

Eternal Inflation[†]

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Abstract

The basic workings of inflationary models are summarized, along with the arguments that strongly suggest that our universe is the product of inflation. It is argued that essentially all inflationary models lead to (future-)eternal inflation, which implies that an infinite number of pocket universes are produced. Although the other pocket universes are unobservable, their existence nonetheless has consequences for the way that we evaluate theories and extract consequences from them. The question of whether the universe had a beginning is discussed but not definitively answered. It appears likely, however, that eternally inflating universes do require a beginning.

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I. Introduction

The question of whether or not the universe had a beginning is, of course, by no means an easy question. When you ask a scientist a question that is not easy, he never gives just one answer, but instead gives a succession of answers. In this case, I would like to offer two levels of answers.

At the first level, I would argue that the answer to the question is yes, the universe had a beginning in the event that is usually referred to as the big bang.

I think that at least 99.9 percent of the people working in scientific cosmology today believe that the universe evolved from a hot dense state, exactly as Sandra Faber spoke about earlier. This theory is strongly supported by the direct observation of the expansion of the universe via the redshift of the light from distant galaxies, by the measurement of the abundances of the light chemical elements, and by the now very precise measurements of both the spectrum and the very small nonuniformities of the cosmic microwave background radiation. Thus, most scientists (including me) believe that the universe as we know it began in a “big bang” some 11 to 16 billion years ago [1].

However, as Sandra has already emphasized, there is another level to the question of beginning. When cosmologists say that they are persuaded that the big bang theory is valid, they are using a rather precisely defined and restricted interpretation of the term “big bang.” As it is used by scientists the term refers only to the expansion of the universe from an initially hot dense state. But it says nothing about whether the universe really began there, or whether there was something else that preceded what we call the big bang.

So, beyond the standard big bang, there is now a very significant body of research concerning the possibility of cosmic inflation [2, 3, 4, 5]. Today I want to talk about inflation, and in particular I want to talk about a very likely ramification called eternal inflation. As you will see, the theory of inflation does not give a clear answer to the question of whether the universe had a beginning, but it does provide at least a context for discussing this question.

To begin, I would like to highlight the distinction between the questions that the standard big bang theory answers and the questions that inflation is intended to answer.

The standard big bang theory is, of course, a very significant scientific theory. It describes how the early universe expanded and cooled from an initially very hot dense state. It describes how the light chemical elements that we observe today were synthesized during the first 200 seconds or so of this expansion period. And finally, although work in this area is still in progress, it seems to describe very well how the matter in the universe eventually congealed to form the stars, galaxies, and clusters that we observe in the universe today.

There is, however, a key issue that the standard big bang theory does not discuss at all: it does not tell us what banged, why it banged, or what happened before it banged. Despite its name, the big bang theory does not describe the bang at all. It is really only the theory of the **aftermath** of a bang.

So, in particular, the standard big bang theory does not address the question of what caused the expansion; rather, the expansion of the universe is incorporated into the equations of the theory as an assumption about the initial state—the state of the universe when the theory begins its description.

Similarly, the standard big bang theory says nothing about where the matter in the

universe came from. In the standard big bang theory all the matter that we see here, now, was already there, then. The matter was just very compressed, and in a form that is somewhat different from its present state. The theory describes how the matter evolved from one form to another as the universe evolved, but the theory does not address the question of how the matter originated.

While inflation does not go so far as to actually describe the ultimate origin of the universe, it does attempt to provide a theory of the bang: a theory of what it was that set the universe into expansion, and at the same time supplied essentially all of the matter that we observe in the universe today.

II. How Does Inflation Work?

I will begin by giving a quick rundown of how inflation works. Some of these issues were already discussed by Sandra Faber, who I thought gave an excellent description. For completeness, however, I will start my explanation at the beginning, but I will try to go more quickly when discussing points that Sandra has already explained.

