What Is the Horizon Problem?

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12 November 2014

Abstract

Cosmological inflation is widely considered an integral and empirically successful component of contemporary cosmology. It was originally motivated by its solution of certain 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, it is unclear precisely what about them is problematic, and therefore precisely which problems inflationary theory is solving. I analyze the structure of these problems, showing how they depend on explicating the sense in which flatness and uniformity are special in the hot big bang model, and the sense in which such special conditions are problematic (in cosmology). I claim that there is no unproblematic interpretation of either problem available whose solution could explain the putative empirical success of inflationary theory. Thus either a new interpretation of such fine-tuning problems is needed, or else an alternate explanation of the theory's success that does not depend on solving these problems.

Word Count: approx. 17,265 (including footnotes and references)

1 Introduction

Various "fine-tuning" problems are widely thought to plague the great triumph of 20th century cosmology, the hot big bang (HBB) model. Chiefly among them are the so-called "horizon problem" and the "flatness problem." These problems were part of the main motivation for the original proposal of the idea of inflation (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 eventually most of the discipline of cosmology.[1] These problems are still typically presented in modern treatments of cosmology to motivate the introduction of cosmological inflation as a solution thereto. Yet they are not problems over the HBB model's consistency or empirical adequacy; rather they raise concerns over the kind of explanation given by the model for certain "observed" features of the universe, namely spatial uniformity and flatness (Earman and Mosterín 1999).

The eventual confirmation of inflationary theory's empirical predictions, particularly the precise spectrum of anisotropies (and perhaps polarization) of the cosmic microwave background (CMB), has cemented its place in the present standard model of cosmology, the ΛCDM model.[2] These predictions were unforeseen at the time of inflation's proposal. We nevertheless have an explanatory story linking inflationary theory's putative success at solving the HBB model's fine-tuning problems with its later successes at making observational predictions, insofar as scientific progress is gauged by solving scientific problems (Kuhn 1996; Laudan 1978). 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 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 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. For these reasons the present paper investigates the nature of fine-tuning in the HBB model and its solution through inflationary theory.[3] Standard presentations of the fine-tuning problems in the cosmological lit-

[1] The history of these problems is interesting and worthy of study, but I will not engage directly with it. The interested reader is directed to (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.

[2] The ΛCDM model incorporates the empirically-verified aspects of the HBB cosmology, with the addition of cold dark matter (CDM) and dark energy (potentially in the form of a cosmological constant Λ), and an early phase of inflationary expansion.

[3] A point of clarification is in order. Often the terms "fine-tuning", "special initial conditions", and "boundary conditions" are used in intuitive and roughly overlapping ways, but there is some conceptual space between them should one like to look for it.

Usually fine-tuning is descriptively applied to parameters in a physical theory, when those parameters must have the values that they have to an "extraordinary" precision, else the theory's predictions would fail, in some cases catastrophically, to match observations. The familiar examples come mostly from particle physics and concern the "unnatural" values of various free parameters in the standard model (Grinbaum 2012; Donoghue 2007). The term is also used in the popularly debated erature (not to mention in popular and even some philosophical accounts) briefly relate the relevant physical facts and conclude with some vague statement, the content of which is that such facts are problematic. Precisely what makes these facts problematic is invariably left unclear.[4]

As arguments for the existence of fine-tuning such presentations are philosophically unsatisfying (if not unsatisfying in the context of physics as well); thus the aim of the first half of this paper (sections 2-3) is to formulate the problems as clearly as possible in order to clarify their nature as scientific problems. Intuitions about the significance of the fine-tuning problems do vary somewhat among cosmologists (and the few philosophical commentators), so I will endeavor to "cast the net" as widely as possible. Nevertheless, I find that cosmologists are best understood as holding that the physical conditions that give rise to the horizon and flatness problems are in some sense "unlikely." The essential point, however, is that none of the intuitive

"fine-tuning for life." Although fine-tuning in this instance also concerns parameters in a physical model, the debate here strays beyond concerns over the explanatory problems of a scientific theory towards theology. In both cases however these parameters are non-dynamical features of a specific theory, are not subject to manipulation, and are typically fixed by observation or experiment.

Initial conditions and boundary conditions are conceptually distinct from such parameters in a certain sense. Initial and boundary conditions are imposed on the dynamical variables of a theory in order to fix a particular trajectory permitted by the dynamics, in the case of initial conditions at a particular time, in the case of boundary conditions at the relevant boundary. To forestall any confusion I emphasize that initial conditions do not have to be specified at some special "initial" time. "Final" conditions, "intermediate time" conditions, etc. would all do just as well for the deterministic, time-reversal symmetric theories of interest. In any case, they vary from model to model, unlike parameters (normally conceived).

There is of course nothing stopping anyone from thinking that parameters can vary, or even that they are "secretly" dynamical in a more fundamental theory, despite there being a clear distinction in how they are treated in a particular fixed theory. Indeed this viewpoint is the relevant one for discussing explanatory problems in science, as these problems link theories whose laws may be differently dynamical. So I will henceforth set this distinction to the side and continue to refer to the special initial conditions of the HBB model as a fine-tuning problem, which is in any case in keeping with what is evident standard practice.

[4]Philosophical analyses of the horizon problem do exist: see, in particular, (Earman 1995, 134-146), (Earman and Mosterín 1999, 17-24), (Smeenk 2003, 224-243), and (Maudlin 2007, 40-44). Earman (1995) makes a number of important points, but does not pursue the analysis far enough (he considers only that the problem might be a lack of a common cause, a failure of Machian intuitions, or that horizons make uniformity unlikely). 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.

interpretations I survey are free of serious difficulties.

