

THE PRINCIPLE OF MEDIOCRITY

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I consider myself an average man, except for the fact that I consider myself an average man.

Michel de Montagne

We live in the aftermath of a great explosion. This awesome event, called somewhat frivolously the big bang, took place about 14 billion years ago. We can actually see some of the cosmic history unfolding before us since that moment—light from remote galaxies takes billions of years to reach our telescopes on earth, so we can see galaxies as they were in their youth. But there is a limit to how far we can see into space. Our horizon is set by the maximum distance light could have traveled since the big bang. Sources more distant than the horizon cannot be observed, simply because their light has not yet had time to reach Earth.

But if there are parts of the universe we cannot detect, who can resist wondering what they look like? Until recently physicists thought that the answer to this question is rather boring: it's just more of the same – more galaxies, more stars. But now, recent developments in cosmology have led to a drastic revision of that view.

According to the new picture, distant parts of the universe are in the state of explosive, accelerated expansion, called “inflation”. The expansion is so fast that in a tiny fraction of a second a region the size of an atom is blown to dimensions much greater than the entire currently observable universe. The expansion is caused by a peculiar form of matter, called “false vacuum”, which produces a strong repulsive force. The word “false” refers to the fact that, unlike the normal “true” vacuum, this type of vacuum is unstable and typically decays after a brief period of time, releasing a large amount of energy. The energy ignites a hot fireball of particles and radiation. This is what happened in our cosmic neighborhood 14 billion years ago – the event we refer to as the big bang.

The idea of inflation was little more than a speculative hypothesis when Alan Guth first proposed it in 1980. But in the late 1990s observations of distant supernovae and of the cosmic microwave background radiation—a faint afterglow of the big bang—gave the theory a boost of corroborating observational evidence. So today, inflation is well on its way to becoming one of the cornerstones of modern cosmology. And since the theory is supported by the data in the observable part of the universe, this gives us reason to believe its conclusions about the parts that we cannot observe.

In a way, inflation is similar to the reproduction of bacteria. There are two competing processes at play: bacteria multiply by division, but occasionally they are also destroyed by antibodies. The outcome depends on which process is more efficient. If the bacteria reproduce faster, their numbers rapidly grow. If destruction is faster, the bacteria quickly die out.

With inflation, the two competing processes are the decay of the false vacuum and its “reproduction” by rapid expansion of the inflating regions. My calculations, and those of Andrei Linde, show that false-vacuum regions multiply much faster than they decay, and thus their volume grows without bound. At this very moment, some

distant parts of the universe are undergoing exponential inflationary expansion. Other regions like ours, where inflation has ended, are also constantly being produced. They form “island universes” in the inflating sea of false vacuum. Because of inflation, the space between the islands rapidly expands, making room for more island universes to form.

Inflation is thus a runaway process that has stopped in our neighborhood, but still continues in other parts of the universe, causing them to expand at a furious rate and constantly spawning new island universes like our own. This never ending process is referred to as “eternal inflation”. The role of the big bang in this scenario is played by the decay of the false vacuum. It is no longer a one-time event in our past: multiple bangs went off before it in remote parts of the universe, and countless others will erupt elsewhere in the future.

Analysis shows that the boundaries of island universes expand faster than the speed of light. (Einstein’s ban on super-luminal speeds applies to material bodies, but not to geometric entities such as the boundary of an island.) It follows that, regrettably, we will never be able to travel to another island, or even send a message there. Other island universes are unobservable, even in principle.

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Back in 1983, when this new worldview was gradually taking shape in my mind, I discussed it with Alan Guth -- Mr. Inflation himself. I told Alan about runaway expansion and how it could be described mathematically. But then, when I was in the middle of unveiling my new dazzling picture of the universe, I noticed that Alan was beginning to doze off. Years later, when I got to know Alan better, I learned that he is a very sleepy fellow. We organize a joint seminar for the Boston area cosmologists, and at every seminar meeting Alan falls peacefully asleep a few minutes after the talk begins. Miraculously, when the speaker is finished, he wakes up and asks the most penetrating questions. Alan denies any supernatural abilities, but not everybody is convinced. So, in retrospect, I should have continued the discussion. But at the time I was not aware of Alan’s magical powers and hastily retreated. (I should add that later Alan Guth became a great enthusiast of eternal inflation.)

