Modern Cosmology: Explaining the Universe

How inductive reasoning and predictive science turns ‘description’ into ‘explanation’—and why that’s okay

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In most scientific practice, physical models are rejected or supported through rigorous, controlled testing. In fields like cosmology, however, the agency of the scientist and capacity to test predictions is limited. In this note, I examine the justification for scientific theories of cosmology—in particular, inflation—and investigate the question of what it is exactly that allows us to do scientific reasoning about the early universe. In particular, I choose the question: How does inflation provide a scientific explanation of our observations?

1 Introduction

On February 4 of this year, science publicizer Bill Nye “The Science Guy” held a much-publicized debate with the vocal Creationist Ken Ham, CEO of Answers in Genesis and founder of the Creation Museum. In his opening statement, Ham presented view that was unfamiliar to many practicing scientists:

> There’s different types of knowledge, and I believe this is where the confusion lies: There’s ‘experimental’ or ‘observational’ science, as we’ll call it. That’s using the scientific method, measurement, observation, experiment, testing; that’s what produces our technology: computers, spacecraft, jet planes... [but], you see, when we’re talking about origins, we’re talking about the *past*... we weren’t there. We can’t observe that, whether it’s molecules-to-man evolution or whether it’s a creation account. When you’re talking about the past, we like to call that ‘origins’ or ‘historical’ science. Knowledge concerning the past. [11]

To Nye, the distinction was decidedly bogus. To Ham’s supporters, however, the claim seemed reasonable: *If we weren’t there to see something, how do we know how it happened?* The answer to this question is actually somewhat nuanced. In fact, it is that *we don’t*—but that’s okay.

When explaining "observational" science, Ham evokes images of scientists holding pipettes over test tubes, sequencing DNA, and inventing electronics. It is an idealization of scientists as people testing and observing phenomena, and generalizing them into patterns, trends, and causal rules that can be tested and sometimes applied in technology. This, surely, is a fine general picture of operational science.

As for "historical" science, one basis for the dichotomy Ham pointed out is this: *the past can't be tested.* Furthermore, to rely on arguments that present observations are "effects" of past "causes" relies on causal laws having held in the past—but we can't test whether a law held before our existence.

Thus we come to the prehistory and the beginning of the universe: the time period disputed by young-Earth creationists. But notwithstanding the creationist arguments, the beginning of the universe is not an easy issue within the scientific community. We aren't capable of producing "test universes" in controlled environments like the laboratory, so the predictive power of our theories may only be indirect and observable in other settings, like high-energy particle accelerators—and even then, there is no provably correct way to link the indirect effects in the atom smasher to the beginnings of the universe, without making assumptions about the simplicity or static nature of physical laws. Furthermore, this means that the basic questions of cosmology can only be answered through *observation* and not *test*, which makes it difficult to establish causation.

Yet, despite these difficulties, we have come up with remarkable and elegant theory of the beginning of the universe that closely matches our measurements: It begins with the big bang, a period of rapid expansion (*inflation*), and the recombination of particles and atoms. These then collapsed over time to produce the mostly homogeneous galactic and cluster structure we see when we look deep into space.

However, an oft-cited requirement to be a scientific theory is that a proposition be *testable.* The theory of inflation, for example, was constructed to match our observations about the homogeneity of the universe, particularly the cosmic microwave background (CMB). It can't be validated on external phenomena because we only have one universe. Thus, the questions I raise in this note are: **How is inflation an *explanation* of what we see, any more than a simple *description* of the structure of the universe and CMB? And how can we validate the theory as *scientific?***

As it turns out, the key lies in Ham's picture of "observational" science. Accepting it has some interesting philosophical implications that bring us to the answer of this question. In Section 2, we will discuss some basic issues in the philosophy of science. Section 3 will discuss the foundations of modern cosmology. Then, in Section 4, we will discuss the importance of simplicity in the study of science, before revisiting inflation theory in Section 5 and then concluding in Section 6.