The key idea—the underlying physics—that makes inflation possible is the fact that most modern particle theories predict that there should exist a state of matter that turns gravity on its head, creating a gravitational repulsion. This state can only be reached at energies well beyond those that we can probe experimentally, but the theoretical arguments for the existence of the state are rather persuasive. It is not merely the prediction of some specific theory, but it is the generic prediction for a wide class of plausible theories. Thus, gravity does not always have to be attractive.*

The gravitational repulsion caused by this peculiar kind of material is the secret behind inflation. Inflation is the proposition that the early universe contained at least a small patch that was filled with this peculiar repulsive-gravity material.[†] There are a variety of theories about how this might have happened, based on ideas ranging from chaotic initial conditions to the creation of the universe as a quantum tunneling event. Despite the ambiguity of this aspect of the theory, there are two things to keep in mind. First, the probability of finding a region filled with this repulsive-gravity material need not be large. I will come back to this

*The possibility of repulsive gravity arises because, according to Einstein’s theory of general relativity, gravitational fields are produced not just by energy or mass densities, but also by pressures. The direction of the field caused by pressure is what you would probably guess: a positive pressure—the kind that we normally see—produces an attractive gravitational field. But the peculiar state of matter that I’m talking about produces a negative pressure, which you might also call a suction. It is in fact a very large negative pressure, resulting in a repulsive gravitational field which is stronger than the attractive field produced by the mass density of the matter. The result is a net gravitational repulsion, which is the driving force behind inflation.

[†]The name for this peculiar gravitationally repulsive state is not well-established. Sandra Faber referred to it as a vacuum with a finite energy density, and sometimes as a false vacuum. In my own technical articles I call it a false vacuum, although I have to explain that for most inflationary models this usage stretches the meaning for which the phrase had previously been used in particle physics. In this article I will refer to it as a repulsive-gravity material. It may seem strange to see the words “vacuum” and “material” used to describe the same thing, but keep in mind that this stuff is **strange**. The word “vacuum” is used to emphasize that it is different from ordinary matter, while I am calling it a material to emphasize that it is different from an ordinary vacuum!

point later, and argue that it is only necessary that the probability is nonzero. Second, the resulting predictions do not depend on how the initial patch was formed. Once the patch exists, inflation takes over and produces a universe that ends up inevitably looking very much like the one that we live in.

The initial patch can be incredibly small. It need be only about one-billionth the size of a single proton. Once the patch exists it starts to rapidly expand because of its internal gravitational repulsion. The expansion is exponential, which means it is characterized by a doubling time, which for a typical inflationary theory might be in the neighborhood of 10^{-37} seconds. So every 10^{-37} seconds the diameter of the patch doubles, and then it doubles again and again during each 10^{-37} -second interval. The success of the description requires about a hundred of these doublings, but there could have been many more. In the course of this expansion, the patch went from being a tiny speck to a size at least as large as a marble.

So the patch of repulsive-gravity material expanded by a huge factor. Whenever a normal material expands its density goes down, but this material behaves completely differently. As it expands, the density remains constant. That means that the total amount of mass contained in the region increased during inflation by a colossal factor.

The increase in mass probably seems strange at first, because it sounds like a gross violation of the principle of energy conservation. Mass and energy are equivalent, so we are claiming that the energy of the matter within the patch increased by a colossal factor. The reason this is possible is that the conservation of energy has a sort of a loophole, which physicists have known at least since the 1930s [6], but haven't talked about very much. Energy is always conserved; there are no loopholes to that basic statement. However, we normally think of energies as always being positive. If that were true, then the large amount of energy that we see in the universe could not possibly have gotten here unless the universe started with a lot of energy. However, this is the loophole: energies are not always positive. In particular, the energy of a gravitational field is negative. This statement, that the energy of a gravitational field is negative, is true both in the context of the Newtonian theory of gravity and also in the more sophisticated context of general relativity.

So, during inflation, total energy is conserved. As more and more **positive** energy (or mass) appears as the patch expands at constant density, more and more **negative** energy is simultaneously appearing in the gravitational field that fills the region. The total energy is constant, and it remains incredibly small because the negative contribution of gravity cancels the enormous positive energy of the matter. The total energy, in fact, could very plausibly be zero. It is quite possible that there is a perfect cancellation between the negative energy of gravity and the positive energy of everything else.

For the theory to be successful, there has to be a mechanism to end the period of inflation—the period of accelerated expansion—because the universe is not undergoing inflation today.[‡] Inflation ends because the repulsive-gravity material is fundamentally unstable. So it doesn't survive forever, but instead decays like a radioactive substance. Like traditional forms of radioactive decay, it decays exponentially, which means that the decay is character-

[‡]Actually there is strong evidence that the expansion of the universe is accelerating in the present era, and the mechanism for this acceleration is believed to be very similar to that of inflation. This acceleration, however, is much slower than the acceleration that inflationary models propose for the early universe, so in any case the rapid acceleration of the early universe must have come to an end.

ized by a half-life. During any period of one half-life, on average half of the repulsive-gravity material will “decay” into normal attractive-gravity material.