The initial response of other colleagues was also less than enthusiastic. Physics is an observational science, they said, so we should refrain from making claims that cannot be observationally confirmed. We cannot observe other big bangs, nor can we observe distant inflating regions. They are all beyond our horizon, so how can we verify that they really exist?

However, surprising as this may seem, the existence of unobservable island universes can be used to make testable predictions in our local region. Even more surprisingly, some of the predictions have already been confirmed! These tests of eternal inflation involve anthropic considerations, which have recently become a subject of great controversy. But before I get to the tests, I would like to discuss some striking – and I would say metaphysical – implications of eternal inflation.

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In the global view of eternal inflation, the boundaries of island universes are the regions where big bangs are happening right now. Newly formed islands are microscopically small, but they grow without limit as they get older. Central parts of large island universes are very old: big bangs once took place there long time ago.

Now they are dark and barren: all stars have long since died there. But regions at the periphery of the islands are new and must be teeming with shining stars.

The inhabitants of island universes, like us, see a different picture. They do not perceive their universe as a finite island. For them it appears as a self-contained, infinite universe. That dramatic difference in perspective is a consequence of the differences imposed by the ways of keeping time appropriate to the global and internal views of the island universe. (According to Einstein's theory of relativity, time is not fixed, but instead is observer dependent.)

In the global view, the definition of a "moment of time" is largely arbitrary, because there is no obvious way to synchronize the clocks of observers in false vacuum and in different island universes. By contrast, to describe one specific island universe from the point of view of its inhabitants, there is a natural rather than arbitrary choice for the origin of time. All observers in a given island universe can count time from the big bang at their respective locations. Their big bang is thus set as time zero. Remarkably, from such an internal viewpoint the island universe is infinite.

Perhaps the easiest way to see this is to count galaxies. In the global view, new galaxies are continually formed near the expanding boundaries, so as time passes, we have an infinite number of galaxies in the limit. In the internal view, all this infinity of galaxies exists simultaneously (say, at time 14 billion years). The implications are extraordinary.

Since each island universe is infinite from the viewpoint of its inhabitants, it can be divided into an infinite number of regions having the same size as our own observable region. My collaborator Jaume Garriga and I call them O-regions for short. As it happens, the most distant objects visible from Earth are about 40 billion light-years away, so the diameter of our own O-region is twice that number.

Imagine, then, an infinite island universe packed with O-regions -- gigantic spheres, 80 billion light-years in diameter each. The key observation is that the number of distinct configurations of matter that can possibly be realized in any O-region—or, for that matter, in any finite system—is finite. One might think that arbitrarily small changes could be made in the system, thus creating an infinite number of possibilities. But that is not the case. If I move my chair by one centimeter, I change the state of our own O-region. I could instead move it by 0.9 centimeter, 0.99 centimeter, 0.999 centimeter, and so forth—an infinite sequence of possible displacements, which more and more closely approach the limit of one centimeter. There is a problem, though. Displacements too close to one another cannot be distinguished, even in principle, because of quantum mechanical uncertainty. As a result, there is only a finite number of distinct states.

The number of possible histories of an O-region is finite as well. A history is described by a sequence of states at successive moments of time. Which histories are possible in quantum physics differ immensely from the ones possible in the classical world. In the quantum world the future is not uniquely determined by the past; the same initial state can lead to a multitude of different outcomes, and so only the probabilities of those outcomes can be determined. Consequently, the range of possible histories is greatly enlarged. Once again, though, the fuzziness imposed by quantum uncertainty makes it impossible to distinguish histories that are too close to each other. An estimate of the number of distinct histories that can unfold in an O-region between the big bang and the present gives 10 to the power 10^{150} . This number is fantastically huge, but the important point is that the number is finite.