2 Science and Causality

Induction

Developing physical theories involves making repeated observations and extrapolating these observations to laws. This process is known as *inductive reasoning*, and curiously, it seems entirely rational but *isn't necessarily valid.* Take the example of Jerry the cat from UT Austin professor Alan K. Cline:

> Jerry was an outdoor cat, and every day, as I was getting in the car and about to come down here, Jerry would be sitting there, and seeing me. And I imagined what was going on in Jerry's mind. Now, the fact is that sometimes Jerry went in the car as well. But [when Jerry was in the car], he always went to the vet. ...So when Jerry saw me getting in the car every day and driving away, Jerry's saying "Alan's going to the vet again!" [7]

The particular case of Jerry's unfortunate conclusion is an example of sampling bias, which scientists try to get rid of by controlling and randomizing experiments. This control, then, can establish *causation* (rather than correlation), which is the philosophical foundation on which any physicist rests in order to sleep comfortably at night.

However, this form of reasoning about causation is inherently incomplete: it is impossible in principle to validate general laws about causation on the basis of observations. Scottish philosopher David Hume is often credited with this point, made in his *Enquiry Concerning Human Understanding*:

> As to past Experience, it can be allowed to give direct and certain information of those precise objects only, and that precise period of time, which fell under its cognizance: but why this experience should be extended to future times, and to other objects, which for aught we know, may be only in appearance similar; this is the main question on which I would insist. [12]

Hume's point was that any inductive generalization relies on the basis that *future events will emulate past events.* And this claim cannot be proven, as it is a general causal relation that would require induction to prove! So in general, it is impossible to conclude causal laws from a set of observations.

Predictive Power

There is a particular constraint we can place on science that is both practically and theoretically necessary: that it has *predictive power.* This is the only way that the pursuit of science can bring us knowledge. If science could only describe or explain known *past events*, then it would not contain any knowledge that wasn't contained in the recorded past events themselves! So the development of theories would be meaningless in terms of the pursuit of knowledge. However, the predictability of the future from the present or past is exactly the notion of *causality* that the problem of induction shows us is impossible to validate! So any scientist who wishes to avoid crushing existential crisis must somehow confront the problem of induction.

Resolving Causality

Putting aside the philosophical difficulties, however, it seems ridiculous to say that it's impossible to predict *anything*. Many scientific results have been experimentally validated time and time again, and all of the technology that underlies modern society relies on nature behaving consistently on some level. But indeed, in order for induction to be valid, we must require data to be valid: nature simply must not create flukes. This means everything happens by some natural law, and brings us to the *principle of causality*:

> The principle of causality is the assertion that any event whatsoever can be causally explained—that it can be deductively predicted. [14]

The particular version of this principle that we're interested in is that in which the 'deductive predictions' can be made on the basis of some set of natural laws and some set of true initial conditions. It is clear that this statement cannot be proven—or disproven—but it is an essential principle to the practice of science. To face this difficulty, philosopher Karl Popper said it best:

> I shall, however, propose a methodological rule which corresponds so closely to the principle of causality that the latter might be regarded as its metaphysical version. It is the simple rule that we are not to abandon the search for universal laws and for a coherent theoretical system, nor ever give up our attempts to explain causally any kind of event we can describe. [14]

The crux of the argument is this: **We need not accept the principle of causality in theory, but we might as well accept it in practice.** Furthermore, it makes sense to assume that physical laws do not vary arbitrarily over time or space. Because there is no other way to do science. The principle of causality must be an underlying assumption in any form of scientific reasoning, and that is okay: After all, it has worked pretty well so far.

The Effects of Causality

The principle of causality has far-reaching effects. It allows us to infer that any event we observe must have some cause that includes both the natural laws and some initial conditions. In the language of physics, these 'initial conditions' are usually nearby values of fields on the 4-dimensional manifold of space-time. This grounds the laws of physics (as differential equations) as causal laws of nature.

In the same way that we can use differential equations to reason in either direction in time,[1] we know from the principle of causality that *everything we observe must have a cause*, and that allows us to reason about long ago in the past, in places very far away—all based on observations that we make here and now.

We now have grounds on which to justify theorizing scientifically about the early universe: we may state conditions that *must*, according to some model of the natural laws, have held some time ago in order to produce the observations we make today, and those statements about the past become a necessary part of the theory in order for it to be consistent.

The analysis of causality in this section almost provides a satisfying account of our approach to cosmology. In the following section, we will take a look at modern cosmology and inflation before returning to the question of how we evaluate our scientific theories.