In the process of decaying, the repulsive-gravity material releases the energy that has been locked up within itself. That energy evolves to become a hot soup of ordinary particles. Initially the decay produces a relatively small number of high-energy particles, but these particles start to scatter off of each other. Eventually the energy becomes what we call *thermalized*, which means that it produces an equilibrium gas of hot particles—a hot primordial soup—which is exactly the initial condition that had always been assumed in the context of the standard big bang theory.

Thus, inflation is an add-on to the standard big bang theory. Inflation supplies the beginning to which the standard big bang theory then becomes the continuation.

III. Evidence for Inflation

So far I have tried to describe how inflation works, but now I would like to explain the reasons why many scientists—including certainly myself—believe that inflation really is the way that our observed universe began. There are six reasons that I will discuss, starting with some very general ideas and then moving to more specific ones.

The first reason is the obvious statement that the universe contains a tremendous amount of mass. It contains about 10^{90} particles within the visible region of the universe. I believe that most non-scientists are somewhat puzzled to hear anyone make a fuss over this fact, since they think, “Of course the universe is big—it’s the whole universe!” However, to a theoretical cosmologist who is hoping to build a theory to explain the origin of the universe, this number seems like it could be an important clue. Any successful theory of the origin of the universe must somehow lead to the result that it contains at least 10^{90} particles. The fundamental theory on which the calculation is based, however, presumably does not contain any numbers nearly so large. Calculations can of course lead to factors of 2 or π , but it would take very many factors of 2 or π to reach 10^{90} . Inflation, however, leads to exponential expansion, and that seems to be the easiest way to start with only small numbers and finish with a very large one. With inflation the problem of explaining why there are 10^{90} or more particles is reduced to explaining why there were 100 or more doubling times of inflation.[§] The number 100 is modest enough so that it can presumably arise from parameters of the underlying particle physics and/or geometric factors, so inflation seems like just the right kind of theory to explain a very large universe.

The second reason is the Hubble expansion itself—the fact that the universe is observed to be in a state of uniform expansion. An ordinary explosion, like TNT or an atomic bomb, does not lead to expansion that is nearly uniform enough to match the expansion pattern of the universe. But the gravitational repulsion of inflationary models produces exactly the uniform expansion that was first observed by Edwin Hubble in the 1920s and 30s.

Third, inflation is the only theory that we know of that can explain the homogeneity and isotropy of the universe—that is, the uniformity of the universe. This uniformity is observed

[§]Since the volume is proportional to the cube of the diameter, during 100 doublings the volume increases by a factor of $(2^{100})^3 = 2^{300} \approx 2 \times 10^{90}$.

most clearly by looking at the cosmic microwave background radiation, which we view as the afterglow of the heat of the big bang. The intensity of this radiation is described by an effective temperature, and it is observed to have the same temperature in every direction to an accuracy of about one part in a hundred thousand, after we correct for our own motion through the cosmic background radiation. In other words, this radiation is incredibly smooth. As an analogy we can imagine a marble that has been ground so smoothly that its radius is uniform to one part in a hundred thousand. The marble would then be round to an accuracy of about a quarter of the wavelength of visible light, about as precise as the best optical lenses that can be manufactured with present-day technology.

In the standard big bang theory there is no explanation whatever for this uniformity. In fact, one can even show that within the context of the standard big bang theory, no explanation for this uniformity is possible. To see this, we need to understand a little about how this cosmic background radiation originated. During the first approximately 300,000 years of the history of the universe, the universe was hot enough so that the matter was in the form of a plasma—that is, the electrons were separated from the atoms. Such a plasma is very opaque to photons, which are constantly scattered by their interactions with the free electrons. Although the photons move of course at the speed of light, they change directions so rapidly that they essentially go nowhere. During the first 300,000 years of the history of the universe, the photons were essentially pinned to the matter.

But after 300,000 years, according to calculations, the universe cooled enough so that the plasma neutralized. The free electrons combined with the atomic nuclei to form a neutral gas of hydrogen and some helium, which is very, very transparent to photons. From then on these photons have traveled in straight lines. So, just as I see an image of you when I observe the photons coming from your face, when we look at the cosmic background radiation today we are seeing an image of the universe at 300,000 years after the big bang. Thus, the uniformity of this radiation implies that the temperature must have been uniform throughout this whole region by 300,000 years after the big bang.

