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The Great Cosmic Roller-Coaster Ride

Could cosmic inflation be a sign that our universe is embedded in a far vaster realm

By Cliff Burgess and Fernando Quevedo

You might not think that cosmologists could feel claustrophobic in a universe that is 46 billion light-years in radius and filled with sextillions of stars. But one of the emerging themes of 21st-century cosmology is that the known universe, the sum of all we can see, may just be a tiny region in the full extent of space. Various types of parallel universes that make up a grand "multiverse" often arise as side effects of cosmological theories. We have little hope of ever directly observing those other universes, though, because they are either too far away or somehow detached from our own universe.

Some parallel universes, however, could be separate from but still able to interact with ours, in which case we could detect their direct effects. The possibility of these worlds came to cosmologists' attention by way of string theory, the leading candidate for the foundational laws of nature. Although the eponymous strings of string theory are extremely small, the principles governing their properties also predict new kinds of larger membranelike objects—"branes," for short. In particular, our universe may be a three-dimensional brane in its own right, living inside a nine-dimensional space. The reshaping of higher-dimensional space and collisions between different universes may have led to some of the features that astronomers observe today.

String theory has received some unfavorable press of late. The criticisms are varied and beyond the scope of this article, but the most pertinent is that it has yet to be tested experimentally. That is a legitimate worry. It is less a criticism of string theory, though, than a restatement of the general difficulty of testing theories about extremely small scales. All proposed foundational laws encounter the same problem, including other proposals such as loop quantum gravity. String theorists continue to seek ways to test their theory. One approach with promise is to study how it might explain mysterious aspects of our universe, foremost among which is the way the pace of cosmic expansion has changed over time.

Going for a Ride

Next year will be the 10th anniversary of the announcement that the universe is expanding at an ever quickening pace, driven by some unidentified constituent known as dark energy. Most cosmologists think that an even faster period of accelerated expansion, known as inflation, also occurred long before atoms, let alone galaxies, came into being. The universe's temperature shortly after this early inflationary period was billions of times higher than any yet observed on Earth. Cosmologists and elementary particle physicists find themselves making common cause to try to learn the fundamental laws of physics at such high temperatures. This cross-fertilization of ideas is stimulating a thorough rethinking of the early universe in terms of string theory.

The concept of inflation emerged to explain a number of simple yet puzzling observations. Many of these involve the cosmic microwave background radiation (CMBR), a fossil relic of the hot early universe. For instance, the CMBR reveals that our early universe was almost perfectly uniform—which is strange because none of the usual processes that homogenize matter (such as fluid flow) would have had time to operate. In the early 1980s Alan H. Guth, now at the Massachusetts Institute of Technology, found that an extremely rapid period of expansion could account for this homogeneity. Such an accelerating expansion diluted any preexisting matter and smoothed out deviations in density.

Equally important, it did not make the universe exactly homogeneous. The energy density of space during the inflationary period fluctuated because of the intrinsically statistical quantum laws that govern nature over subatomic distances. Like a giant photocopy machine, inflation enlarged these small quantum fluctuations to astronomical size, giving rise to predictable fluctuations in density later in cosmic history.

What is seen in the CMBR reproduces the predictions of inflationary theory with spectacular accuracy. This observational success has made inflation the leading proposal for how the universe behaved at very early times. Upcoming satellites, such as the European Space Agency's Planck observatory that is scheduled for launch next year, will look for corroborating evidence.

But do the laws of physics actually produce this inflation? Here the story gets murkier. It is notoriously difficult to get a universe full of regular forms of matter to accelerate in its expansion. Such a speedup takes a type of energy with a very unusual set of properties: its energy density must be positive and remain almost constant even as the universe dramatically expands, but the energy density must then suddenly decrease to allow inflation to end.

At first sight, it seems impossible for the energy density of anything to remain constant, because the expansion of space should dilute it. But a special source of energy, called a scalar field, can avoid this dilution. You can think of a scalar field as an extremely primitive substance that fills space, rather like a gas, except that it does not behave like any gas you have ever seen. It is similar to but simpler than the better-known electromagnetic and gravitational fields. The term "scalar field" simply means that it is described by a single number, its magnitude, that can vary from location to location within space. In contrast, a magnetic field is a vector field, which has both a magnitude and a direction (toward the north magnetic pole) at each point in space. A weather report provides examples of both types of field: temperature and pressure are scalars, whereas wind velocity is a vector.