3 Cosmology

Cosmology is the study of the large-scale structure and distant past of our universe. Right off the bat, we know that the sort of reasoning we must do in cosmology is of a different flavor than in experimental science.

The Flavor of Cosmology

First, cosmology is not *predictive*. There is only one universe that we can observe, so it is difficult to say whether we can make claims about what it *should* look like: it doesn't make sense to develop a theory of the evolution of hypothetical universes and use *ours* as evidence for it, unless we make the assumption that *our universe is somehow typical*—a controversial assumption that can take a number of different forms, with various implications (discussed in Section 5). Even to predict the long-term evolution of our universe is futile, at least for the moment, because it seems that we will not be able to observe any meaningful structural changes in the universe within the cosmological blink that is our lifetimes.

Second, cosmology does not naturally *generalize*. This is a related issue: because we only have one universe to examine, we can't necessarily (again, without more assumptions) develop a general theory of universes—only a specific description of our universe. Whether this is satisfactory as a scientific theory, or as an "explanation," is unclear. (This issue is further discussed in Section 4.)

However, despite its apparent status as "descriptive" of our universe, which ideologically may make it difficult, cosmology also has the *practical* difficulty of necessarily being "explanatory" of our *current* observations, by asserting something about the state of affairs in the past. Indeed, it is "predictive" only in the sense that we may construct models that have as-of-yet unmeasurable implications, but as our measurement technology improves,

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[1] This does not mean that we can *completely* determine the past from the future, even if the future is completely determined by the past. As in thermodynamics in general and Ricci flows in particular, order tends to descend into chaos and information tends to fall away over time.

we may test these implications through observation (as in the recent BICEP2 experiment) in a way that feels very much like executing controlled tests of our predictions.

The Mathematical Basis of Cosmology

Modern cosmology is the application of the theory of general relativity to the notion of the expanding universe. This begins with the determination of the form of a metric that represents the large-scale structure of space-time as we see it when we look far past the stars of our own galaxy. To ground ourselves, we note three central observations:[2]

(1) **The universe is homogeneous.** No matter where direction we look in the universe, we see the same density, distribution, and types of galaxies. As far as we can tell, there is no significant large-scale variation in the structure of the universe from place to place.

(2) **The universe is isotropic.** In addition to homogeneity from place to place, our observations of deep space indicate that there is no directional preference to the structure of the universe.

(3) **The universe is expanding at an accelerating rate.** All of the distant galaxies we observe are moving away from our own, and the speed at which they are receding scales superlinearly with their distance from us. This seems to indicate that all of space is expanding at an increasing rate, since further galaxies (which we see earlier in time) are further than a linear extrapolation of the movement of nearby galaxies would indicate.

If we take these factors into account,[3] we may construct the general form taken by the large-scale metric of the universe. We find that the necessary and sufficient form of the metric to match these conditions is the *Robertson-Walker metric*

$$ds^2 = -dt^2 + R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right] \tag{1}$$

where k is some constant and $R(t)$ is the scale factor of the universe (i.e., the amount by which it has expanded) at time t. Furthermore, because of our freedom to scale the r coordinate, we need only consider the cases of $k = 0$, $k = 1$, and $k = -1$ without loss of generality.

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[2] The account in this section was taken from [17], where a more thorough and complete analysis may be found in the chapter on cosmology.

[3] We must also accept a few more assumptions, in particular that there is a reference frame in which we may slice the universe into hypersurfaces of constant time and *see* the universe as homogeneous, isotropic, and expanding in a homogeneous and isotropic way. This, however, is also supported by observation by the fact that our measurements indicate that *our reference frame is such a frame.* We also ignore the random velocities of galaxies and consider only their movement by the large-scale expansion.