To think about whether the temperature of the observed universe could have equilibrated by this early time, we could try to imagine fancifully that the universe was populated by little purple creatures, whose sole purpose in life was to make the temperature as uniform as possible. We could imagine that each purple creature was equipped with a little furnace, a little refrigerator, and a cell phone so that they could communicate with each other. The communication, however, turns out to be an insurmountable problem. A simple calculation shows that in order for them to achieve a uniform temperature by 300,000 years, they would need to be able to communicate at about a hundred times the speed of light. But nothing known to physics allows communication faster than light, so even with dedicated purple creatures we could not explain the uniformity of the cosmic background radiation.

So in the standard version of the big bang theory, before inflation is introduced, one simply has to hypothesize that the universe started out uniform. The initial uniformity would then be preserved, since the laws of physics are by assumption the same everywhere. This approach allows one to accommodate the uniformity of the universe, but it is not an explanation.

Inflation gets around this problem in a very simple way. In inflationary theories the universe evolves from a very tiny initial patch. While this patch was very small, there

was plenty of time for it to become uniform by the same mechanism by which a slice of pizza sitting on the table cools to room temperature: things tend to come to a uniform temperature. Once this uniformity is established on the scale of the very tiny patch, inflation can take over and magnify the patch to become large enough to encompass everything that we observe. Thus, inflation provides a very natural explanation for the uniformity of the universe.

Reason number four is known as the flatness problem. It is concerned with the closeness of the mass density of our universe to what cosmologists call the *critical density*. The critical density is best defined as that density which would cause the universe to be spatially flat. To understand what this means, one must understand that, according to general relativity, the geometry of space is determined by the matter that it contains. If the mass density of the universe is very high, the space will curve back on itself to form a closed universe, the three-dimensional analogue of the two-dimensional surface of a sphere. The sum of the angles in a triangle would exceed 180° , and parallel lines would meet if they are extended. If the mass density is very low, the space would curve in the opposite way, forming an open universe. The sum of the angles in a triangle would then be less than 180° , and parallel lines would diverge if they were extended. But with just the right mass density (for a given expansion rate) the spatial geometry will be exactly Euclidean, just like what we all learned in high school— 180° in every triangle, and parallel lines remain parallel no matter how far they are extended. This borderline case is the critical density.[¶]

Cosmologists use the Greek letter Ω (Omega) to denote the ratio of the average mass density of the universe to the critical density:

$$\Omega \equiv \frac{\text{actual mass density}}{\text{critical mass density}} .$$

Today there is growing evidence that Ω is equal to one to within about 10% [7], but the issue is not completely settled. For purposes of this discussion, therefore, I will begin with the uncontroversial statement that Ω lies somewhere in the interval between 0.1 and 2.

You would probably not expect that much could be concluded from such a noncommittal starting point, but in fact it tells us a lot. When one looks at the equations describing the evolution of the universe, it turns out that $\Omega = 1$ is an unstable equilibrium point, like a pencil balanced on its tip. If the pencil is started exactly vertical and stationary, the laws of Newtonian mechanics imply that it will remain vertical forever. But if it is not absolutely vertical, it will rapidly start to fall in whichever direction it is leaning. Similarly, if Ω began exactly equal to 1, it would remain 1 forever. But any deviation from 1 will grow rapidly as the universe evolves. Thus, for Ω to be anywhere in the ballpark of 1 today, it must have started extraordinarily close to 1. For example, if we extrapolate backwards to 1 second after the big bang, Ω must have been 1 to an accuracy of 15 decimal places [8]. While 1

[¶]To clear up a possible source of confusion, I mention that the critical density has often been described in the semi-popular literature as the borderline between eternal expansion and eventual collapse. If Einstein's cosmological constant is zero, as most of us thought a few years ago, then this definition is equivalent to the one given above. Recent evidence, however, suggests that the cosmological constant may be nonzero, in which case the two definitions are not equivalent. In that case, the one given in the text agrees with the definition used in the technical literature, and is also the definition that is relevant to the current discussion.

second may sound like an extraordinarily early time at which to be discussing an 11- to 16-billion-year-old universe, cosmologists have pretty much confidence in the extrapolation. The nucleosynthesis processes, which are successfully tested by present measurements of the abundances of the light chemical elements, were already beginning at 1 second after the big bang.