The second half of the paper (sections 4-5) begins by introducing the idea of inflation by demonstrating the basic mechanism behind it, as well as covering how inflation is understood to solve the HBB fine-tuning problems. 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 conclude by evaluating the inflationary program's success at solving the fine-tuning problems. Under some interpretations inflation does indeed solve them, but since no interpretation is problem free there remains some important philosophical work in understanding the success of inflation. Either some interpretation must be fleshed out that shows how inflation solves the HBB model's fine-tuning problems, or else an alternate explanation of inflationary theory's successes, one not relying on problem solving, is necessary.

2 Fine-Tuning Problems in Big Bang Cosmology

There are perhaps any number of aspects of big bang cosmology that one could find puzzling, 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 rehearse the standard presentations of the two problems and introduce the relevant physics. It is useful to go into the details in order to understand

[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. (Linde 1990) and (Linde 1984) outline several other potential problems with HBB cosmology, many of which are external problems like the magnetic monopole problem.

[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 include Liddle and Lyth (2000); Dodelson (2003); Mukhanov (2005); Weinberg (2008); Peter and Uzan (2009); Ellis et al. (2012).

the problems, but the argument they are meant to support is simple. We assume the HBB model and observe certain cosmological conditions (flatness and isotropy). It is either the case that the HBB model explains these observed conditions by fixing certain initial conditions or they are explained by some novel dynamical mechanism. But the HBB model has particle horizons that preclude introducing some 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. The following sections clarify and support this argument.

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

[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." 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 "observers" who are at rest with respect to the universe's expansion, i.e. they follow 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.

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 or perhaps even before the time of recombination, and remained so afterwards.

That is the basic story, but some further details are worth rehearsing. 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 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 scale factor when the universe is expanding): $\rho_\gamma \propto a^{-4}$ (faster than volumetrically). The energy density of photons, being bosons, is given by the energy density of particles with a Bose-Einstein distribution:

$$\rho_\gamma = 2 \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{p}{e^{p/T} - 1} \tag{1}$$

(where p is the momentum of the photons), which, with some simplifying assumptions (Dodelson 2003, 40-41), yields the expression

$$\rho_\gamma = \frac{\pi^2}{15} T^4 \tag{2}$$

(where T is their temperature). It follows, since $\rho_\gamma \propto a^{-4}$, that $T \propto a^{-1}$, or more precisely

$$a(t) = \frac{T_0}{T}, \tag{3}$$

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 (as one would expect).

Higher densities give rise to high reaction rates for the various particular constituents of the universe, and through these constant interactions the universe usually

[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 $(0, \infty)$.

finds itself in a state of equilibrium. 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 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, namely 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 or as far back as one is willing to assume that the model remains accurate; or 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 (at least insofar as laws are thought to operate "locally" or "causally") The HBB model has causal structures called particle horizons, across whose boundaries interactions are not possible. These particle horizons are behind the name "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 traces out all the paths that (non-interacting) light 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).[11] One can imagine the boundary of the

[11]Some of the material on horizons is covered in (Earman 1995). (Davis and Lineweaver 2004)

particle horizon expanding as a sphere of light emitted from the initial point of the worldline. Thus the particle horizon at a time separates objects into two sets: those that "could have been observed" and those that "could not have been observed." 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.[12]

Rather than explaining particle horizons in detail, let me instead give an intuitive illustration of the claim that dynamical explanations of the uniformity of the CMB are precluded by particle horizons. Consider a sample N of photons reaching the Earth from the celestial north pole, and a sample S of photons reaching the Earth from the celestial south pole. At the time of recombination N intersects the path of some fundamental observer N_* and S intersects the path of some fundamental observer S_*. It turns out that the particle horizon of N_* up to the time of recombination does not overlap at all with the particle horizon of S_* up to the time of recombination, i.e. N and S themselves are completely causally disconnected until their arrival at the Earth. They could never have interacted in the past, nor could anything else have served as a common cause for them both—yet they have the identical blackbody spectrum at the identical temperature. How could this be?

Indeed, the situation is considerably more "conspiratorial" than this. There is an astronomically large number of causally disconnected patches that we are now observing in the CMB, the precise number depending on how far back in time one assumes the HBB model applies. So we observe uniformity, yet no "normal" dynamical mechanism, i.e. one that acts causally, could possibly have brought it about. The reaction to these circumstances by contemporary cosmologists is almost uniformly one of suspicion.

Here is an explicit calculation for further illustration. The particle horizon of the observable universe at the present time (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 the 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:

$$\chi_{obs,*} = \frac{a_*}{a_0}\chi_{obs,0} \sim 10^{-3} \times 10^{28}\text{cm} = 10^{25}\text{cm} \tag{4}$$

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).

[12]Minkowski space, for example, is a spacetime that does not have particle horizons.

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

$$\frac{\chi_{obs,*}}{\chi_{cmb,*}} \sim \frac{10^{25}\text{cm}}{10^{23}\text{cm}} \sim 10^2 \tag{5}$$

Thus the observed CMB can be divided into 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 (see, e.g., similar caluclations in Mukhanov (2005, 227)). How could all of these causally disconnected patches have the same temperature?

The local 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 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 would be expected to hold. The presence of particle horizons makes it impossible, however, since there has not even been enough time for the causally disconnected regions in the universe to interact at all, much less come to an equilibrium.

The upshot of these illustrations is that no realistic dynamical process could account for uniformity in the HBB universe, since it is usually assumed that any such realistic dynamical mechanism must act causally (the thought being that interactions occur "locally" in GTR and quantum field theory).[13]. 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 and therefore dependent on a "conspiracy of initial conditions." Thus it follows that the only viable explanation of uniformity in the CMB in the HBB model is that the initial conditions of the universe, at some sufficiently early time, had to be quite nearly homogeneous and isotropic.

[13]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.