The scalar field that drove inflation, dubbed the "inflaton" field, evidently caused the expansion to accelerate for a long period before switching off abruptly. The dynamics were like the first moments of a roller-coaster ride. The coaster initially climbs slowly along a gentle hill. ("Slowly" is a relative term; the process was still very fast in human terms.) Then comes the breathtaking plunge during which potential energy is converted to kinetic energy and ultimately heat. This behavior is not easy to reproduce theoretically. Physicists have made a variety of proposals over the past 25 years, but none has yet emerged as compelling. The search is hampered by our ignorance of what might be going on at the incredibly high energies that are likely to be relevant.

Brane Bogglers

During the 1980s, as inflation was gaining credence, an independent line of reasoning was making progress toward reducing our ignorance on that very issue. String theory proposes that subatomic particles are actually tiny one-dimensional objects like miniature rubber bands. Some of these strings form loops (so-called closed strings), but others are short segments with two ends (open strings). The theory attributes all the elementary particles ever discovered, and many more undiscovered, to different styles of vibration of these types of strings. The best part of string theory is that, unlike other theories of elementary particles, it organically contains gravity within itself. That is, gravity emerges naturally from the theory without having been assumed at the outset.

If the theory is correct, space is not quite what it appears to be. In particular, the theory predicts that space has precisely nine dimensions (so spacetime has 10 dimensions once time is included), which represent six more than the usual three of length, breadth and height. Those extra dimensions are invisible to us. For instance, they may be very small and we may be oblivious to them simply because we cannot fit into them. A parking lot may have a hairline fracture, adding a third dimension (depth) to the pavement surface, but if the fracture is small, you will never notice it. Even string theorists have difficulty visualizing nine dimensions, but if the history of physics has taught us anything, it is that the true nature of the world may lie beyond our ability to visualize directly.

Despite its name, the theory is not just about strings. It also contains another kind of object called a Dirichlet brane—D-brane, for short. D-branes are large, massive surfaces that float within space. They act like slippery sheets of flypaper: the ends of open strings move on them but cannot be pulled off. Subatomic particles such as electrons and protons may be nothing more than open strings and, if so, are stuck to a brane. Only a few hypothetical particles, such as the graviton (which transmits the force of gravity), must be closed strings and are thus able to move completely freely through the extra dimensions. This distinction offers a second reason not to see the extra dimensions: our instruments may be built of particles that are trapped on a brane. If so, future instruments might be able to use gravitons to reach out into the extra dimensions.

D-branes can have any number of dimensions up to nine. A zero-dimensional D-brane (D0-brane) is a special type of particle, a D1-brane is a special type of string (not the same as a fundamental string), a D2-brane is a membrane or a wall, a D3-brane is a volume with height, depth and width, and so on. Our entire observed universe could be trapped on such a brane—a so-called brane world. Other brane worlds may float around out there, each being a universe to those trapped onboard. Because branes can move in the extra dimensions, they can behave like particles. They can move, collide, annihilate, and even form systems of branes orbiting around one another like planets.

Although these concepts are provocative, the acid test of a theory comes when it is confronted with experiments. Here string theory has disappointed because it has not yet been possible to test it experimentally, despite more than 20 years of continued investigation. It has proved hard to find a smoking gun—a prediction that, when tested, would decisively tell us whether or not the world is made of strings. Even the Large Hadron Collider (LHC)—which is now nearing completion at CERN, the European laboratory for particle physics near Geneva—may not be powerful enough.

Seeing the Unseen Dimensions

Which brings us back to inflation. If inflation occurs at the high energies where the stringy nature of particles becomes conspicuous, it may provide the very experimental tests that string theorists have been looking for. In the past few years, physicists have begun to investigate whether string theory could explain inflation. Unfortunately, this goal is easier to state than achieve.

To be more specific, physicists are checking whether string theory predicts a scalar field with two properties. First, its potential energy must be large, positive and roughly constant, so as to drive inflation with vigor. Second, this potential energy must be able to convert abruptly into kinetic energy—the exhilarating roller-coaster plunge at the end of inflation.

The good news is that string theory predicts no shortage of scalar fields. Such fields are a kind of consolation prize for creatures such as ourselves who are stuck in three dimensions: although we cannot peer into the extra dimensions, we perceive them indirectly as scalar fields. The situation is analogous to taking an airplane ride with all the window shades lowered. You cannot see the third dimension (altitude), but you can feel its effects when your ears pop. The change in pressure (a scalar field) is an indirect way of perceiving the dimension.