To bring the theory of gravity into the picture is to apply the Einstein equation to say something about this metric. This introduces the energy-momentum tensor **T**, which we also assume obeys our homogeneity and isotropy conditions. In fact, all of these conditions together leave only one independent component of the Einstein tensor, which can be expressed in this statement of the Einstein equation:

$$G_{tt} + \Lambda g_{tt} = 8\pi T_{tt}. \tag{2}$$

Here, Λ is a "cosmological constant" of exactly the sort that Einstein predicted (and subsequently regarded as his biggest blunder) introduced to address accelerating expansion. The Λ term on the left indicates the presence of the terms

$$\rho_\Lambda = \frac{\Lambda}{8\pi}$$

and

$$p_\Lambda = -\rho_\Lambda$$

within **T**. This "dark energy" ρ_Λ with (negative!) pressure p_Λ remains unexplained, but presumably drives the acceleration of the universe's expansion. With a little bit more mathematics, we come to this equation representing the expansion of the universe over time:

$$\frac{3\dot{R}^2}{8\pi R^2} = -\frac{3k}{8\pi R^2} + \rho + \rho_\Lambda \tag{3}$$

where ρ denotes the energy density of matter and radiation across the universe.[4] In this equation, ρ decreases with increasing R and ρ_Λ remains constant.

Notwithstanding the values of ρ_Λ and curvature constant k, the initial value[5] of the density ρ and expansion rate $\frac{\dot{R}}{R}$ determines the fate of the universe as either collapsing back in a "big crunch," expanding at an asymptotically linear rate into infinity, or (in a very particular, unstable equilibrium) expand more and more slowly over time at a rate approaching but never reaching 0.

Furthermore, the fact that ρ_Λ is constant means that, if the radius ever gets large enough for ρ_Λ to strongly dominate the right side of the equation (i.e., there is no "big crunch"), $\dot{R}$ becomes proportional to R and—since p_Λ is negative—the universe experiences exponential growth.

Inflation theory was initially motivated by two apparent problems that arise out of this description of the universe: The *horizon problem* and the *flatness problem*.

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[4] We may further break this down into the relativistic (radiation) and non-relativistic (matter) components of the energy density, which each scale differently with R, but that distinction is not important for our discussion of inflation.

[5] Since our theory actually does not extend to the *very* beginning, we may concern ourselves with the values at some early time t_0.

The Horizon Problem

Not only the arrangement of galaxies, but even the cosmic microwave background (CMB), the "background noise" behind everything we see out in space, is extremely uniform. This seems counter-intuitive to many physicists, because of the restriction in relativity that information (so to speak) may only travel at the speed of light, and no faster.

When we look in two opposite directions and see radiation coming from over 10 billion light-years away (the order of the age of the universe) in the CMB, we conclude that the radiating sources are 20 billion light-years apart. At this distance, there is no way that the points could have interacted with each other. But it remains that they radiate with nearly the *exact same energy!*

This seems to many physicists to be a conundrum, called the *horizon problem*: the overwhelming uniformity of the CMB seems to have resulted from some communication between points in the early universe, but this communication should not have been possible given their distance apart.

The Flatness Problem

If we fit Equation 3 to the trend of expansion that we observe in near and distant galaxies, it turns out that the value of ρ is *extremely* close—within the error of our measurement—to that exact value that results in a universe that expands forever at an ever-decreasing rate. This is particularly interesting because this equilibrium is extremely unstable: a value of ρ significantly below this would result in a universe that would quickly collapse (before, say, life like humanity had the chance to form). In fact, in order to result in a universe like the one we live in the initial rate of expansion would have to be fine-tuned to within one part in 10^{55}.

Physicists consider this an extremely strong assumption to make in order for the universe to have the apparent *flatness* that it does, but it seems to be required in the standard (non-inflationary) model of relativistic cosmology. This issue is called the *flatness problem.* For a more thorough explanation of this problem and the horizon problem, see Alan Guth's original paper on the theory of inflation [9], which we will now address.

Inflation

The theory of *inflation* was proposed by physicist Alan Guth in 1981 as a solution to both the horizon and the flatness problems. It posits that in the early universe, there was a period of very fast (exponential) expansion, which "smoothed out all of the kinks" so to speak, and resulted in the only-very small variations—about one part in 10^5—that we see in the CMB today. It also has the side effect of "smoothing out" the curvature to be nearly flat, accounting for the flatness problem.

Formally, inflation in its early formulation[6] involves an extra term in Equation 3. If this term somehow behaved like a cosmological constant and *only* dominated the right side of the equation in the early stages of the universe, that could suffice to describe the early-universe exponential expansion posited in the basic premise of the theory.