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. Singularity avoidance remains a motivation in present theoretical research, but it is not necessarily a motivation for inflation, nor is it needed to avoid fine-tuning issues.[14]

Nevertheless, the existence of particle horizons plays 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 certainly justifiable. In the following I will prefer referring to the general problem of explaining the uniformity of the universe as the uniformity problem, although the term "horizon problem" is well-entrenched as referring to this problem as well. I will occasionally use "horizon problem" to refer to the horizon constraint; I hope 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 ($k = 0$).[15] Since there is a sense 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

[14] Soviet precursors working on similar ideas to Guth's were in fact motivated by avoiding an initial singularity (Smeenk 2005). See, e.g. (Starobinsky 1980).

[15] Three-dimensional examples are unfortunately not so easy to visualize, so these illustrations will have to suffice.

CMB strongly constrain the density parameter $\Omega = \rho/\rho_{crit}$ to very close to one.

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:

$$1 - \Omega(a) = \frac{-k}{(aH)^2}. \tag{6}$$

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. So we can rewrite the previous equation as

$$|1 - \Omega(a)| = \left(\frac{1}{aH}\right)^2. \tag{7}$$

From this equation one 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 $p = w\rho$ for some number w. Differentiating the Friedman equation with which we started and using the continuity equation, one finds

$$\frac{\mathrm{d}\Omega}{\mathrm{d}\ln a} = \Omega(\Omega - 1)(1 + 3w). \tag{8}$$

We wish to see how Ω behaves under slight perturbations from the critical density, so we 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

$$\delta(a) = \epsilon a^{(1+3w)}. \tag{9}$$

Thus flatness is unstable under small perturbations so long as $(1 + 3w)$ is positive, i.e. the strong energy condition is satisfied.[16] Since the strong energy condition is indeed assumed to hold in the HBB model at early times, one concludes 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 $\Omega < 1$).[17] The current density parameter is bounded between $\Omega_+ = 1.0079$ and $\Omega_- = .9969$. According to the previous equation, at recombination the density parameter must have been $\Omega = 1 \pm 10^{-6}$; at the GUT scale $\Omega = 1 \pm 10^{-40}$, i.e. extremely close to flatness.

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.

[16] Energy conditions are often assumed to hold for various purposes. For example, in standard versions of the singularity theorems the strong energy condition (SEC),

$$\left(T_{ab} - \frac{1}{2}T g_{ab}\right)\xi^a \xi^b \geq 0, \tag{10}$$

with ξ a timelike vector, is assumed to hold. For FRW spacetimes the SEC is satisfied iff

$$(\rho + p) \geq 0 \qquad \text{and} \qquad (\rho + 3p) \geq 0. \tag{11}$$

The weak energy condition (WEC) is

$$T_{ab}\xi^a \xi^b \geq 0, \tag{12}$$

for ξ a timelike vector. For FRW spacetimes the weak energy condition is satisfied iff

$$\rho \geq 0 \qquad \text{and} p \geq -\rho. \tag{13}$$

The weak energy condition is satisfied for the kinds of energy and matter considered in cosmology. Dust and radiation (and combinations thereof) satisfy the strong energy condition, but a cosmological constant dominated universe does not.

[17] Because of these facts, the flatness problem is occasionally called the "age problem." The question behind the problem is, "How did the universe get to be as old as it is?"

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 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.[18] 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 standard 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 unsatisfying. This dissatisfaction is exemplified through the identification of the uniformity problem and the flatness problem, and it is directed toward the initial conditions that must be assumed. But what makes the HBB explanation problematic, such that an alternate (dynamical) explanation is demanded? That is the question to be addressed in this section. Unfortunately there is no good answer, I claim, for all of the intuitive answers given by cosmologists (and philosophers) are fraught with significant difficulties.

To begin, 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 above, 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 a comment suggesting that such facts are "puzzling" and yield "impressive numbers" (Guth

[18] "The gripe cannot be that the standard big bang model is not empirically adequate, for it certainly can be fitted to the data at issue. Nor can there be a legitimate complaint to the effect that the standard big bang model offers no explanation of the uniformity of the [CMB]" Earman and Mosterín (1999, 19).

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). One could easily multiply examples further, yet one would only find similar reactions.[19]

Few authors note that the HBB model is empirically adequate to the observed uniformity, but some do. Among those who do, one finds suggestions that the horizon problem indicates that the HBB model has "shortcomings in predictive power" (Baumann 2009) or that such models "give no insight" (Misner 1969) into the uniformity of the CMB.[20]

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[19]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.

The sort of explanations found in statistical physics differ from the paradigmatic cases of mechanics, however, as one attempts to show that some "generic" behavior results dynamically with high probability. Yet it is often supposed by philosophers that the success of this sort of "equilibrium" explanation depends on the assumption of a certain "special initial condition"—low entropy in the past, as it is usually claimed. (There is plenty of dissent however e.g. (Earman 2006; Wallace 2011).) In this case it has been argued that there is a legitimate demand for explanation (Price 2002, 1996), and also contrarily that there is no reason to expect that such an explanation should be forthcoming (Callender 1998, 2004). So, in the statistical mechanical case there is at least a putative demand for explanation for a certain empirically supported feature of the world: Why was the entropy of the universe low to begin with? Price argues that such initial conditions demand explanation because they are *special*: unlikely, non-generic, improbable, etc. on the standard approach to counting states. As the discussion below shows, there is thus a strong analogy with the uniformity and flatness problems.

[20]Misner is often acknowledged to have been instrumental in promoting the horizon problem (although not under that name) as a problem for cosmology. He adopted an uncharacteristic attitude (for the time) towards cosmology which has been widely adopted: "Rather than taking the unique problem of relativistic cosmology to be the collection and correlation of observational data sufficient to distinguish among a small number of simple cosmological solutions of Einstein's equations, I suggest that some theoretical effort be devoted to calculations which try to 'predict' the presently observable universe" (Misner 1968). See (Smeenk 2003) for historical comments on

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 the problem. Certainly philosophers have made claims that fit this general pattern (Munitz 1986; Earman 1995; Earman and Mosterín 1999; Maudlin 2007). 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).[21] But in most cases these available analyses misdiagnose cosmologists' concerns, replacing them with the 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 rather more systematic in surveying various ways that these initial conditions are physically special, and why special initial conditions of these kinds are problematic.

