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The Universe on a Brane

SPECULATIONS ON SPACE AND TIME IN M-THEORY

String theory has one of the most twisted histories of any scientific breakthrough. Even today, more than three decades after its initial articulation, most string practitioners believe we still don't have a comprehensive answer to the rudimentary question, What is string theory? We know a lot *about* string theory. We know its basic features, we know its key successes, we know the promise it holds, and we know the challenges it faces; we can also use string theory's equations to make detailed calculations of how strings should behave and interact in a wide range of circumstances. But most researchers feel that our current formulation of string theory still lacks the kind of core principle we find at the heart of other major advances. Special relativity has the constancy of the speed of light. General relativity has the equivalence principle. Quantum mechanics has the uncertainty principle. String theorists continue to grope for an analogous principle that would capture the theory's essence as completely.

To a large extent, this deficiency exists because string theory developed piecemeal instead of emerging from a grand, overarching vision. The *goal* of string theory—the unification of all forces and all matter in a quantum mechanical framework—is about as grand as it gets, but the theory's evolution has been distinctly fragmented. After its serendipitous discovery more than three decades ago, string theory has been cobbled together as one group of theorists has uncovered key properties by studying *these* equations, while another group has revealed critical implications by examining *those.*

String theorists can be likened to a primitive tribe excavating a buried spacecraft onto which they've stumbled. By tinkering and fiddling, the tribe would slowly establish aspects of the spacecraft's operation, and this would nurture a sense that all the buttons and toggles work together in a coordinated and unified manner. A similar feeling prevails among string theorists. Results found over many years of research are dovetailing and converging. This has instilled a growing confidence among researchers that string theory is closing in on one powerful, coherent framework—which has yet to be unearthed fully, but ultimately will expose nature's inner workings with unsurpassed clarity and comprehensiveness.

In recent times, nothing illustrates this better than the realization that sparked the *second superstring revolution*—a revolution that has, among other things, exposed another hidden dimension entwined in the spatial fabric, opened new possibilities for experimental tests of string theory, suggested that our universe may be brushing up against others, revealed that black holes may be created in the next generation of high-energy accelerators, and led to a novel cosmological theory in which time and its arrow, like the graceful arc of Saturn's rings, may cycle around and around.

The Second Superstring Revolution

There's an awkward detail regarding string theory that I've yet to divulge, but that readers of my previous book, *The Elegant Universe*, may recall. Over the last three decades, not one but *five* distinct versions of string theory have been developed. While their names are not of the essence, they are called *Type I*, *Type IIA*, *Type IIB*, *Heterotic-O*, and *Heterotic-E*. All share the essential features introduced in the last chapter—the basic ingredients are strands of vibrating energy—and, as calculations in the 1970s and 1980s revealed, each theory requires six extra space dimensions; but when they are analyzed in detail, significant differences appear. For example, the Type I theory includes the vibrating string loops discussed in the last chapter, so-called *closed strings*, but unlike the other string theories, it also contains *open strings*, vibrating string snippets that have two loose ends. Furthermore, calculations show that the list of string vibrational patterns and the way each pattern interacts and influences others differ from one formulation to another.

The most optimistic of string theorists envisioned that these differences would serve to eliminate four of the five versions when detailed comparisons to experimental data could one day be carried out. But, frankly, the mere existence of five different formulations of string theory was a source of quiet discomfort. The dream of unification is one in which scientists are led to a unique theory of the universe. If research established that only one theoretical framework could embrace both quantum mechanics and general relativity, theorists would reach unification nirvana. They would have a strong case for the framework's validity even in the absence of direct experimental verification. After all, a wealth of experimental support for both quantum mechanics and general relativity already exists, and it seems plain as day that the laws governing the universe should be mutually compatible. If a particular theory were the unique, mathematically consistent arch spanning the two experimentally confirmed pillars of twentieth-century physics, that would provide powerful, albeit indirect, evidence for the theory's inevitability.

But the fact that there are five versions of string theory, superficially similar yet distinct in detail, would seem to mean that string theory fails the uniqueness test. Even if the optimists are some day vindicated and only one of the five string theories is confirmed experimentally, we would still be vexed by the nagging question of why there are four other consistent formulations. Would the other four simply be mathematical curiosities? Would they have any significance for the physical world? Might their existence be the tip of a theoretical iceberg in which clever scientists would subsequently show that there are actually five other versions, or six, or seven, or perhaps even an endless number of distinct mathematical variations on a theme of strings?

During the late 1980s and early 1990s, with many physicists hotly pursuing an understanding of one or another of the string theories, the enigma of the five versions was not a problem researchers typically dealt with on a day-to-day basis. Instead, it was one of those quiet questions that everyone assumed would be addressed in the distant future, when the understanding of each individual string theory had become significantly more refined.

But in the spring of 1995, with little warning, these modest hopes were wildly exceeded. Drawing on the work of a number of string theorists (including Chris Hull, Paul Townsend, Ashoke Sen, Michael Duff, John Schwarz, and many others), Edward Witten—who for two decades has been the world's most renowned string theorist—uncovered a hidden unity that tied all five string theories together. Witten showed that rather than being distinct, the five theories are actually just five different ways of mathematically analyzing a *single* theory. Much as the translations of a book into five different languages might seem, to a monolingual reader, to be five distinct texts, the five string formulations appeared distinct only because Witten had yet to write the dictionary for translating among them. But once revealed, the dictionary provided a convincing demonstration that—like a single master text from which five translations have been made—a single master theory links all five string formulations. The unifying master theory has tentatively been called *M-theory*, *M* being a tantalizing placeholder whose meaning—Master? Majestic? Mother? Magic? Mystery? Matrix?—awaits the outcome of a vigorous worldwide research effort now seeking to complete the new vision illuminated by Witten's powerful insight.

