assumption, a

Indeed there is always room for more explanation. But here one can make the connection to another area of physics, say a microphysical theory of matter, to ground the assumption.

[29] There are certainly theoretical motivations to preserve some degree of descriptive power in cosmology. Insofar as one thinks that relativistic spacetimes are the appropriate models of the universe (because, for example, one holds that gravity is the relevant "force" on cosmological scales), there is a strong presumption that GTR tells us precisely what the permissible cosmologies are. Yet insofar as one believes that GTR has limited ranges of applicability or unphysical models, intuitions on which cosmologies are realistic diverge from this presumption.

[30] "My guess is that there really is only one consistent theory of nature that has no free parameters at all" (Guth, 1987); "What the cosmologist requires, therefore, is a theory which is able to account in detail for the contents of the universe. To do this completely it should imply that the universe contains no accidental features whatsoever" (Sciama, 2009, 167). These views are captured in a conjecture of Einstein: "I would like to state a theorem which at present can not be based upon anything more than upon a faith in the simplicity, i.e. intelligibility, of nature: there are no arbitrary constants. . . that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory)" (Einstein, 1959, 63).

phase of accelerating expansion where the strong-energy condition is violated, relaxes the horizon constraint, reverses the instability of flatness, and gives rise to the possibility (at least) of a dynamical explanation of uniformity. In this section I briefly explain how inflation is generally understood to solve the uniformity and flatness problems, i.e. by explicitly relaxing the horizon constraint of the HBB model. As with §2, this section best serves readers who are not very familiar with contemporary cosmology, although I do correct some common misconceptions that persist in the cosmological literature. Those readers who are well-acquainted with inflationary theory may nevertheless wish to skip to the following section, where I assess whether inflation truly solves the problems it sets out to solve.

As argued in §2, The existence of horizons precludes any local dynamical explanation of uniformity (and flatness). If the horizon constraint were relaxed, then one might expect that a dynamical explanation would become possible. Indeed, if the entire observable universe were within a single horizon volume at a sufficiently early time (at least by recombination), then it would appear to be possible to give some such local causal explanation. So long as the strong energy condition is maintained, this is not possible—there is a past singularity in the HBB model limiting the age of the universe and therefore the distance radiation could travel before recombination. The inflationary approach is to propose a phase of the universe where the strong energy condition is violated which is smoothly "spliced into" the big bang story. A period of sufficient inflationary expansion (and, crucially, finding a way for it to end) then leads to a universe where the entire observable universe shares a common past.[31]

It is often remarked in expositions of inflation that a sufficient amount of inflation puts the constituents of the observable universe in causal contact such that a thermal equilibration process can lead to uniformity. But this cannot be how the CMB photons came to have the same temperature—the huge amount of expansion during inflation thins all particles out such that the post-inflation universe is essentially empty.[32] The inflationary solution to the uniformity problem actually depends crucially on a post-inflation phase of the universe known as reheating, where the supposed decay of the scalar field responsible for inflation repopulates the universe uniformly with particles (except for a spectrum of inhomogeneities due to "quantum fluctuations"). Reheating depends on quantum field theoretic considerations beyond the scope of this paper, but for present concerns it is worth remarking that by no means is there a completely adequate model of reheating at this time (Amin et al., 2015). Such a model is obviously crucial for the empirical adequacy of the inflationary proposal, even apart from it being required to solve the uniformity problem.

Inflation addresses the flatness problem more directly. Recall that one can rewrite the Friedman equation as

$$1 - \Omega(a) = \frac{-k}{(aH)^2}. \tag{8}$$

With $1/(aH)^{-1}$ being driven towards zero by inflation (during inflation a increases greatly while H remains approximately constant), $\Omega(a)$ is driven to one, i.e. the critical density. For this reason it is often said that spatial flatness is an attractor solution in inflationary universes or that $\Omega \approx 1$ is a generic prediction of inflation (Mukhanov, 2005, 233). The dynamical instability of flatness in the standard big bang universe is in any case reversed (flatness becomes a point of stability instead of metastability), for which reason it is claimed that inflation makes it "more likely" that the present universe should appear flat.