In fact, particle theorists like myself are attempting to push the history of the universe back to what we call the Planck time, about 10^{-43} seconds, which is the era when quantum gravity effects are believed to have been important. Since our understanding of quantum gravity is still very primitive, we generally make no attempt to discuss the history of the universe at earlier times. But if we attempt to extrapolate the history of the universe back to the Planck time without invoking inflation, we find that Ω at the Planck time must have been equal to 1 to an accuracy of 58 decimal places.

Without inflation, there is no explanation for the initial value of Ω . The big bang theory is equally self-consistent for any initial value of Ω , so one has no a priori reason to prefer one value over another. But if the theory is to agree with observation, one must posit an initial value of Ω that is extraordinarily close to 1.

With inflation, on the other hand, during the brief inflationary era the evolution of Ω behaves completely differently. Instead of being driven away from 1, during inflation Ω is driven very strongly towards 1. So with inflation you could assume that Ω started out as 1, 2, 10, 10^3 , or 10^{-6} . It doesn't matter. As long as there was enough inflation, then Ω would have been driven to 1 to the extraordinary accuracy that is needed.

The fifth reason for believing the inflationary description is the absence of magnetic monopoles. Grand unified particle theories, which unify all the known particle interactions with the exception of gravity, predict that there should be stable particles that have a net magnetic charge. That is, these particles would have a net north pole or a net south pole, which is very different from an ordinary bar magnet which always has both a north pole and a south pole. These magnetic monopoles are, according to our theories, extraordinarily heavy particles, weighing about 10^{16} times as much as a proton. In the traditional big bang theory, without inflation, they would have been copiously produced in the early universe. If one assumes a conventional cosmology with typical grand unified theories, one concludes that the mass density of magnetic monopoles would dominate all other contributions by an absurdly large factor of about 10^{12} [9]. Observationally, however, we don't see any sign of these monopoles.

Cosmic inflation provides a simple explanation for what happened to the monopoles: in inflationary models, they can easily be diluted to a negligible density. As long as inflation happens during or after the era of monopole production, the density of monopoles is reduced effectively to zero by the enormous expansion associated with inflation.

The sixth and final reason that I would like to discuss for believing that the universe underwent inflation is the prediction that the theory makes for the detailed structure of the cosmic background radiation. That is, inflation makes very definite predictions not only for the uniformity that we see around us, but it also predicts that there should be small deviations from that uniformity due to quantum uncertainties. The magnitude of these deviations depends on the details of the underlying particle theory, so inflation will not be able to predict the magnitude until we really understand the particle physics of very high

energies. However, the shape of the spectrum of these nonuniformities—i.e., the way that the intensity varies with wavelength—depends only slightly on the details of the particle physics. For typical particle theories, inflationary models predict something very close to what is called the Harrison-Zel’dovich, or scale-invariant spectrum. These nonuniformities are viewed as the seeds for the formation of structure in the universe, but they can also be seen directly in the nonuniformities of the cosmic background radiation, at the level of about one part in 100,000. Fig. 1 shows a graph of the recent data from the BOOMERANG experiment, plotted against a theoretical curve derived for an inflationary model [10].