Air pressure represents the weight of the column of atmosphere above your head. What do the scalar fields of string theory represent? Some correspond to the size or shape of space in the unseen directions and are known by the mathematical term of geometric “moduli” fields. Others represent the distance between brane worlds. For instance, if our D3-brane approached another D3-brane, the distance between the two could vary slightly with location because of ripples in each brane. Physicists in Toronto might measure a scalar field value of 1 and physicists in Cambridge a value of 2, in which case they could conclude that the neighboring brane is twice as far from Cambridge as from Toronto.

To push two branes together or contort extra-dimensional space takes energy, which can be described by a scalar field. Such energy might cause branes to inflate, as first proposed by Georgi Dvali of New York University and Henry S.-H. Tye of Cornell University in 1998. The bad news is that the first calculations for the various scalar fields were not encouraging. Their energy density proved to be very low—too low to drive inflation. The energy profile more resembled a train sitting on level ground than a slowly climbing roller coaster.

Introducing Antibranes

That is where the problem stood when the two of us—together with Mahbub Majumdar, then at the University of Cambridge, and Govindan Rajesh, Ren-Jie Zhang and the late Detlef Nolte, all then at the Institute for Advanced Study in Princeton, N.J.—began thinking about it in 2001.

Dvali, Sviatoslav Solganik of N.Y.U. and Qaisar Shafi of the University of Delaware developed a related approach at the same time.

Our innovation was to consider both branes and antibranes. Antibranes are to branes what antimatter is to matter. They attract each other, much as electrons attract their antiparticles (positrons). If a brane came near an antibrane, the two would pull each other together. The energy inside the branes could provide the positive energy needed to start inflation, and their mutual attraction could provide the reason for it to end, with the brane and antibrane colliding to annihilate each other in a grand explosion. Fortunately, our universe does not have to be annihilated to benefit from this inflationary process. When branes attract and annihilate, the effects spill over into nearby branes.

When we calculated the attractive force in this model, it was too strong to explain inflation, but the model was a proof of principle, showing how a steady process could have an abrupt ending that might fill our universe with particles. Our hypothesis of antibranes also inspired new thinking on the long-standing question of why our universe is three-dimensional.

The next level of refinement was to ask what happens when space itself, not just the branes within it, becomes dynamic. In our initial efforts, we had assumed the size and shape of extra-dimensional space to be fixed as the branes moved around. That was a serious omission, because space bends in response to matter, but an understandable one, because in 2001 nobody knew how to compute this extra-dimensional bending explicitly within string theory.

Space Warps

Within two years the situation changed dramatically. In 2003 a new theoretical framework known as KKLT, for its creators' initials, was developed by Shamit Kachru, Renata Kallosh and Andrei Linde of Stanford University, together with Sandip Trivedi of the Tata Institute of Fundamental Research in Mumbai. Their framework describes the circumstances in which the geometry of the extra dimensions is very stiff and so does not flex too much as things move around within it. It predicts a huge number of possible configurations for the extra dimensions, each corresponding to a different possible universe. The set of possibilities is known as the string theory landscape. Each possibility might be realized in its own region of the multiverse.

Within the KKLT framework, inflation can happen in at least two ways. First, it could result from the gravitational response of extra dimensions to brane-antibrane motion. The extra-dimensional geometry can be very peculiar, resembling an octopus with several elongations, or "throats." If a brane moves along one of these throats, its motion through the warped dimensions weakens the brane-antibrane attraction. This weakening enables the slow-roll process that gives rise to inflation, perhaps solving the main problem with our original proposal.

Second, inflation could be driven purely by changes in the geometry of the extra dimensions, without the need for mobile branes at all. Two years ago we and our colleagues presented the first stringy inflationary scenario along the second of these lines. This general process is called moduli inflation because moduli fields, which describe the geometry, act as the inflatons. As the extra dimensions settle into their current configuration, the three normal dimensions expand at an accelerated pace. In essence, the universe sculpts itself. Moduli inflation thus relates the size of the dimensions we see to the size and shape of those we cannot.