It may be of interest to see slightly more detail on how inflation specifically solves the horizon problem through accelerated expansion of the universe.[33] First, let us see how the horizon changes during different phases of the HBB universe (radiation domination and matter domination) in order to make a comparison to the inflationary universe. Matter-radiation equality occurs when the energy density of matter Ω_m equals the energy density of radiation Ω_r. This occurs at a scale factor of

$$a_{eq} = \frac{\Omega_r}{\Omega_m} \approx 3 \times 10^{-4}, \tag{9}$$

[31] Cosmologists often quote amounts of expansion in terms of "e-foldings"; an e-folding is a measure of expansion in base e given by the natural log of the ratio of scale factors, a later scale factor to an earlier one.

[32] This is, however, how inflationary theory solves the monopole problem. If magnetic monopoles are produced through a GUT phase transition, a sufficient amount of inflation will sweep them far enough away from one another that it becomes astronomically unlikely that one could have been observed.

[33] (Earman, 1995, 150-2) gives a similar calculation to the one I give below with which some readers may be familiar, but as far as I can tell there appear to be some significant mistakes. Although correct such calculations can be easily found in the cosmological literature, e.g. (Lesgourges, 2006), for the reader's convenience I provide my own version here.

which is somewhat before recombination ($a_* \approx 9 \times 10^{-4}$).[34]

The increase in (co-moving) size of the particle horizon radius over a change in scale factor $\delta a = a_2 - a_1$ is given by the following expression

$$\chi_{\delta a} = \int_{a_1}^{a_2} \frac{\mathrm{d}a}{a^2 H}. \tag{10}$$

During matter domination the Hubble parameter H is inversely proportional to $a^{3/2}$. Thus we can set $H(a) = H_0 a^{-3/2}$ for any a during matter domination, where H_0 is the present Hubble parameter. Let us evaluate the contribution to the present particle horizon since recombination, by integrating from $a_1 = a_*$, the scale factor at recombination, to the present, where by definition the scale factor is $a_2 = 1$:

$$\chi_{(*,1)} = \frac{1}{H_0} \int_{a_*}^{1} \frac{\mathrm{d}a}{a^{1/2}} = \frac{2}{H_0}(1 - a_*^{1/2}). \tag{11}$$

The universe was matter-dominated before recombination (as just noted), and radiation-dominated before matter-radiation equality. Data indicate that the redshift of recombination is approximately 1090, and the redshift of matter-radiation equality is 3250. These correspond to scale factors of 0.0009 and 0.0003 respectively. Thus only a small amount of expansion occurred during matter domination before recombination (the universe expanded three-fold), so it is a reasonable approximation to take matter-radiation equality to occur at recombination. Setting $H = a_*^{1/2} H_0 / a^2$, we evaluate the integral from some initial time where the HBB model is assumed valid, $a_1 = a_i$, to recombination, $a_2 = a_*$:

$$\chi_{(0,*)} = \frac{1}{a_*^{1/2} H_0} \int_{a_i}^{a_*} \mathrm{d}a = \frac{1}{H_0} \frac{a_* - a_i}{a_*^{1/2}}. \tag{12}$$

Therefore the present particle horizon is given by $\chi_{(0,1)} = (2 - a_*^{1/2})/H_0$. The ratio of the particle horizon at recombination to the present particle horizon is

$$\frac{\chi_{(0,*)}}{\chi_{(0,1)}} = \frac{a_*^{1/2}}{2 - a_*^{1/2}} \approx 0.015, \tag{13}$$

where the term proportional to a_i has been dropped because it is negligible. In the HBB universe almost all of the distance light could have traveled has been since recombination (not surprisingly, given what has been said about the horizon problem).

Let us formulate a condition for "causal contact." Imagine that "at the big bang" two massless, non-interacting particles with the same temperature are released in opposite directions. When recombination occurs they will each have traveled a co-moving distance of $\chi_{(0,*)}$. Imagine now that they are reflected so that they travel back towards one another. If they meet exactly at the present time or any time after, then they each must have traveled a distance at least equal to the present co-moving horizon radius, $\chi_{(*,1)}$. So the minimum condition for causal contact is

$$\chi_{(0,*)} \geq \chi_{(*,1)}. \tag{14}$$

In an FRW universe that undergoes a radiation- to matter-dominated transition the condition is equivalent to the condition that $a_* \geq 4/9$. The scale factor at recombination (and matter-radiation equality) is clearly much, much smaller than this value ($a_* = 9 \times 10^{-4}$). So we see that it is not possible that CMB photons all have a shared causal past, i.e. we have another presentation of the horizon problem.