The way this is done is by positing the existence of a scalar *inflation field.* This field would show up in Equation 3 and be governed by a peculiar potential function: for, if much of the energy of the universe were in this field, and the potential sloped very slowly downward with the growth of the universe, then the value in the equation would be nearly constant during this time, leading to exactly the exponential expansion required by inflation theory. Then, at some point, the potential can drop off quickly and the energy held by the inflation field would be dumped back into the other fields, creating the matter and radiation that populates the universe today while stopping the exponential expansion, resulting in, from then on, the standard picture (related above) of relativistic cosmology.

This formulation of inflation did a very good job of producing the apparently "fine-tuned" details that were causing problems for cosmologists before. Whether that means inflation is *correct* is a slightly different issue. After all, the potential associated with the inflation field has a very peculiar form, and even if it explains our observations, it itself remains to be explained.

So, all things considered, is inflation theory a solid scientific model of the early universe? Before looking into this question, we will take another look back at the philosophy of science, to determine what it is that really makes a "good" model.

4 The Importance of Aesthetic

The theory of inflation, as proposed by Linde [13], does closely predict what we observe in the CMB. However, it is the *only* theory that would make such a prediction? Not at all. At the end of Section 2, we discussed how our physical theories extend into the past: the conditions we *must* assert about the past are the *weakest* ones that would produce the observations we see today. This means that in principle, we may allow for other explanations: for example, that the universe "just so happened" by chance to be as homogeneous as it is.

Description versus Explanation

That doesn't seem like much of a theory, though. It sounds a little bit like the following: Suppose I see an apple fall out of a tree, and I react by positing a physical law that "that apple fell out of that tree." It's a *description* rather than an *explanation* like, say, a theory of gravity. But what makes these two statements fundamentally different?

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[6] I describe here not Guth's 1981 proposal of inflation, but the *slow-roll* inflation proposed by Andrei Linde in 1982 .[13] It also purported to resolve several other open problems in cosmology at the time.

In fact, the two statements are both true, and both sufficient to describe the behavior of the apple in question. Whether the description qualifies as an 'explanation' is another, fuzzier issue. One clear difference between the "apple-fell" law and a theory of gravity is that gravity *generalizes.* It is a concise explanation that predicts (fairly accurately) a wide range of phenomena.

This notion of generalization highlights why a preference for gravity over a large set of "apple-fell" laws (for every falling event we've observed) is so intuitively obvious, but *a preference for the theory of inflation is not so obvious.* It goes back to the issue that we have only one universe that we can reason about, so the theory does not generalize in an obvious way. So, "inflation" appears like a *description* of what seems to have happened in the early universe in order to produce what we see today.

The Probabilistic Approach

So if it's not generality, then why does the theory of inflation seem more reasonable than the theory of "it just happened"? One argument is that it is extremely *unlikely* that it would've "just happened" and that inflation would produce a universe like ours under a wider range of initial conditions. However, we can't argue about the (posterior) probabilities of such theories solely from the evidence of the current state of the universe: we would also require a *prior* probability distribution over possible initial conditions of the universe. This is not something we can gather from experiment or observation, since we only have one universe. So the probability argument, in its simplest form, seems to fall flat. (This will be revisited in Section 5.)

Aesthetic

What we really use to evaluate our theories may come down to something much more human, and more difficult to quantify. S. Chandrasekhar put it well in his 1987 book *Truth and Beauty: Aesthetics and Motivations in Science.* In this selection, he reacted to the amazing observation that stationary black holes are fully described in relativity theory by their mass and angular momentum, in the Kerr model:

> In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity, discovered by the New Zealand mathematician, Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the universe. This shuddering before the beautiful, this incredible fact that a discovery motivated by a search after the beautiful in mathematics should find its exact replica in Nature, persuades me to say that beauty is that to which the human mind responds at its deepest and most profound. [6]

The "beauty" that he mentions is sometimes called "elegance," "simplicity," or "aesthetic," and is often considered the hallmark of a good scientific theory or argument. This idea has been around for a long time, usually attributed to the English Franciscan friar William of Ockham of the 14th century. (the methodological principle of choosing the simplest explanation is often called *Ockham's razor.*)

The reverence we have for simplicity is apparent in Albert Einstein's later reaction to his own theory of the "cosmological constant," which he famously regarded as his biggest blunder in the development of the theory of relativity. The reason it is regarded as a mistake (even today, as we're finding out he may not have been completely wrong) is that he posited this cosmological constant in order to justify his preconception that the universe should be static: this was something *not* supported by evidence, and so he was *adding unnecessary complexity*, so to speak, to the theory. That he considered it such a big mistake (even though it produced a consistent theory) shows how simplicity rules all.