Let us now take stock of the situation. The theory of inflation tells us that island universes are internally infinite, so that each of them comprises an infinite number of O-regions. And quantum uncertainty implies that only a finite number of histories can unfold in any O-region. The initial states of the O-regions at the big bang are set by random quantum processes during inflation, so all possible initial states are represented in the ensemble. Putting those statements together, it follows that every single history should be repeated an infinite number of times within any of the island universes—including, of course, the one we inhabit.

Among the infinitely replayed scripts are some very bizarre histories. For example, a planet similar to our Earth can suddenly collapse to form a black hole. Such an event is extremely unlikely, but all that means is that, before encountering it, one would have to survey an enormous number of O-regions within our island universe.

A striking consequence of the new picture of the world is that there should be an infinity of regions with histories absolutely identical to ours. That's right, scores of your duplicates are now reading copies of this article. They live on planets exactly like Earth, with all its mountains, cities, trees, and butterflies. There should also be regions where histories are somewhat different from ours, with all possible variations. For example, some readers will be pleased to know that there are infinitely many O-regions where Al Gore is the President of the United States.

In this astonishing worldview, our Earth and our civilization are anything but unique. Instead, countless identical civilizations are scattered across the infinite expanse of the cosmos. With humankind reduced to absolute cosmic insignificance, our descent from the center of the world, a process begun by Copernicus, is now complete.

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I now turn to possible observational tests of eternal inflation. The clue to the structure of the universe may be right in front of our eyes, encoded in the values of the fundamental constants. According to string theory, the quantities we call “constants of nature” – like Newton’s gravitational constant or the electron mass -- may in fact be variables that can take a wide spectrum of values. This has been discussed on *Edge* by Lenny Susskind. Despite some recent fire that string theory has attracted, it remains the best candidate we now have for the fundamental theory of nature. (There are also other particle physics theories predicting variation of the “constants”. I will mention one example below.)

Quantum fluctuations in the course of eternal inflation ensure that all possible values of the constants are realized somewhere in the universe. As a result, remote regions of the universe may drastically differ in their properties from our observable region. The values of the constants in our vicinity are determined partly by chance and partly by how suitable they are for the evolution of life. The latter effect is called anthropic selection.

If some “constant” varies from one region of the universe to another, its value cannot be predicted with certainty, but we can still try to make a statistical prediction. Suppose, for example, I want to predict the height of the first man I am going to see when I walk out into the street. Having consulted the statistical data on the height of men in the United States, I find that the height distribution follows a bell curve with a median value at 1.77 meters. The first man I meet is not likely to be a giant or a dwarf, so I expect his height to be in the mid-range of the distribution. To make the

prediction more quantitative, I can assume that he will not be among the tallest 2.5% or shortest 2.5% of men in the United States. The remaining 95% have heights between 1.63 and 1.90 meters. If I predict that the man I meet will be within this range of heights and then perform the experiment a large number of times, I can expect to be right 95% of the time. This is known as a prediction at 95% confidence level.

In order to make a 99% confidence level prediction, I would have to discard 0.5% at both ends of the distribution. As the confidence level is increased, my chances of being wrong get smaller, but the predicted range of heights gets wider and the prediction less interesting.

A similar technique can be used to make predictions for the constants of nature. Suppose the Statistical Bureau of the Universe collected and published the values of some constant X measured by observers in different parts of the universe. We could then discard 2.5% at both ends of the resulting distribution and predict the value of X at a 95% confidence level.