Now we let us see how an inflationary stage can solve the problem. An inflationary stage's dynamics depend on the details of the inflationary model, but the Hubble parameter in simple models remains approximately constant (we choose an equation of state $w = -1$, the equation of state for a cosmological constant, for simplicity). The particle horizon grows as before, but radiation domination only begins after the end of inflation, at a_f:

$$\chi_{(*,1)} = \frac{2}{a_*^{1/2} H_0}(a_*^{1/2} - a_*) \qquad\qquad \chi_{(f,*)} = \frac{1}{a_*^{1/2} H_0}(a_* - a_f). \tag{15}$$

[34]Matter-dark energy equality occurred much more recently, at a scale factor of about $a_{eq2} \approx 0.6$. Therefore the universe has only expanded slightly since then (only about half an e-folding), so dark energy domination will be neglected in these calculations.

The particle horizon grows during inflation according to

$$\chi_{(i,f)} = \frac{1}{H_f}\int_{a_i}^{a_f}\frac{\mathrm{d}a}{a^2} = \frac{1}{H_f}\frac{a_f - a_i}{a_i a_f}, \tag{16}$$

where $H_f = a_*^{1/2}H_0/a_f^2$. So

$$\chi_{(i,f)} = \frac{1}{a_*^{1/2}H_0}\frac{a_f}{a_i}(a_f - a_i). \tag{17}$$

The factor a_f/a_i gives the expansion during inflation, and, since it appears in the expression for the growth of the particle horizon, is ultimately responsible for solving the horizon problem. Combining the particle horizon during inflation and radiation domination gives

$$\chi_{(i,*)} = \frac{1}{a_*^{1/2}H_0}\left[a_f\left(\frac{a_f}{a_i} - 1\right) + a_*\right], \tag{18}$$

where the term proportional to a_i has been dropped because it is negligible. Applying the causal contact condition defined above, the following inequality is easily derived (neglecting additional small terms):

$$\frac{a_f}{a_i} \geq 2\frac{a_*^{1/2}}{a_f}. \tag{19}$$

This inequality demonstrates that the amount of inflationary expansion required to solve the horizon problem depends on the energy scale where inflation takes place. Taking a_f as a_{gut}, one finds that around 63 e-foldings of inflation are required. If a_f is instead taken to be approximately 1 TeV, only around 33 e-foldings are required (since less expansion occurs during the shorter radiation-dominated stage).

5. Solving Fine-Tuning: From the Hot Big Bang to Inflation

Having presented how inflationary cosmology is understood to solve (or at least address) the HBB model's fine-tuning problems, I now turn to evaluating this claim. The main negative point I will emphasize is that even accepting an intuitive likelihood interpretation of the HBB model's fine-tuning problems, it cannot be said that inflation is able to solve them—even granting the weakest standard of success. If the problems are understood differently, e.g. as depending on instability or symmetry, then inflation may provide a solution, depending on how the problem is explicated. But again, as I argued in §3, it is not at all clear how these ways of interpreting fine-tuning problems can be adequately justified. Nevertheless, it is of some interest to set aside concerns over justification in order to see which interpretations of the fine-tuning problems are successfully addressed by inflationary theory.

Consider first the uniformity problem. Uniformity in the CMB's temperature suggests an equilibrium explanation, but the existence of particle horizons in the early universe precludes its possibility. Inflation attacks the horizon constraint directly, but ironically at the cost of the possibility of such an equilibrium explanation, as mentioned in the previous section. The phase of inflationary expansion essentially empties the universe of particles (a point that is demonstrated through the various so-called "cosmic no hair theorems"). In a way the uniformity problem is solved by the expansion through inflation—the universe does become uniform—but certainly not in the way one would have liked: the hot big bang is supposed to be hot and dense, not cold and rare. Inflation thus sounds rather more like a failure to solve to the uniformity problem than a solution thereto. Nevertheless it is worth noting that a seemingly ad hoc maneuver leads to interesting non-ad hoc theoretical consequences—the inflationary epoch not only increases the particle horizon an exponential amount, but by doing so greatly dilutes the density of energy in space.