It is useful to write out the argument of the previous section explicitly:

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:

1. Uniformity and flatness are special initial conditions. (But in what way?)
2. Special initial conditions are problematic. (But why?)
3. Therefore, uniformity and flatness are problematic initial conditions (give inadequate explanations).

Misner's approach and its influence.

[21] My eventual analysis actually agrees with this statement, but fills in the details for why explanatory deficiencies are problematic in the context of cosmology.

Why are uniformity and flatness special? 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 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 of (Earman 1995; Earman and Mosterín 1999). Regarding such large numbers, for example, they 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)

Clearly, the tone of the footnote leaves little doubt that the authors believe there is no such substantive difference. Yet a careful analysis of the problems shows that there are nevertheless significant 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. So it is at least plausible that the numbers to which Guth refers do arguably have a significance beyond their size or accuracy when suitably interpreted, and do make for a substantive difference within the relevant context. This difference is not simply in terms of "colossal" numbers, but in real features of the cosmology in question. An analysis that dwells on the unreflective remarks of cosmologists rather than their physical intuitions will, I think, surely miss the mark.

Whether cosmologists have a "fascination" or any other psychological reaction to such numbers is therefore (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.[22] 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 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."[23,24] 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.[25]

[22]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."

[23]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)). 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) recognizes 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).

[24]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).

[25]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.

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.[26]. 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, though, 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: 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. 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. So, one might invoke a heuristic that a maximal degree of symmetry is unphysical, or adopt the operative heuristic that cosmological models should not exhibit dynamical instabilities.[27]

It is therefore possible to identify the HBB model's initial conditions as special in a clear sense. But then one should be able to explain why high degrees of symmetry and dynamical instability are problematic in cosmology. It does not seem to be the case, anyway, that models with high degrees of symmetry or dynamical instabilities necessarily lack predictive or explanatory power. Indeed one often finds physical phenomena exhibiting precisely these characteristics, where these characteristics are used essentially to explain phenomena.[28] Is there some other way these characteristics are problematic in the context of cosmology? Perhaps there is, but one at least finds no suggestion of how in the commentaries of cosmologists, or anywhere else for that matter. So, although I find the explication of specialness as simplicity of some

[26]The interplay of naturalness and anthropic arguments is explored in various chapters of (Carr 2007), especially (Donoghue 2007; Dimopoulos and Thomas 2007). The influence of particle physics on cosmology has led to naturalness becoming an important heuristic in cosmology as well (Linde 1990, 2007)

[27]It is certainly not clear, however, that stability is necessarily a good heuristic demand in cosmology. See, e.g., (Coley and Tavakol 1992).

[28]Chaotic systems in particular come to mind as systems exhibiting precise dependence on initial conditions, and there is indeed a lack of predictive power in such systems. But systems exhibiting dynamical instability do not necessarily behave chaotically—the HBB model, for example, does not.

interest, it is quite unclear how simplicity is problematic in the context of cosmology. Without such an explication, it cannot be said that simplicity is at the heart of the HBB model's fine-tuing problems.

What cosmologists do say frequently is that uniformity and flatness are "unlikely" or "improbable." 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.[29]

There are, however, significant challenges to adopting improbability as the explication of specialness in this context. 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 theoretical problems with defining a natural probability measure on the space of possible cosmologies are well-detailed in Schiffrin and Wald (2012); Curiel (2014), but there are as well a number of philosophical problems with making sense of probability in cosmology that cast doubt on interpreting specialness as improbability in the context of these problems.[30] In any case, it is important to recognize that the success of problematizing uniformity and flatness in this way depends crucially on successfully meeting these challenges. An honest assessment of the prospects of meeting these challenges, however, is rather dark.

Nevertheless, if uniformity and flatness are indeed improbable, it is at least possible to explain why they are problematic—precisely because improbable initial conditions lack explanatory power (and therefore 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

[29] 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). It is important to stress that this is not the only possible understanding of fine-tuning problems however.

[30] Briefly, here are two significant issues (Ellis 2007; Smeenk 2013): Due to the uniqueness of the universe it is difficult to know what the appropriate reference class for cosmological probabilities is. It is also not apparent what the empirical significance of such probabilities is, beyond the absurd image of a creator throwing darts at a board of possible universes (Penrose 1979).

credences. Winning the lottery is improbable, but a winning lottery ticket in hand changes that assessment drastically. The analogy is not especially strong though. 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 have been otherwise (for all we know) than what the HBB model tells us; if they were indeed different, then our HBB explanation of the present conditions fails. Thus the problem is that improbable initial conditions lack explanatory power compared to an explanation that is robust with respect to the initial conditions.

Agreeing with Earman (1995, 146) and Smeenk (2003, 239), some may not be convinced that lacking explanatory power is all that problematic for a theory (using 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 than the latter. But when they are not, it is not so clear that the more 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). For example, if one assumes the strong energy condition, then the only permissible expanding FRW models are decelerating. Observations that suggest that the universe's expansion is decelerating would be explained by the nature of matter in such a model: The truth of the strong energy condition explains these observations[31,32] But adding additional constraints on a theory limits the descriptive possibilities of that theory, thus 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, one should recognize the general costs to excluding descriptive possibilities (less unification of phenomena, lack of simplicity, etc.) and balance 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.[33] Indeed one occasionally hears expressed the idea that the perfect

[31] This is merely an example. Observations of course suggest that the expansion of the universe is accelerating, hence the inclusion of Λ in the ΛCDM model.

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

[33] There are certainly theoretical motivations to preserve some degree of descriptive power in

cosmology would include no free parameters, would leave no cosmological feature accidental, etc.[34] Thus there is considerable motivation in cosmology to pursue theories with greater explanatory power. A theory that lacks it, especially one that is thought to be correct only at certain averaging scales and in certain energy regimes, can legitimately be seen as problematic.