What would be the meaning of such a prediction? If we randomly picked observers in the universe, their observed values of X would be in the predicted interval 95% of the time. Unfortunately, we cannot perform this experiment, because all regions with different values of X are beyond our horizon. We can only measure X in our local region. What we can do, though, is to think of ourselves as having been randomly picked. We are just one in the multitude of civilizations scattered throughout the universe. We have no reason to believe a priori that the value of X in our region is very large or small, or otherwise very special compared with the values measured by other observers. Hence, we can predict, at 95% confidence level, that our measurement will yield a value in the specified range. The assumption of being unexceptional is important in this approach; I called it “the principle of mediocrity”.

In lieu of the data from the Statistical Bureau of the Universe, we have to derive the statistical distribution from the fundamental theory, combined with the theory of eternal inflation. If the resulting predictions agree with the measurements, this would provide evidence for the theory; if not, the theory can be ruled out at a specified confidence level.

Of course, we have no idea how to calculate the number of observers, because of our ignorance about the origins of life and intelligence. But this problem can be circumvented if we focus on the variation of the constants that do not directly affect the physics and chemistry of life. The counting of observers can then be reduced to the counting of galaxies (since all galaxies in this case will have about the same number of observers).

This strategy has been applied to the cosmological constant, with a very encouraging result. Steven Weinberg and Andrei Linde were the first to suggest that the cosmological constant should be non-zero if anthropic selection is at work. The first quantitative attempts based on the principle of mediocrity were by me and by George Efstathiou. A few years later, it came as a complete shock to most physicists when observational evidence for a nonzero cosmological constant was first announced. It was in a rough agreement with the anthropic expectations. The most recent calculations, using the data from WMAP satellite, give the probability of about 25% for the observed value – a good agreement for a statistical model of this kind. Moreover, despite numerous attempts, no other plausible explanation for the observed cosmological constant has been suggested.

Critics often argue that anthropic predictions cannot be falsified, but this is simply not true. If the cosmological constant turned out to be an order of magnitude

smaller than its actual value, the underlying model would be ruled out at 95% confidence level.

Another recent application of the principle of mediocrity, unrelated to string theory, is to the amount of dark matter in the universe. As its name suggests, dark matter cannot be seen directly, but its presence is manifested by the gravitational pull it exerts on visible objects. The composition of dark matter is unknown. One of the best motivated hypotheses is that it is made up of very light particles called axions. The density of axionic dark matter is set by quantum fluctuations during inflation and varies from one place in the universe to another. Its value affects the formation of galaxies; hence there is an anthropic selection effect. In a recent paper, Max Tegmark, Anthony Aguirre, Martin Rees and Frank Wilczek calculated the resulting probability distribution. They found that the observed value of the dark matter density is close to the peak of the bell curve, in excellent agreement with the theory.

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The reluctance of many physicists to embrace anthropic explanations is easy to understand. The standard of accuracy in physics is very high, you might say unlimited. For example, the theoretically calculated magnetic moment of the electron agrees with the observed value up to the 11th decimal point. In fact, failure to agree at this level would be a cause for alarm, since any disagreement, even in the 11th decimal point, would indicate some gap in our understanding of the electron.

Anthropic predictions are not like that. The best we can hope for is to calculate the statistical bell curve. Further improvements in the calculation of that curve will not lead to a dramatic increase in the accuracy of the prediction. If the observed value falls within the predicted range, there will still be a lingering doubt that this happened by sheer dumb luck. If it doesn't, there will be doubt that the theory might still be correct, but we just happened to be among a few percent of observers at the tails of the bell curve.

It's little wonder that, given a choice, physicists would not give up their old paradigm in favor of anthropic selection. But nature has already made her choice. We only have to find out what it is. If the constants of nature are variable, then, whether we like it or not, the best we can do is to make statistical predictions based on the principle of mediocrity.

The observed value of the cosmological constant gives a strong indication that there is indeed a huge eternally inflating universe out there, with constants varying from one region to another. The evidence for this view is, of course, indirect, as it will always be. This is a circumstantial case, where we are not going to hear eyewitness accounts or see the murder weapon. But if, with some luck, we make a few more successful predictions, we may still be able to prove the case beyond reasonable doubt.