Why simplicity should be a hallmark of scientific theories—which, above all, must be concerned with *truth*—seems to be a question that extends beyond just practical concerns (i.e., "simpler theories are easier to work with"). Instead of trying to answer this difficult question directly, an interesting line of inquiry is this: if we can't say why simplicity *should* be considered important, can we say why it *is?* Jürgen Schmidhuber, a researcher at the Dalle Molle Institute for Artificial Intelligence (IDSIA) in Switzerland, has developed what he calls a *formal theory of creativity*, which provides one answer to this question. He designs agents with "intrinsic motivation" driven by curiosity: a desire to discover patterns in the world, mathematically formalized as the improvement of a compression algorithm on perceived data (he called this *compression progress*) [15]. He argues that this same system is what drives humans to have fun, create art, and do science:

> If the history of the entire universe were computable, and there is no evidence against this possibility, then its simplest explanation would be the shortest program that computes it. Unfortunately there is no general way of finding the shortest program computing any given data. Therefore physicists have traditionally proceeded incrementally, analyzing just a small aspect of the world at any given time, trying to find simple laws that allow for describing their limited observations better than the best previously known law, essentially trying to find a program that compresses the observed data better than the best previously known program... For example, Newton's law of gravity can be formulated as a short piece of code which allows for substantially compressing many observation sequences involving falling apples and other objects. Although its predictive power is limited... it still allows for greatly reducing the number of bits required to encode the data stream, by assigning short codes to events that are predictable with high probability under the assumption that the law holds. Einstein's general relativity theory yields additional compression progress as it compactly explains many previously unexplained deviations from Newton's

> predictions.
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> Most physicists believe there is still room for further advances. Physicists, however, are not the only ones with a desire to improve the subjective compressibility of their observations. Since short and simple explanations of the past usually reflect some repetitive regularity that helps to predict the future, *every* intelligent system interested in achieving future goals should be motivated to compress the history of raw sensory inputs in response to its actions, simply to improve its ability to plan ahead. [16]

Indeed, the preference for beauty and simplicity can be said to lie in our desire to maximize our ability to predict our future with our limited time and computation resources (in our brains and computers alike), in order to maximize the reward we can obtain from the world in our limited time in conscious existence. In this respect, perhaps it is our mortality that drives us to seek out beauty in the universe.

5 Inflation Revisited

Unfortunately, all of this talk the importance of aesthetic does not do much to tell us which theories to prefer over which—but that's exactly what we should expect. Different scientists have different versions of "beauty" (perhaps you could say in Schmidhuber's language that their brains have different compression functions) and it is not always obvious whether one theory is simpler than another. As CalTech physics professor Sean Carroll says,

> The *entire point* of inflation is to make the initial conditions of our observable universe seem more "natural." Inflation is a process, not a law of nature. If you don't care about naturalness, and are willing to say "things just happened that way," there is absolutely no reason to ever think about inflation. So the success or failure of inflation as a scenario depends on how natural it really is. [2]

How 'natural' is Inflation?

This question may be approached subjectively (and sensibly) in the following way: If we consider the configuration of our observable universe to be something 'strange' or 'unnatural,' then inflation can be a decent explanation only if it is *less* unnatural than the "it just happened" explanation. Early formulations of inflation relied on a very particular kind of potential function $V(\phi)$ with respect to the inflation field ϕ. This may not seem like much of an explanation, as we have the freedom to tweak the function $V(\phi)$ all we want in order to match what we observe anyway. However, more recent thinking indicates that a simple function $V(\phi) \propto \phi^2$ best matches our observations [4]. Whether this is satisfactory is, of course, up to a subjective judgment.