The inflationary mechanism thus leads to new problems, especially how to transition smoothly to the empirically confirmed parts of the big bang story. Has reheating solved this problem? As said, the verdict is not yet clear. Still, one can at least say that inflation renders it *possible* to give a robust dynamical explanation of uniformity via reheating, whereas otherwise it had to be merely posited.[35] Pending a clearly motivated and detailed account of reheating, however, one must as yet conclude that inflation has not definitively solved the uniformity problem.

[35] In this vein, a key contribution of inflation is that it shows a way to make the origins of the big bang an object of scientific study, a point Marc Davis emphasizes: "That's what is so impressive—when you can actually push back your ignorance to a point where you can address a question that you didn't think was in the bounds of science at all." (Lightman and Brawer, 1990, 352).

Let us turn to the flatness problem. If the flatness problem is assumed to concern the dynamical instability of flatness in FRW spacetimes (by assuming a stability constraint on cosmological models), then inflation solves the problem by reversing the instability of flatness. It is rather surprising that classical inflation addresses, merely by positing a stage of accelerated expansion, the horizon constraint and the "stability constraint" simultaneously. While the horizon constraint is addressed in an essentially ad hoc way, the stability constraint appears to be solved by serendipity. There is surely something of a "common cause" here: Horizons exist in part because matter in the HBB universe obeys the strong energy condition, but matter obeying the strong condition also causes flatness to be dynamically unstable in FRW spacetimes. Defined as a stage of accelerating expansion, inflation implies that the strong energy condition is violated, from which it follows that an inflationary stage increases the particle horizon, and also that flatness is a point of dynamical stability during inflation.

Differently interpreted, however, the uniformity and flatness problems are not so clearly solved by inflation (even assuming that reheating is successful). In particular, when one views fine-tuning problems as "likelihood" problems, there is no convincing proof that inflation has solved them at all. Not only is it doubtful whether any precise sense of probability can be applied to the space of cosmologies (Schiffrin and Wald, 2012; Curiel, 2014), it is also not clear that inflation would itself be in any sense "likely" on such a measure.[36] For anyone interested in the justification of inflation as part of the standard model of cosmology, these probability issues are among the most pressing—at least if one understands HBB fine-tuning as a probability problem and inflation a solution thereof.

In the task of evaluating a theory's success at solving a problem, one should specify reasonable success conditions. So let us suppose for the sake of argument that the project of addressing the probability problems of inflationary cosmology remains tenable despite the serious challenges it faces, and consider briefly what it would take to solve the fine-tuning problems interpreted as likelihood problems. There are various ways one might approach the likelihood problem, and therefore what counts as a solution to the problem. One possibility is that special initial conditions must be "explained away," in the sense that fine-tuning must be completely eliminated. Another is that fine-tuning is not a bump to push under the rug: to explain fine-tuning one must remove or lessen the fine-tuning in question without introducing further fine-tuning of an equal or greater magnitude. Finally, one might hold that solving fine-tuning only requires making the fine-tuned values more likely, without consideration of other possible fine-tunings. Although inflation has been criticized for not meeting any of these conditions, I claim that we should only demand that the last condition by met by any putative solution to a fine-tuning problem understood as a likelihood problem.

Evidently many physicists view the elimination of initial conditions as something of an ultimate goal of physics.[37] Be that as it may, inflation certainly does not succeed at realizing this implausible goal. In whichever guise inflation takes, initial conditions of some kind or another are required (Vachaspati and Trodden, 1999; Brandenberger, 2007; Carroll, forthcoming). Although I refrained from discussing the implementation of inflation as a scalar field, it is perhaps enough for now to point out that single-field inflation models possess potentials that can be characterized by two numbers: ϵ_v, which for inflation to occur, must satisfy the condition $\epsilon_v < 1$ (the potential must have a region which causes accelerated expansion of the universe); η_v, which for inflation to last long enough to solve the horizon problem must satisfy a further condition $|\eta_v| < 1$ (Liddle and Lyth, 2000). In a rough way one can think of ϵ being a condition on "how high" the field starts on the potential and η being a condition on "how far away" from the minimum of the potential (the "true vacuum") the field starts on the potential. Only potentials of certain shapes satisfy these conditions; even with a valid potential, however, the field must have special initial conditions in order for inflation to occur, and occur sufficiently long to solve the fine-tuning problems (Turok, 2002, 3457). Although other inflationary models differ from the single-field case, they too invariably have initial conditions that require varying amounts of fine-tuning.