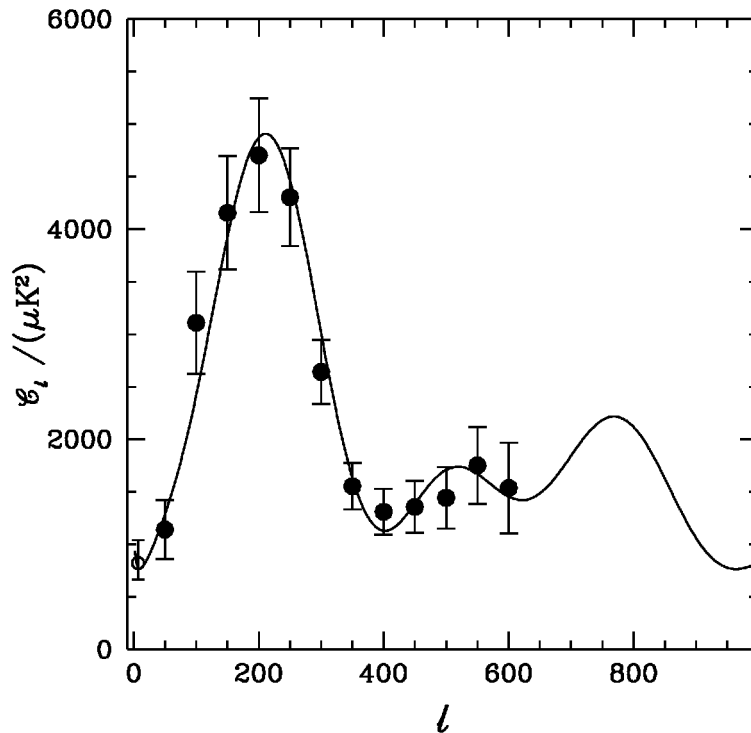


Figure 1: Spectrum of the cosmic background radiation anisotropies, as measured by the BOOMERANG experiment. The intensity of fluctuations is shown as a function of the angular size parameter ℓ , where the angular size of a fluctuation is roughly $180^\circ/\ell$. The black line is a theoretical curve corresponding to a standard inflationary model with $\Omega = 1$. The mass density in the model is composed of 5% baryons, 25% cold dark matter, and 70% cosmological constant. The data and theoretical curve were taken from Ref. [10].

IV. Eternal Inflation: Mechanisms

Having discussed the mechanisms and the motivation for inflation itself, I now wish to move on the main issue that I want to stress in this article—eternal inflation, the questions that it can answer, and the questions that it raises.

Before going on, I should clarify that the different topics that I am discussing have various levels of certainty. The standard big bang theory, as far as cosmologists are concerned,

appears to be essentially certain to all but a few of us. Inflation seems to be by far the most plausible way that the big bang could have started, but it is not so well established as the big bang itself. I should also admit that inflation is vague. It is not really a theory, but a class of theories, so there is a significant amount of flexibility in describing its predictions. Eternal inflation, which I am about to describe, seems to me to be an almost unavoidable consequence of inflation. This point, however, is somewhat controversial. In particular, I believe that the following speaker, Neil Turok, will argue either that eternal inflation does not happen, or that it is in any case not relevant to understanding the properties of the observable universe. I, however, will argue that eternal inflation does happen, and is relevant.

By eternal inflation, I mean simply that once inflation starts, it never ends [11, 12, 13]. The term “future-eternal” would be more precise, because I am not claiming that it is eternal into the past—I will discuss that issue at the end of the talk.

The mechanism that leads to eternal inflation is rather straightforward to understand. Recall that we expect inflation to end because the repulsive-gravity material is unstable, so it decays like a radioactive substance. As with familiar radioactive materials, the decay of the repulsive-gravity material is generally exponential: during any period of one half-life, on average half of it will decay. This case is nonetheless very different from familiar radioactive decays, however, because the repulsive-gravity material is also expanding exponentially. That’s what inflation is all about. Furthermore, it turns out that in essentially all models, the expansion is much faster than the decay. The doubling-time for the inflation is much shorter than the half-life of the decay. Thus, if one waits for one half-life of the decay, half of the material would on average convert to ordinary matter. But meanwhile the part that remains would have undergone many doublings, so it would be much larger than the region was at the start. Even though the material is decaying, the volume of the repulsive-gravity material would actually grow with time, rather than decrease. The volume of the repulsive-gravity material would continue to grow, without limit and without end. Meanwhile pieces of the repulsive-gravity material decay, producing a never-ending succession of what I call *pocket universes*.

In Fig. 2 I show a schematic illustration of how this works. The top row shows a region of repulsive-gravity material, shown very schematically as a horizontal bar. After a certain length of time, a little less than a half-life, the situation looks like the second bar, in which about a third of the region has decayed. The energy released by that decay produces a pocket universe. The pocket universe will inflate to become huge, so to its residents the pocket universe would look like a complete universe. But I will call it a pocket universe because there is not just one, but an infinite number of them.

On the second bar, in addition to the pocket universe, we have two regions of repulsive-gravity material. On the diagram I have not tried to show the expansion, because if I did I would quickly run out of room on the page. So you are expected to remember on your own that each bar is actually bigger than the previous bar, but is drawn on a different scale so that it looks like it is the same size. To discuss a definite example, let us assume that each bar represents three times the volume of the previous bar. In that case, each region of repulsive-gravity material on the second bar is just as big as the entire bar on the top line.