Strings in the Sky

The stringy inflation models, unlike many other aspects of string theory, might be tested observationally in the near future. Cosmologists have long thought that inflation would produce gravitational waves, ripples in the fabric of space and time. String theory may alter this prediction, because the existing stringy inflation models predict unobservably weak gravitational waves. The Planck satellite will be more sensitive to primordial gravitational waves than current instruments are. If it were to detect such waves, it would rule out all the models of string inflation proposed so far.

Also, some brane inflation models predict large linear structures known as cosmic strings, which naturally arise in the aftermath of brane-antibrane annihilation. These strings could come in several types: D1-branes or fundamental strings blown up to enormous size, or a combination of the two. If they exist, astronomers should be able to detect them by the way they distort the light coming from galaxies.

Despite the theoretical progress, many open questions remain. Whether inflation indeed occurred is not entirely settled. If improved observations cast doubt on it, cosmologists will have to turn to alternative pictures of the very early universe. String theory has inspired several such alternatives, in which our universe existed before the big bang, perhaps as part of a perpetual cycle of creation and destruction. The difficulty in these cases is to describe properly the transition that marks the moment of the big bang.

In summary, string theory provides two general mechanisms for obtaining cosmic inflation: the collision of branes and the reshaping of extra-dimensional spacetime. For the first time, physicists have been able to derive concrete models of cosmic inflation rather than being forced to make uncontrolled, ad hoc assumptions. The progress is very encouraging. String theory, born of efforts to explain phenomena at minuscule scales, may be writ large across the sky.

Stringlish

String Theory
A candidate unified theory of all physical forces and particles.

Inflation
A period of accelerated cosmic expansion early in the history of the universe.

Observable Universe
The sum of all we can see. Also called “our universe.”

Other Universe
An unobserved region of spacetime, perhaps having distinct properties and laws of physics.

calabi-yau
Six-dimensional shape of hidden dimensions.

Brane
Short for “membrane.” It can be a two-dimensional sheet (like an ordinary membrane) or a lower- or higher-dimensional variant.

Field
A form of energy that fills space like a fog.

Scalar Field
A field described by a single number at every position. Examples: temperature, inflaton field.

Moduli
Scalar fields that describe the size and shape of hidden space dimensions.

AnnIhilate
To convert completely to radiation, as happens when matter and antimatter or branes and antibranes collide.

WHAT'S NEXT

* Tests of gravitational-wave predictions by the Planck satellite and proposed gravitational-wave detectors

* Telescope searches for cosmic strings

* Theoretical work to understand the initial moment of the big bang

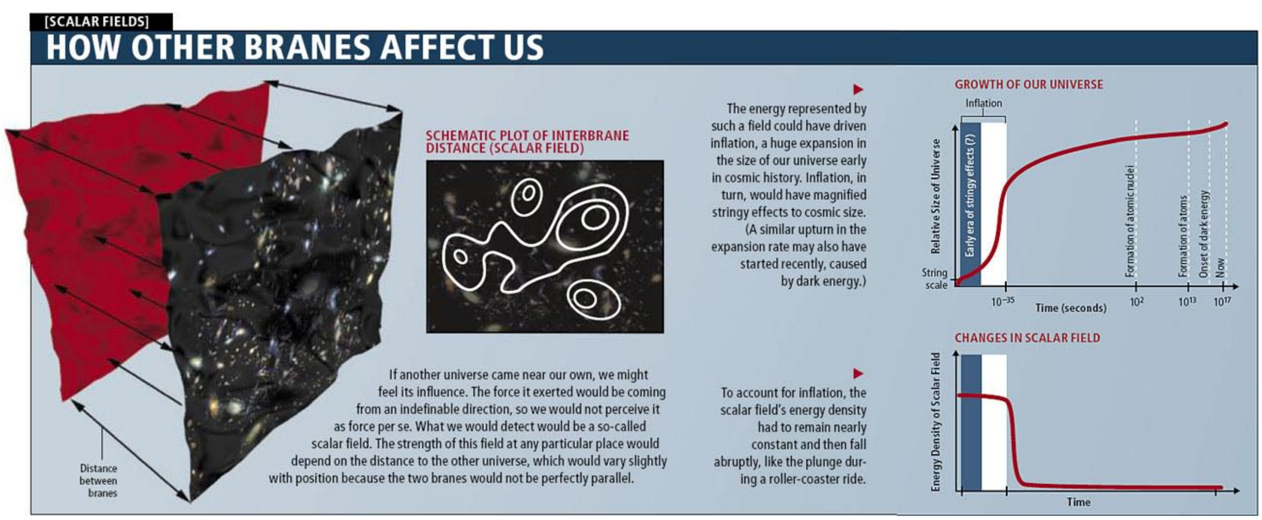
* Continued efforts to determine whether string theory can explain inflation

* Study of the possibility of communicating with other universes

Why Is Our Universe 3-D?