If a solution to the fine-tuning problems must not introduce further fine-tuning of the order of the original fine-

[36](Ijjas et al., 2013, §3), for example, use the sort of naive "indifference measure" found in many inflation papers to argue that the Planck satellite's results disfavor inflation. Such claims should of course be taken with a grain of salt, given that such "measures" are ill-defined and poorly justified. Also, I have confined my discussion to single universe cosmology, but it is worth noting that measure problems continue to trouble inflation in multiverse scenarios as well. See (Smeenk, 2014) for a detailed analysis of measure problems in the multiverse.

[37]Sciama, for example, urged that we must find some way of eliminating the need for an initial condition to be specified: "Only then will the universe be subject to the rule of theory...this provides us with a criterion so compelling that the theory of the universe which best conforms to it is almost certain to be right" (Sciama, 2009, 2). Sciama was making this claim in the context of the major debate in cosmology of last century, that between the steady state model and the HBB model (Kragh, 1996), but such an idea appears to be a powerful motivation to many proponents of inflation as well.

tuning, then inflation appears to fail here as well, since, as just pointed out, inflationary models have significant fine-tunings of their own. Yet this standard is an unreasonable demand to place on a solution. One should expect that solving one problem can introduce others. If solving one problem does introduce new ones, this does not mean that the original problem was not solved. It just means that the solution comes at a price. In any case, it is not necessarily a mark against a solution for introducing new fine-tuning problems, since these other problems may be more tractable and have natural solutions of their own.[38] More importantly, solving a fine-tuning problem, even if it introduces new fine-tuned parameters of its own, may contribute to a progressive research program by offering new predictions for empirical test, or by exhibiting unexpected explanatory connections and other non-empirical signs of progress.

I claim that the only reasonable standard of success is the weakest one mentioned: that solutions must make the fine-tuned conditions (sufficiently) more likely. In a transparent sense this is just what it means to solve a fine-tuning problem, understood as a likelihood problem. If the problem is that something is unlikely, the solution to that problem makes that thing more likely. It must be stressed, however, that showing that inflation does indeed make uniformity and flatness more likely faces the many challenges of incorporating probability into cosmology as discussed in §3. The difficulties are both philosophical and technical, and of such a degree that, even with a weak condition on success, it seems that cosmologists can only have slim hopes of successfully solving the fine-tuning problems so understood. Thus, insofar as the HBB model's fine-tuning problems are probability problems, the likely verdict, for not only now but the foreseeable future, is that inflationary theory fails to solve them, even on the weakest reasonable standard of success.

To sum up this section, we have seen that inflation solves the horizon problem directly by relaxing the horizon constraint, but essentially in an ad hoc way. Whether this counts in the favor of inflationary theory depends on how one views ad hoc solutions to conceptual problems. The flatness problem is indeed solved by inflation when considered as a dynamical instability problem as well. Although it is often said that inflation solves the uniformity problem too, it plainly does not without some way to transition from the post-inflation vacuum to the empirically verified epochs of the hot big bang universe. Since the details of reheating remain unclear, it can hardly be said that inflation has definitively solved the uniformity problem, although it can certainly be claimed that inflation has afforded cosmologists with the possibility of providing a physical solution. If one interprets fine-tuning problems as probability problems, then at least one requirement, for which I have argued, is that inflation should decrease the fine-tuning of the HBB model. But as yet there is not even a justifiable way to assign cosmological probabilities, much less show that inflation is probable and increases the probability of uniformity and flatness.

6. Concluding Remarks

I have argued in the body of this paper that there is no unproblematic interpretation of the HBB model's fine-tuning problems available for which it can be said that inflation solves them truly. In §2 I showed how the HBB explanation of presently observed flatness and uniformity depends on flat and uniform initial conditions. In §3 I surveyed possible interpretations of the uniformity and flatness problems suggested by the comments of cosmologists in order to determine why such initial conditions are special and why such special conditions are problematic. I then argued that none of these interpretations are without significant technical or conceptual difficulties. Setting such difficulties aside, I showed next (§4) how inflation is understood to address the uniformity and flatness problems. §5 then evaluated the claim that inflation does indeed solve them. Insofar as the flatness problem is an instability problem, inflation can be said to solve it. But on no other interpretation which I considered can it be said (currently) that inflation solves the HBB model's fine-tuning problems.