The process can then repeat. If we wait the same length of time again, the situation will be as illustrated on the third bar of the diagram, which represents a region that is 3

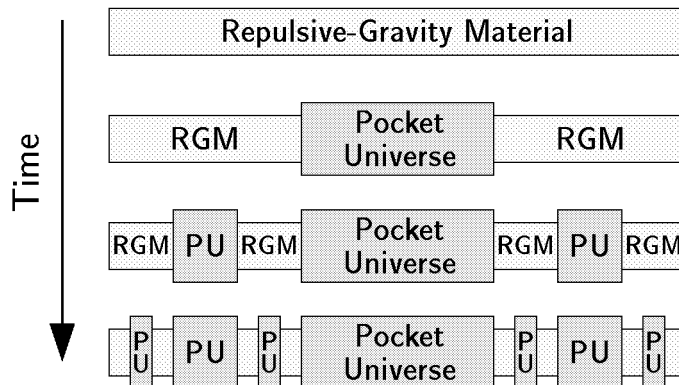


Figure 2: A schematic diagram to illustrate the fractal structure of the universe created by eternal inflation. The four horizontal bars represent a patch of the universe at four evenly spaced successive times. The expansion of the universe is not shown, but each horizontal bar is actually a factor of three larger than the preceding bar, so each region of repulsive-gravity material is actually the same size as the others. During the time interval between bars, $1/3$ of each region of repulsive-gravity material decays to form a pocket universe. The process repeats ad infinitum, producing an infinite number of pocket universes.

times larger than the second bar, and 9 times larger than the top bar. For each region of repulsive-gravity material on the second bar, about a third of the region decays and becomes a pocket universe, leaving regions of repulsive-gravity material in between. Those regions of repulsive-gravity material are again just as big as the one we started with on the top bar. The process goes on literally forever, producing pocket universes and regions of repulsive-gravity material between them, ad infinitum. The universe on the very large scale acquires a fractal structure.

The illustration of Fig. 2 is of course oversimplified in a number of ways: it is one-dimensional instead of three-dimensional, and the decays are shown as if they were very systematic, while in fact they are random. But the qualitative nature of the evolution is nonetheless accurate: eternal inflation really leads to a fractal structure of the universe, and once inflation begins, an infinite number of pocket universes are produced.

V. Eternal Inflation: Implications

The pocket universes other than our own are believed to be completely unobservable, so one can question whether it makes any scientific sense to talk about them. I would argue that it is valid science, because we are pursuing the consequences of a theory for which we already have other evidence. Of course the theory of inflation has to rest on the evidence that we can observe, but once we are persuaded by these observations, then I think that we should also believe the other implications, even if they involve statements that cannot be directly confirmed.

If one accepts the existence of the other pocket universes, then one can still question

whether they have any relevance to the pursuit of science. I will argue that, even though these other universes are unobservable, their existence nonetheless has consequences for the way that we evaluate theories and extract consequences from them.

One question for which eternal inflation has relevance is the question of the ultimate beginning of the universe—what can be learned about it, and how can we learn it? In the following talk, Neil Turok will describe his work with Stephen Hawking [14] and others on the origin of the universe as a quantum event. He will argue that hypotheses about the form of the initial wave function lead to statistical consequences for our universe that can in principle be directly tested. However, if eternal inflation is a valid description of the universe (as I think it is), then I would expect that all such hypotheses about the ultimate beginning of the universe would become totally divorced from any observable consequences. Since our own pocket universe would be equally likely to lie anywhere on the infinite tree of universes produced by eternal inflation, we would expect to find ourselves arbitrarily far from the beginning. The infinite inflating network would presumably approach some kind of a steady state, losing all memory of how it started, so the statistical predictions for our universe would be determined by the properties of this steady state configuration, independent of hypotheses about the ultimate beginning. In my opinion theories of the ultimate origin would remain intellectually interesting, and with an improved understanding of the fundamental laws of physics, such theories might even eventually become compelling. But I expect that any detailed consequences of such a theory would be completely washed out by the eternal evolution of the universe. Thus, there would be no way of relating the properties of the ultimate origin to anything that we might observe in today's universe.

