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The multiverse: How we're tackling the challenges facing the theory

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The idea of a multiverse consisting of "parallel universes" is a popular science fiction trope, recently explored in the Oscar-winning movie "Everything Everywhere All At Once." However, it is within the realm of scientific possibility.

It is important to state from the start that the existence (or not) of the multiverse is a consequence of our present understanding of the fundamental laws of physics—it didn't come from the minds of whimsical physicists reading too many sci-fi books.

There are different versions of the multiverse. The first and perhaps most popular version comes from quantum mechanics, which governs the world of atoms and particles. It suggests a particle can be in many possible states simultaneously—until we measure the system and it picks one. According to one interpretation, all quantum possibilities that we didn't measure are realized in other universes.

Eternal inflation

The second version, the cosmological multiverse, arises as a consequence of cosmic inflation. In order to explain the fact that the universe today looks roughly similar everywhere, the physicist Alan Guth proposed in 1981 that the early universe underwent a period of accelerated expansion. During this period of inflation, space was stretched such that the distance between any two points were pushed apart faster than the speed of light.

The theory of inflation also predicted the existence of the primordial seeds which grew into cosmological structures such as stars and galaxies. This was triumphantly detected in 2003 by observations of tiny temperature fluctuations in the cosmic microwave background, which is the light left over from the Big Bang. It was subsequently measured with exquisite precision by the space experiments WMAP and Planck.

Due to this remarkable success, cosmic inflation is now considered the de facto theory of the early universe by most cosmologists.

But there was a (perhaps unintended) consequence of cosmic inflation.

During inflation, space is stretched and smoothed over very large scales—usually much larger than the observable universe. Nevertheless, cosmic inflation must end at some point, else our universe wouldn't have been able to evolve to what it is today.

But physicists soon realized that if inflation really is true, some regions of space-time would continue to inflate even as inflation ended in the others. The regions that continue to inflate can be considered a separate, inflating universe. This process continues indefinitely, with inflating universes producing even more inflating universes, creating a multiverse of universes.

This phenomenon is dubbed "eternal inflation." First described by physicists Paul Steinhardt and Alex Vilenkin in 1983, eternal inflation remained a curious artifact of cosmic inflation until the early 21st century, when it was combined with an idea from string theory to produce a controversial yet compelling explanation of why our physical laws are what they are today.

String theory is not yet proven, but it is presently our best hope for a theory of everything—uniting quantum mechanics and gravity. However, physically realistic string theories must possess ten or more dimensions (rather than our normal three spatial dimensions plus time). Thus, to describe our present universe, six or more of these dimensions must be "compactified"—curled up in a such way that we can't see them.

The mathematical procedure for this is known. The problem (some might say the feature) of this process is that there are at least 10^{500} ways to do this compactification—and this mind-bogglingly huge set of possibilities is called the "string landscape." Each compactification will yield a different set of physical laws, potentially corresponding to a different universe. This begs two crucial questions: where are we in the string landscape, and why?

Eternal inflation provides an elegant answer to the first question: each inflating universe of the multiverse realizes a different point in the string landscape, so all possible physical laws can exist somewhere in the multiverse. But why is our universe so great at producing intelligent life like us? Well, some universes should, statistically speaking, be like ours—and we live in the universe in which our physical laws are the ones we observe.

However, this view is highly controversial—many argue it is not a scientific argument and it has spurred an intensive inquiry.

Testability

The obvious challenge with the multiverse is its observability. Suppose it does exist, is it then possible to observe the other universes, even in principle? For the quantum multiverse, the answer is no—different universes don't communicate. But in the inflationary multiverse, the answer is "yes, if we are lucky."

Since the different universes occupy the same physical space, neighboring universes could in principle collide with each other, possibly leaving relics and imprints in our observable universe. A research collaboration led by Hiranya Peiris of University College London and Matthew Johnson of the Perimeter Institute showed that such collisions should indeed leave imprints on the cosmic microwave background (light left over from the Big Bang) that can be searched for—although so far, these signatures have not been found.

The next challenge is theoretical. Some theorists have suggested that most of the universes in the string landscape are actually mathematically inconsistent—unable to exist in the way our universe does. They instead exist in a swampland of solutions—and in particular, solutions of string theory which permit cosmic inflation seem to be difficult to find.

There is deep disagreement among string theorists and cosmologists on whether string theory can describe inflation, even in principle. This conundrum is both vexing and exciting—it suggests that one of the two ideas is wrong, either of which will lead to a revolution in theoretical physics.

Finally, the very premise of cosmic inflation is now being challenged. The raison d'etre of cosmic inflation is that, regardless of how the early universe looked, inflation would dynamically drive the cosmos to the smooth universe we see today. However, it has never been rigorously investigated whether cosmic inflation can actually begin in the first place.

This is because the equations describing the beginning of the process are too complicated to solve analytically. But this question is now being rigorously tested by several research groups around the world, including my own at King's College London, where the power of modern high performance computing is brought to bear on solving these formerly intractable equations. So watch this space.