To recap this final analysis, the most intuitive analysis of the uniformity and flatness problems (as understood by cosmologists) depends on the initial conditions being special because they are improbable; improbable 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—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.

The fact that these improbable initial conditions are unverifiable represents a significant theoretical risk; as a matter of risk reduction in theory construction, theorists would prefer to hedge their bets on a theory with greater explanatory resources (some dynamical mechanism that drives the universe towards the observed conditions) and to reject the HBB explanation of uniformity and flatness. Yet 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.

This argument hinges on the success of substantiating the attributions of probability in cosmology, a task that faces many serious challenges. Other explications of

cosmology. Namely 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.

[34] "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)

specialness in cosmological fine-tuning problems, such as a high degree of symmetry or dynamical instability, could be substituted, but do not clearly problematize the HBB model's explanations of these problems. Thus I conclude that there appears to be no problem free analysis of the HBB model's fine-tuning problems.

4 Inflation

Inflationary theory, in its basic version, suggests that the universe underwent a phase of accelerated expansion very early in its history. In this section I rehearse the basic dynamics of inflation and show how it is generally understood to solve the uniformity and flatness problems. A few brief remarks on the general strategy of inflation and how it solves the fine-tuning problems of the HBB model will serve as an introduction before turning to the more detailed presentation.

The argument of the previous section is meant to give substance to rejecting the HBB explanation of the observed conditions. If the initial conditions that are necessary to explain them are problematic because special, then some assumption in the argument that compelled these initial conditions on us must be rejected as well. One might, for example, reject fundamental assumptions such as the cosmological principle or the validity of GTR at early times. The existence of horizons also 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, without the need to reject the more fundamental assumptions. Indeed, if the entire observable universe were within a single horizon volume at a sufficiently early time (at least by recombination, say), then it would appear to be possible to give some such "causal" explanation. As I will explain below, this minimally requires an amount of expansion in the early universe equal to the amount of expansion after the earliest time when we believe the HBB model is valid. 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 amount of expansion possible. 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.

The inflationary solution to the horizon problem is said to give "dynamical" solutions to the uniformity and flatness problems.[35] It is often remarked that a

[35]Inflation is also claimed to solve a host of other "problems" with the HBB model—see (Linde

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.[36] The solution to this problem is 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 spectrum of inhomogeneities due to "quantum fluctuations").[37,38]

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

$$1 - \Omega(a) = \frac{-k}{(aH)^2}. \tag{14}$$

With $1/(aH)^{-1}$ being driven towards zero by inflation (a increases greatly while H remains constant), $\Omega(a)$ is driven to one, i.e. the critical density. It is therefore 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 thereby reversed (flatness becomes a point of stability instead of metastability), and (it is claimed) it is more likely that the present universe should appear flat. Whether inflation truly solves the problems it sets out to solve will be assessed in the final section, after explaining precisely how inflation works (classically).

1990, 16ff) or (Linde 1984, 939ff) for explanations of how inflation does so. These problems are for various reasons not relevant to the present context of discussion.

[36]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.

[37]Reheating depends on the quantum field theoretic considerations beyond the scope of this paper, so nothing more will be said about it for now; it is however crucial for the success of the inflationary proposal.

[38]It is also claimed that inflation is an effective mechanism for smoothing inhomogeneities. Since the FRW universe is homogeneous by assumption, one must investigate this claim in a larger context of inhomogeneous models.

4.1 Classical Dynamics of Inflation

A standard way to define inflation is as a stage in the early universe where the Hubble radius is decreasing:[39]

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{aH}\right) < 0. \tag{15}$$

It is often described as a stage of accelerated expansion, or a stage where "gravity acts repulsively" (Mukhanov 2005, 230).[40] Both of these follow directly from the above condition. It may be illuminating to demonstrate these facts. First, take the temporal derivative of the Hubble radius:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{aH}\right) = -\frac{1}{(aH)^2}\ddot{a} < 0. \tag{16}$$

It follows that $\ddot{a} > 0$. Thus the given condition, decreasing Hubble radius, implies accelerated expansion.

Next consider the second FRW dynamical equation, the continuity equation, and impose the condition $\ddot{a} > 0$:

$$-\frac{4}{3}\pi(\rho + 3p) = \frac{\ddot{a}}{a} > 0. \tag{17}$$

It follows immediately from this equation that

$$p < -\frac{1}{3}\rho, \tag{18}$$

and, assuming the weak energy condition holds, that the stress-energy responsible for inflation has negative pressure. The negative pressure during inflation represents a violation of the strong energy condition, $p > -\frac{1}{3}\rho$. The strong energy condition captures, in a sense, that gravity is attractive in GTR (Malament 2012, 166). Normal matter obeys the condition and gravitates (attractively). So during an inflationary stage gravity acts "repulsively."

Finally, it is sometimes remarked that inflation is a stage of exponential expansion. What is usually meant by exponential expansion is the amount of expansion,

[39] The Hubble radius is defined as the (physical) distance at which space is receding at the speed of light: $d_H = H^{-1}$. Cosmologists often use "co-moving" coordinates, where distances between fundamental observers remain constant (distances are divided by the scale factor). In co-moving coordinates this distance is $\chi_H = (aH)^{-1}$.

[40] It is somewhat misleading to describe accelerated expansion as gravity acting repulsively, insofar as normal matter still gravitates attractively. The sense in which gravity acts repulsively is how accelerated expansion affects the structure of spacetime.

not necessarily the rate that the expansion occurs. The standard measure of expansion is given in terms of *e-foldings*, which is the amount of time for the scale factor to grow by a factor of e. Depending on when inflation takes place different numbers of e-foldings are required to solve the horizon problem. If H is exactly constant, i.e. has the form of a cosmological constant, then the scale factor does, however, increase exponentially with time.