Although I believe that the inflating network would approach a steady state, I should admit that attempts to pursue this idea quantitatively have run into several technical problems. First, the evolution of eternally inflating universes leads to physics that we do not understand. In particular, quantum fluctuations tend to drive the repulsive-gravity material to higher and higher energy densities, where the poorly understood effects of quantum gravity become more and more important [15, 16]. Second, even if we impose enough assumptions so that the evolution of the eternally inflating universe can be described, we still do not know how to define probabilities on the infinite set of pocket universes that is produced [17]. The problem is akin to asking what fraction of the integers are odd [18]. Most people would presumably say that the answer is $1/2$, since the integers alternate between odd and even. However, the ambiguity of the answer can be seen if one imagines other orderings for the integers. One could, if one wished, order the integers as 1,3, 2, 5,7, 4, 9,11, 6, ..., always writing two odd integers followed by one even integer. This list includes each integer exactly once, but from this list one would conclude that $2/3$ of the integers are odd. Thus, the answer seems to depend on the ordering. For eternally inflating universes, however, there is no natural ordering to the regions of spacetime that comprise the entire universe. There are well-founded proposals for defining probabilities [19], but at least in my opinion there is no definitive and compelling argument.

A second implication of eternal inflation is that the probability for inflation to start—the question of how likely it is for an initial speck of repulsive-gravity material to form—becomes essentially irrelevant. Inflation only needs to begin once, in all of eternity. As long as the probability is nonzero, it does not seem relevant, and perhaps it is not even meaningful,

to ask if the probability is large or small. If it is possible, then it will eventually happen, and when it does it produces literally an infinite number of universes. Unless one has in mind some competing process, which could also produce an infinite number of universes (or at least an infinite space-time volume), then the probability for inflation to start has no significance.

The third and final implication of eternal inflation that I would like to discuss pertains to the comparison of theories. I would argue that once one accepts eternal inflation as a logical possibility, then there is no contest in comparing an eternally inflating version of inflation with any theory that is not eternal.

Consider the analogy of going into the woods and finding some rare species of rabbit that has never before been seen. You could either assume that the rabbit was created by a unique cosmic event involving the improbable collision of a huge number of molecules, or you could assume that the rabbit was the result of the normal process of rabbit reproduction, even though there are no visible candidates for the rabbit's parents. I think we would all consider the latter possibility to be far more plausible. Once we become convinced that universes can eternally reproduce, then the situation becomes very similar, and the same logic should apply. It seems far more plausible that our universe was the result of universe reproduction than that it was created by a unique cosmic event.

VI. Did the Universe Have a Beginning?

Finally, I would like to discuss the central topic of this session, the question of whether or not the universe had a beginning.

The name *eternal inflation*, as I pointed out earlier, could be phrased more accurately as *future-eternal inflation*. Everything that has been said so far implies only that inflation, once started, continues indefinitely into the future. It is more difficult to determine what can be said about the distant past.

For the explicit constructions of eternally inflating models, the answer is clear. Such models start with a state in which there are no pocket universes at all, just pure repulsive-gravity material filling space. So there is definitely a beginning to the models that we know how to construct.

In 1993 Borde and Vilenkin [20] proved a theorem which showed under fairly plausible assumptions that every eternally inflating model would have to start with an *initial singularity*, and hence must have a beginning. In 1997, however, they [21] noted that one of their assumed conditions, although valid at the classical level, was violated by quantum fluctuations that could be significant in eternally inflating models. They concluded that their earlier proof would not apply to such cases, so the door was open for the construction of models without a beginning. They noted, however, that no such models had been found.

At the present time, I think it is fair to say that it is an open question whether or not eternally inflating universes can avoid having a beginning. In my own opinion, it looks like eternally inflating models necessarily have a beginning. I believe this for two reasons. The first is the fact that, as hard as physicists have worked to try to construct an alternative, so far all the models that we construct have a beginning; they are eternal into the future, but not into the past. The second reason is that the technical assumption questioned in the 1997

Borde-Vilenkin paper does not seem important enough to me to change the conclusion, even though it does undercut the proof. Specifically, we could imagine approximating the laws of physics in a way that would make them consistent with the assumptions of the earlier Borde-Vilenkin paper, and eternally inflating models would still exist. Although those modifications would be unrealistic, they would not drastically change the behavior of eternally inflating models, so it seems unlikely that they would change the answer to the question of whether these models require a beginning.

So, as is often the case when one attempts to discuss scientifically a deep question, the answer is inconclusive. It looks to me that **probably** the universe had a beginning, but I would not want to place a large bet on the issue.

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