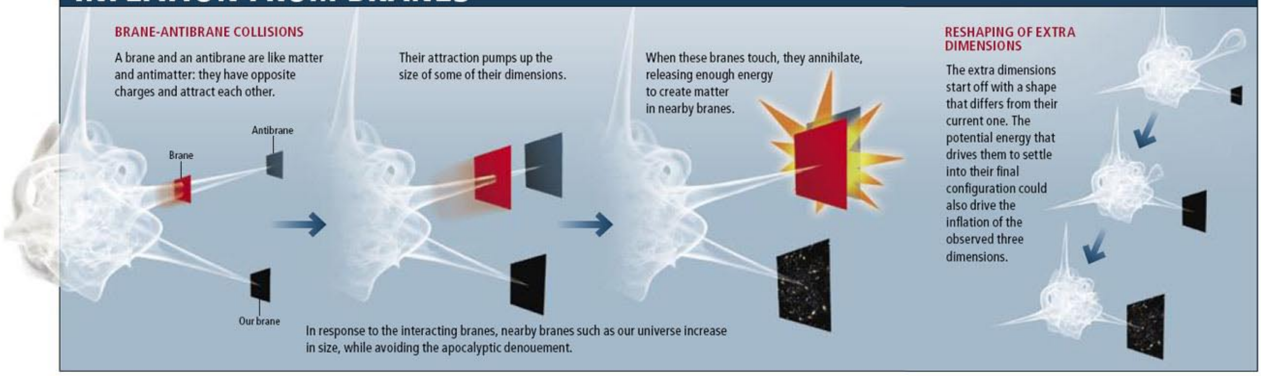
When a brane and antibrane meet, they do not annihilate directly to energy. Instead they first fragment into shards. These shards are smaller branes and antibranes; they occupy two fewer dimensions than the original ones did. For instance, if the initial brane and antibrane spanned seven spatial dimensions (a D7-brane and antibrane), they fragment into many D5-branes and antibranes. These shards, in turn, annihilate into D3-branes and antibranes and thence into D1-branes. Only at that point do they vanish altogether.

The cascade of brane-antibrane annihilation tends to remove large branes, which easily find their antibrane doppelgangers and so annihilate. Smaller branes, such as the D3 and D1 varieties, have greater difficulty bumping into antibranes in the vastness of nine-dimensional space. Lisa Randall of Harvard University and Andreas Karch of the University of Washington generalized our results to include nine expanding dimensions. This process may help explain why most branes, like ours, tend to have fairly few dimensions.



[TWO SCENARIOS]