Inflation is generally supposed to occur in the very early universe, but the details depend on the particular inflationary model. The only constraint is that sometime after inflation ends the standard hot big bang picture, at least the part that relies on well-confirmed theory and observations, must begin.[41]

4.2 Inflation as a Solution to the Horizon Problem

The crucial realization, made originally by Guth, is that one simple assumption, a 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 of a dynamical explanation of uniformity.

The way that inflation relaxes the horizon constraint merits a more detailed explanation than that given above. First, let us see how the horizon changes during different phases of the HBB universe (radiation domination, matter domination, and dark energy 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:

$$a_{eq} = \frac{\Omega_r}{\Omega_m} \approx 3 \times 10^{-4}. \tag{19}$$

Thus matter-radiation equality occurs at redshift $z_{eq} \approx 3250$, well before recombination ($z_* \approx 1090$).[42,43]

[41] Inflation is usually implemented by a scalar field called the inflaton. This scalar field has unknown connections to particle physics, although at various times it has been thought that the Higgs field could be the inflaton. See (Smeenk 2003) for more.

[42] Redshifts are a convenient and common way to describe distances and times in cosmology. What is happening right in front of you is effectively at redshift 0; the initial singularity of the big bang occurs at infinite redshift. To convert between redshifts z and scale factors a, one uses the following relation:

$$1 + z = 1/a. \tag{20}$$

[43] Matter-dark energy equality occurred much more recently, at about a redshift of $z_{eq} \approx 0.7$. Therefore the universe has only expanded slightly since then (only about an e-folding), so dark energy domination will be neglected in these calculations.

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

$$\chi_{\delta a} = \int_{a_1}^{a_2} \frac{\mathrm{d}a}{a^2 H}. \tag{21}$$

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 $a_2 = 1$:

$$\chi_{(*,1)} = \frac{1}{H_0} \int_{a_*}^{1} \frac{\mathrm{d}a}{a^{1/2}} = \frac{2}{H_0}(1 - a_*^{1/2}). \tag{22}$$

The universe was matter-dominated before recombination (as just noted), and radiation-dominated before matter-radiation equality. Data indicates 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, $a_2 = a_*$:

$$\chi_{(0,*)} = \frac{1}{a_*^{1/2} H_0} \int_{a_i}^{a_*} \mathrm{d}a = \frac{1}{H_0} \frac{a_* - a_i}{a_*^{1/2}}. \tag{23}$$

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

$$\frac{\chi_{(0,*)}}{\chi_{(0,1)}} = \frac{a_*^{1/2}}{2 - a_*^{1/2}} \approx 0.015, \tag{24}$$

where the term proportional to a_i has been dropped because it is negligible. In the HBB universe, not surprisingly, almost all of the distance light could have traveled has been since recombination.

Almost all of the *expansion* happened during radiation domination however. During matter-domination (and dark energy domination) the universe undergoes about $\ln(a_0/a_{eq}) \approx \ln(3 \times 10^3) \approx 8$ e-foldings of expansion. Assuming that the HBB model is valid at the GUT scale, the universe undergoes $\ln(a_{eq}/a_{gut}) \approx \ln(3 \times 10^{21}) \approx 50$ e-foldings of expansion before matter-radiation equality.

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 distance of $\chi_{(0,*)}$.[44] 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 horizon distance, $\chi_{(*,1)}$. So the minimum condition for causal contact is

$$\chi_{(0,*)} \geq \chi_{(*,1)}. \tag{25}$$

In an FRW universe that undergoes a radiation- to matter-dominated transition the condition is equivalent to $a_* \geq 4/9$. The scale factor at recombination (and matter-radiation equality) is clearly much, much smaller than this value, and therefore, again, it is clearly not possible that CMB photons have a shared causal past.

Now I demonstrate how an inflationary stage can solve the horizon problem. An inflationary stage's dynamics depend on the details of the inflationary model, but the Hubble parameter in simple models remains approximately constant (I 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:

$$\chi_{(*,1)} = \frac{2}{a_*^{1/2} H_0}(a_*^{1/2} - a_*) \qquad \chi_{(f,*)} = \frac{1}{a_*^{1/2} H_0}(a_* - a_f). \tag{26}$$

The particle horizon grows during inflation according to

$$\chi_{(i,f)} = \frac{1}{H_f} \int_{a_i}^{a_f} \frac{\mathrm{d}a}{a^2} = \frac{1}{H_f} \frac{a_f - a_i}{a_i a_f}, \tag{27}$$

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

$$\chi_{(i,f)} = \frac{1}{a_*^{1/2} H_0} \frac{a_f}{a_i}(a_f - a_i). \tag{28}$$

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

[44] These distances are co-moving distances, the physical distance divided by the scale factor.

the horizon problem. Combining the particle horizon during inflation and radiation domination gives

$$\chi_{(i,*)} = \frac{1}{a_*^{1/2} H_0} \left[a_f \left(\frac{a_f}{a_i} - 1 \right) + a_* \right], \tag{29}$$

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):

$$\frac{a_f}{a_i} \geq 2 \frac{a_*^{1/2}}{a_f}. \tag{30}$$

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 inflation claims to solve the HBB model's fine-tuning problems and how it relaxes the horizon constraint, I conclude by evaluating those claims and their significance. The main negative point I will make is that inflation (probably) does not solve them, at least insofar as the problems are seen to depend on improbable initial conditions in the HBB model and one grants 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 it is not clear how other ways of interpreting fine-tuning problems can be substantiated as conceptually problematic.

To review, the existence of particle horizons is not so much a problem in this context as a constraint on solutions to the uniformity and flatness problems. Horizons preclude a local dynamical explanation of uniformity and flatness that does not rely on simply assuming these conditions. Assuming these special initial conditions is therefore required in order to explain present observations. Viewing these special initial conditions as problematic, physicists believe that a better explanation of the observed conditions which they are meant to explain must be possible, and so reject the HBB explanation.