Penrose's Argument and the Likelihood of Our Universe

Trying to decide on 'naturalness' without relying on subjective criteria often results in something like the probabilistic argument of the previous section. Oxford physicist Roger Penrose has argued against inflation since the 1970s, bringing this reasoning to bear. Carroll summarizes Penrose's point as follows:

> The advent of inflation in the early 1980's seemed to change things — it showed how to get a universe just like ours starting from a tiny region of space dominated by "false vacuum energy." But a more careful analysis shows that inflation doesn't really change the underlying problem — sure, you can get our universe if you start in the right state, but that state is even more finely-tuned than the conventional Big Bang beginning. [1]

Notwithstanding Penrose's more recent claims that string theory is a "fashion," quantum mechanics is "faith," and inflation a "fantasy" [8], Carroll put this argument to work in calculations published in his note with Heywood Tam titled "Unitary Evolution and Cosmological Fine-Tuning" [5]. The position is based on the assumption of 'unitary' (roughly, time-reversible) laws of physics and arguments about the number of possible states (or sets of initial conditions) of the universe. This form of argumentation relies in a way on a uniform probability distribution over these states. This sort of reasoning has proven very effective in thermodynamics, and the machinery for reasoning about the "extraordinariness" of our universe has been developed over the past few decades. As Carroll says,

> Our universe looks very unusual. You might think we have nothing to compare it to, but thats not quite right; given the particles that make up the universe (or the quantum degrees of freedom, to be technical about it), we can compare their actual configuration to all the possible configurations they could have been in. The answer is, our observed universe is highly non-generic, and in the past it was even more non-generic, or finely tuned. One way of describing this state of affairs is to say that the early universe had a very low entropy. [1]

Carroll and Tam's conclusion, as he roughly stated in terms of 'likelihood,' was this:

> We find that inflation is very unlikely, in the sense that a negligibly small fraction of possible universes experience a period of inflation. On the other hand, our universe is unlikely, by exactly the same criterion. So the observable universe didn't "just happen"; it is either picked out by some general principle, perhaps something to do with the wave function of the universe, or it's generated dynamically by some process within a larger multiverse. And inflation might end up playing a crucial role in the story. We don't know yet, but it's important to lay out the options to help us find our way. [1]

Their line of reasoning indicates that Penrose's argument against inflation may turn back on itself—but we can't be sure. Whether this argument is an effective one is not a question with a satisfactory answer. However, there *is* a response to this argument internal to the theory of inflation, which we come to now.

Eternal Inflation

The inflation story does not necessarily begin and end with a single universe. Rather, it begins with one and could possibly end with an infinity of universes, as explained by Alan Guth in a 2001 talk by the name of "Eternal Inflation" [10].

Here's how the argument works: quantum fluctuations *during* the period of inflation could mean that inflation does not necessarily end and the same time everywhere: the slight jitter in ϕ would mean that it begins "dumping" matter into the universe in some places before in others. These other places, in turn, would continue inflating and create a whole new arena in which the quantum jitter can do the same thing again, and so on ad infinitum. But it remains that each of these "dumping" events is actually separated by an *exponentially expanding* (inflating) region of space-time! So in effect, inflation leads to the creation of an infinite number of mutually isolated universes. The theory, then, is simply that ours is one of those universes, and because of the infinite number of universes produced by any one inflation event, it is not at all unlikely that a universe like ours will form.

This argument, once again, presupposes a particular method of "sampling" from possible universes (i.e., a probability distribution over them) in order to make sense of the question of how likely our universe is. While it provides an answer to Penrose's (and Carroll's) arguments related above, it retains the same conceptual difficulty that inflation had in the first place.

6 Conclusion

We have seen how the pursuit of science must presuppose a predictable and static set of natural laws. We have also seen how the pursuit of science is impossible in practice without accepting the notion of *simplicity* of physical theories. Cosmology as a field has posed a great challenge to scientific thinking: it has become difficult to know what exactly is an effective scientific argument about the very early stages of the universe, and how much these arguments depend on our reliance on simplicity.

As a personal note, I will relate that I initially expected when I set out to write this paper to come to the conclusion that cosmic inflation is very reasonable, and a simple, nicely explanatory candidate for a theory of the early universe. Now, I honestly have no idea what to think. However, regardless of what I think, it has become clear that we can definitely do valid scientific reasoning about the early universe. The very same principles of “observational” science, as Ken Ham calls it, allow us—or even *require* us—to reason using evidence about what the universe looked like long in the past.

Whether inflation will continue to hold up (and it seems to be doing so, in light of the recent BICEP2 result [3]) is a fascinating question that will surely develop further as we peer deeper into space and discover more about the fundamental nature of our universe.

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