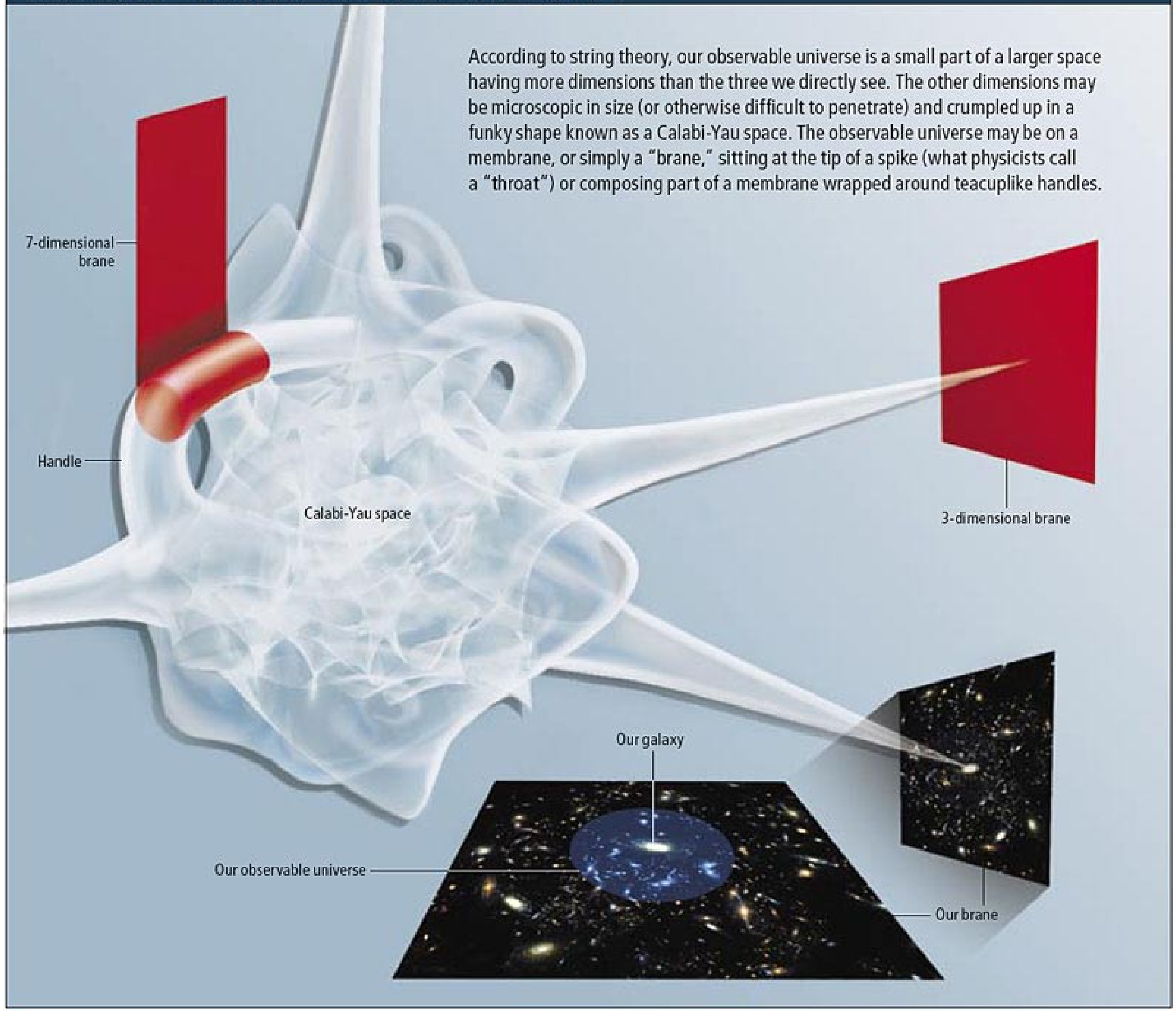
INFLATION FROM BRANES



[THE BASICS]

MANY UNIVERSES IN ONE

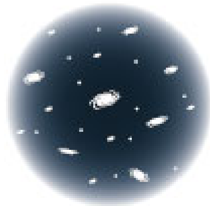
According to string theory, our observable universe is a small part of a larger space having more dimensions than the three we directly see. The other dimensions may be microscopic in size (or otherwise difficult to penetrate) and crumpled up in a funky shape known as a Calabi-Yau space. The observable universe may be on a membrane, or simply a "brane," sitting at the tip of a spike (what physicists call a "throat") or composing part of a membrane wrapped around teacuplike handles.



POWERS OF TEN

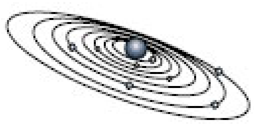
Natural phenomena occur on many scales. The fine details tend not to affect the large-scale workings, making it hard to test quantum theories of gravity such as string theory. But cosmic inflation allows the absurdly small to affect the astronomically big.

10^{26} meter:
Observable universe



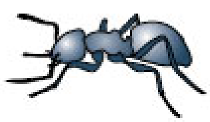
10^{21} meter:
Milky Way galaxy

10^{13} meter:
Solar system

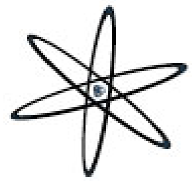


10^{7} meter:
Earth

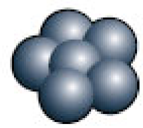
10^{-2} meter:
Insect



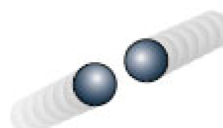
10^{-10} meter:
Atom



10^{-15} meter:
Atomic nucleus



10^{-18} meter:
Smallest distance probed by particle accelerators



10^{-18} to 10^{-35} meter:
Typical size of fundamental strings and of extra dimensions

10^{-35} meter:
Minimum meaningful length in nature

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