Inflationary theory attempts to solve the fine-tuning problems by modifying the HBB model. Conceiving inflation as a stage of accelerated expansion in the early universe, one sees that the inflationary approach attacks the two fine-tuning problems by directly addressing a common constraint: the size of the horizons. Accelerated expansion in the early universe (pre-HBB universe) increases the size of the particle horizon by the ratio of scale factors post-inflation to pre-inflation (28)-(30). By positing a period of accelerated expansion preceding the hot big bang universe (in particular the uniform, flat initial condition of the hot big bang universe), inflationary theory increases the size of the present particle horizon so that all of the physics of the HBB model, in particular recombination, occurs within a single causal patch. Surprisingly, addressing the horizon problem in this way automatically solves the flatness problem—when it is considered as a stability problem—as accelerated expansion makes spatial flatness a dynamical attractor (it is dynamically unstable with decelerated expansion). Inflation also gives rise to the possibility of a causal explanation of uniformity through post-inflation reheating.

So has inflationary theory solved the HBB model's fine-tuning problems? Although it can be made reasonably clear what the uniformity and flatness problems are (at least to the standard found in the standard treatments in cosmological texts), such that a proposal like inflation is widely accepted as a solution to them, the difficulty in definitively characterizing what precisely is problematic about the special initial conditions means that it is difficult to say whether inflation truly solves the fine-tuning problems. Different ways of construing the problems lead to different evaluations of success.

Suppose, for the moment, that the horizon problem was not merely a constraint on solving the HBB model's fine-tuning problems, but was a problem in its own right. Does inflation solve this horizon problem? If the problem is the existence of horizons, then inflation does not (necessarily) remove horizons, so it is not a solution. But if the problem is instead that the observable universe does not fit in a single horizon volume in the early universe, then obviously yes, inflation is a solution. Yet it does so in essentially an ad hoc way. I take it that most philosophers find ad hoc explanations (theories, etc, etc.) unsatisfying.[45] In the case at hand, if the addition of a pre-big bang inflationary stage were only to achieve the relaxation of the horizon constraint sufficiently and affected nothing else, it would be quite difficult to see how the maneuver accomplished anything of epistemic or methodological value. But we need not consider such a possibility, since the sort of theory modifications made in science usually have effects that range far beyond their intended consequences, and in this case certainly do.

[45](Lakatos 1970) is a paradigmatic example of this view, arguing that ad hoc maneuvers are a sign of a degenerating research program. There is respectable dissent however. Laudan claims, for example, that "an ad hoc theory is preferable to its non-ad hoc predecessor" (Laudan 1978, 116), by way of solving more problems than its predecessor.

Suppose then that one wants to solve the uniformity problem and one recognizes that the horizon problem is a constraint on the former problem's solution. Uniformity in the CMB's temperature suggests an equilibrium explanation, but the existence of particle horizons in the early universe precludes its possibility. By the inflationary maneuver the constraint of horizons is avoided, but at the cost of this possibility of an equilibrium explanation. Inflation essentially *empties* the universe of particles (this is typically demonstrated in so-called "cosmic no hair theorems"). So in a way the uniformity problem is solved—the universe does become uniform—but not in a way that is consistent with observation. Inflation therefore sounds rather like a failed solution to the uniformity problem. Nevertheless an ad hoc maneuver leads to 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 also leads to new problems, namely how to transition smoothly to the empirically confirmed parts of the big bang story. Has reheating solved this problem? The verdict unfortunately is not yet clear. An illuminating discussion of reheating here would require bringing in quantum considerations beyond the scope of this paper, so suffice it to say that reheating is not well understood, in part because the microphysical details of inflation are unknown. Nevertheless, 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.[46]

Let us turn to the flatness problem now. 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. The horizon constraint is addressed in an ad hoc way, but the stability constraint appears to be solved by serendipity. There is 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 (as demonstrated in the section on inflation above) that the strong energy condition is violated, from which it follows that an

[46] 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 echoes: "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).

inflationary stage increases the particle horizon and flatness is a dynamical attractor during inflation.

Differently considered, however, the uniformity and flatness problems are not so clearly solved by inflation. In particular, when one views fine-tuning problems as "likelihood" problems (which appears to be the most intuitive analysis of the problem), there is no convincing proof that inflation has solved the HBB's fine-tuning problems. Not only is it uncertain whether there is an objective sense of probability on the space of possible universes, it is also not clear that inflation would itself be in any sense "likely" on such a measure (Schiffrin and Wald 2012; Curiel 2014). 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.

Let us suppose that the project of addressing the probability problems of inflationary cosmology remains tenable despite the serious challenges it faces. There are various ways one might interpret 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. I consider how inflation fares on each of these in turn.

Evidently many physicists view the elimination of initial conditions as something of an ultimate goal of physics.[47] Be that as it may, inflation certainly does not succeed at realizing this goal. In whichever guise inflation takes, initial conditions of some kind or another are required (Vachaspati and Trodden 1999; Brandenberger 2007). 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_ν, which for inflation to occur, must satisfy the condition $\epsilon_\nu < 1$ (the potential must have a region which causes accelerated expansion of the universe); η_ν, which for inflation to last long enough to

[47] 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.

solve the horizon problem must satisfy a further condition $|\eta_\nu| < 1$ (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.

Penrose criticizes inflation (Penrose 1989) (in part) for failing to solve the special initial condition problem of statistical mechanics, embodied by the improbability of the low entropy initial state of the universe.[48] He argues that if the second law of thermodynamics is true, then the states of the universe during inflation all must have lower entropy than the initial HBB state one is trying to explain, and therefore the states during inflation must be less likely than the initial states of the big bang (by statistical mechanical arguments). There are two points to make. The first is that requiring inflation to solve the low entropy problem is an unfair demand unless the goal of inflation is to eliminate all initial conditions. Inflation can certainly be a successful theory without solving all the problems that an envisaged theory of initial conditions, e.g. quantum gravity, should solve. Secondly, if Penrose's argument is sound, it adds significantly to the challenges of interpreting HBB fine-tuning problems as likelihood problems.