I conclude with some remarks concerning the larger significance of this investigation and its results. As I suggested in the introduction, inflation is arguably a successful theory due to its empirical successes, i.e. it represents real progress over the HBB model. Yet its adoption was based ostensibly on its success at solving conceptual problems with the HBB model. I claimed in the previous section, however, that if we interpret the HBB model's fine-tuning problems as depending on improbable initial conditions, then inflation is (probably) not a solution to them. Therefore

[38]For example, Smeenk observes that " inflation exchanges the degrees of freedom associated with the spacetime geometry of the initial state for the properties of a field (or fields) driving an inflationary stage. This exchange has obvious advantages if physics can place tighter constraints on the relevant fields than on the initial state of the universe" (Smeenk, 2013, 634).

either the likelihood interpretation of the fine-tuning problems is incorrect and there is another sensible interpretation of these problems, or these problems were not important drivers of scientific progress in cosmology. In the latter case there must be another rational explanation for the adoption and eventual empirical success of inflationary theory, else it seems that inflation was just a tremendously lucky guess. This latter view clashes strongly with the attitude that science progresses rationally. Only in the absence of an alternative should we be inclined toward it.

Although cosmologists appear to favor the improbability interpretation, there are plausible other ways of interpreting the special initial conditions of the HBB model in a way that inflation does solve them. It may be, then, that the fine-tuning of the HBB model is real, and inflation does provide the solution to the fine-tuning problems. But it has not yet been made clear what is problematic about fine-tuning understood in these alternate ways; attempting to make it so seems to me to be a worthy project.

It is also possible that conceptual problems like these are not important or reliable drivers of scientific discovery, or at least not in this case. That is to say, it may be that thinking about such problems leads to the proposal of new theories, yet nothing in the problem statement actually tracks a real, objective problem of the previous theory. If that were the case, it is not so important to ask, "Does inflation solve the HBB's fine-tuning problems?" Rather one might be led to ask different questions; for example: "Why is inflation a good theory?" or "Why was inflation a good theory when it was proposed?" As stated in the introduction, the best argument for inflation now is that it suggests new empirical predictions which can be and have been verified observationally. But when inflation was proposed, none of these observational consequences was known. At that time there was nothing to suggest that inflationary models were more empirically adequate than the HBB model, but theorists enthusiastically adopted them. Were there reasons to think the inflationary approach was better than continuing with the theoretical framework of the HBB model?

One of the most salient features of the inflationary mechanism is that it relaxes the horizon constraint while also reversing the dynamical instability of flatness in FRW models. Does this "unexpected explanatory coherence" have any methodological significance? This fact about violating the strong energy condition in FRW models was there all along, but was overlooked (perhaps because "matter" that failed to satisfy the strong energy condition was not thought to exist) until Guth stumbled upon it (more or less accidentally). But without a prior investigation of the issue, the discovery that both problems are connected together might be seen as a strong suggestion to pursue the solution that solves both. Such a discovery mirrors in a way the unexpected empirical confirmation of novel predictions of a theory, the latter an often acknowledged virtue of a theory. Thus there is a suggestion that in this episode non-empirical theory confirmation has played an important role, and has led to further progress in cosmology.[39]

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[39]Amplifying this line of thought, Dawid (2013) argues that unexpected explanatory coherence (UEC) can be an important facet of assessing a theory's viability and confirmation, particularly in the case of theories like string theory or in the case of cosmology where empirical confirmation often remains out of current, foreseeable, or even potential reach—"it gives the impression that physicists are on the right track" (Dawid, 2013, 45). But an argument from UEC can hardly be conclusive—there may be, for example, "so far insufficiently understood theoretical interconnections at a more fundamental level, of which the theory in question is just one exemplification among many others" (Dawid, 2013, 46), or the correct theory may solve the problems in independent ways, such that the coherence previously found was ultimately irrelevant and misleading.

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