If a solution to the fine-tuning problems must not introduce further fine-tuning of the order of the original fine-tuning, then inflation appears to fail here as well, since, as just pointed out, inflationary models have significant fine-tunings of their own. From the point of view of theory choice, this standard is an unreasonable demand to place on a solution. Just as it is unreasonable to demand that a solution to a fine-tuning problem removes all fine-tuning or even solves other important ones (low entropy problem, cosmological constant problem, etc.), it is unreasonable to expect that solving one problem does not introduce others. These other problems may be more tractable and have solutions of their own.[49] More importantly, solving a fine-tuning problem, even if it introduces new fine-tuned parameters of its own, may

[48] "I think it's all coupled to the second law of thermodynamics problem. The horizon problem is a minor part of that problem. It's not the big problem and, in a sense, that's what I always thought" (Lightman and Brawer 1990, 427).

[49] " In effect 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).

contribute to a progressive research program by offering new predictions for empirical test, or perhaps unexpected explanatory connections and other non-empirical signs of progress.[50]

Viewing fine-tuning problems as likelihood problems, it seems that the most generous standard to hold solutions to is the weakest one: that they must make the fine-tuned conditions (sufficiently) more likely. Showing that inflation does indeed make uniformity and flatness more likely faces the many challenges of incorporating probability into cosmology as I have emphasized. The difficulties are both philosophical and technical, and of such a degree that, even with a weak condition on success, I believe 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 is that inflationary theory fails to solve them, even on the weakest reasonable standard of success.

6 Concluding Remarks

Various well-known approaches to scientific methodology focus centrally on problems in science and how solutions of these problems may lead to progress (Popper 2002; Kuhn 1996; Laudan 1978). Inflation is arguably seen as 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 either the likelihood interpretation of the fine-tuning problems is incorrect and there is another sensible interpretation thereof, or these problems were not important drivers of scientific discovery and there must be another rational explanation for the adoption and eventual empirical success of inflationary theory.

Although cosmologists appear to favor the improbability interpretation, it is plausible that they are simply mistaken about the conceptual nature of the problems. One does not need a philosophical analysis of specific scientific problems to recognize a solution, which is to say that physicists get by well enough without dwelling on

[50]Critics often complain that extensions of the standard model of particle physics, "beyond the standard model" (BSM) physics, like GUTs, supersymmetry (SUSY), string theory, etc., introduce new, unexplained parameters. It is reasonable to think of this as a cost (for simplicity reasons if for nothing else), but for the reason just given it is not necessarily a failure either. There are many other considerations involved in advancing a scientific research program besides simple parameter counting and naive fine-tuning comparisons.

the more philosophical aspects of scientific methodology. Thus their remarks need not be taken fully at face value. There are indeed 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.[51] But it is not at all clear what is problematic about fine-tuning understood in these alternate ways.

Perhaps then problems are not important or reliable drivers of scientific discovery, or at least not in this case. It may be that thinking about problems leads to proposals of new theories, yet nothing in the problem statement tracks a real, objective problem of the previous theory. In that case, it is not so important to ask, "Does inflation solve the HBB's fine-tuning problems?" Rather it is more important to ask, "Why is inflation a good theory?" or "Why was inflation a good theory when it was proposed?"

Answering these questions puts one in the context of theory choice. Perhaps 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?

Perhaps it is enough that a theory should merely "pull its own weight," by, say, offering a more fruitful framework for investigations, or by giving better explanations while suffering no empirically significant loss of descriptive power. Inflationary theory does arguably provide a more fruitful framework for theorizing about the early universe, and arguably explains our universe better than the HBB model. Such theoretical virtues are often seen as important in the context of theory choice, but are not however usually considered epistemic virtues. They have pragmatic value, but are not truth-conducive. If that is correct, then it seems an astonishing case of epistemic luck that cosmologists plumped for a theory that appeared to save no recalcitrant empirical phenomena nor solve any inconsistency in the standard model, but which later was strikingly confirmed empirically.

I also remarked that one salient feature 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 FRW models was there all along, but

[51] This claim may be accused of simply "moving the goalposts;" if so, I accept it. The placement of the goalposts was bad in the first place and there may well have been perfectly reasonable locations closer at hand, had one considered the nature of the problems carefully.

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 non-empirical theory confirmation has played an important role in the progress of cosmology through this episode.[52]

These, anyway, are some possible philosophical ramifications of my analysis of HBB fine-tuning. To recap, that analysis established first that the HBB model must rely on initial conditions to explain the observed conditions of flatness and uniformity. Secondly, there are various interpretations available of how these initial conditions problematize the HBB model, the most intuitive of which is that these conditions are improbable and therefore lack explanatory power. Nevertheless, none of these interpretations are free of problems, so it is unclear whether HBB fine-tuning can be substantiated. Thirdly, inflation putatively solves the fine-tuning problems by relaxing the horizon constraint, thus reversing the instability of flatness in FRW models and making possible a dynamical explanation of uniformity via reheating. Fourthly, whether inflation in fact solves the fine-tuning problems depends on how those problems are explicated. Insofar as they are understood as probability problems, it is unlikely that inflation solves them, even if one makes the conditions of success as weak as possible, since the nature of cosmological probabilities remains opaque. The further significance of this analysis, as I suggested in the introduction and these concluding remarks, is that, on pain of giving up on the notion of rational scientific progress, either one must make good another interpretation of fine-tuning problems, or reconsider the epistemic status of theoretical virtues, such as fruitfulness and explanatory power, or non-empirical theory confirmation as a way to ground the viability of inflationary theory and explain its empirical successes.

[52]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, forseeable, 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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