This revolutionary discovery was a gratifying leap forward. String theory, Witten demonstrated in one of the field's most prized papers (and in important follow-up work with Petr Hořava), *is* a single theory. No longer did string theorists have to qualify their candidate for the unified theory Einstein sought by adding, with a tinge of embarrassment, that the proposed unified framework lacked unity because it came in five different versions. How fitting, by contrast, for the farthest-reaching proposal for a unified theory to be, itself, the subject of a meta-unification. Through Witten's work, the unity embodied by each individual string theory was extended to the whole string framework.

Figure 13.1 sketches the status of the five string theories before and after Witten's discovery, and is a good summary image to keep in mind. It illustrates that M-theory is not a new approach, per se, but that, by clearing the clouds, it promises a more refined and complete formulation of physical law than is provided by any one of the individual string theories. M-theory links together and embraces equally all five string theories by showing that each is part of a grander theoretical synthesis.

The Power of Translation

Although Figure 13.1 schematically conveys the essential content of Witten's discovery, expressed in this way it might strike you like a bit of inside baseball. Before Witten's breakthrough, researchers thought there were

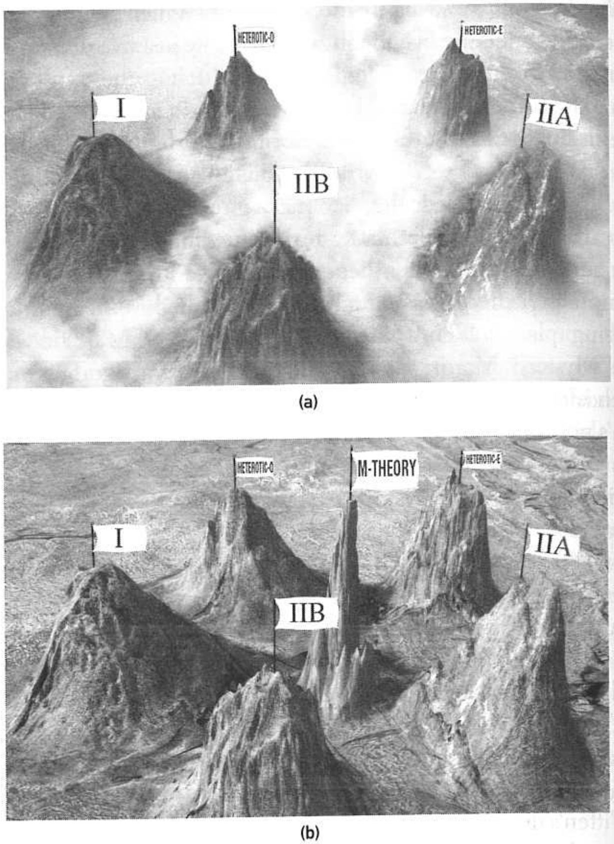


Figure 13.1: **(a)** Schematic portrayal of the five string theories, prior to 1995. **(b)** Schematic portrayal of the meta-unification revealed by M-theory.

five separate versions of string theory; after his breakthrough, they didn't. But if you'd never known that there were five purportedly distinct string theories, why should you care that the cleverest of all string theorists showed they aren't distinct after all? Why, in other words, was Witten's discovery revolutionary as opposed to a modest insight correcting a previous misconception?

Here's why. Over the past few decades, string theorists have been stymied repeatedly by a mathematical problem. Because the exact equations describing any one of the five string theories have proven so difficult to extract and analyze, theorists have based much of their research on

approximate equations that are far easier to work with. While there are good reasons to believe that the approximate equations should, in many circumstances, give answers close to those given by the true equations, approximations—like translations—always miss something. For this reason, certain key problems have proved beyond the approximate equations' mathematical reach, significantly impeding progress.

For the imprecision inherent in textual translations, readers have a couple of immediate remedies. The best option, if the reader's linguistic skills are up to the task, is to consult the original manuscript. At the moment, the analog of this option is not available to string theorists. By virtue of the consistency of the dictionary developed by Witten and others, we have strong evidence that all five string theories are different descriptions of a single master theory, M-theory, but researchers have yet to develop a complete understanding of this theoretical nexus. We have learned much about M-theory in the last few years, but we still have far to go before anyone could sensibly claim that it is properly or completely understood. In string theory, it's as if we have five translations of a yet-to-be-discovered master text.

Another helpful remedy, well known to readers of translations who either don't have the original (as in string theory) or, more commonly, don't understand the language in which it's written, is to consult several translations of the master text into languages with which they are familiar. Passages on which the translations agree give confidence; passages on which they differ flag possible inaccuracies or highlight different interpretations. It is this approach that Witten made available with his discovery that the five string theories are different translations of the same underlying theory. In fact, his discovery provided an extremely powerful version of this line of attack that is best understood through a slight extension of the translation analogy.

Imagine a master manuscript infused with such an enormous range of puns, rhymes, and offbeat, culture-sensitive jokes, that the complete text cannot be expressed gracefully in any single one of five given languages into which it is being translated. Some passages might translate into Swahili with ease, while other portions might prove thoroughly impenetrable in this tongue. Much insight into some of the latter passages might emerge from the Inuit translation; in yet other sections that translation might be completely opaque. Sanskrit might capture the essence of some of these tricky passages, but for other, particularly troublesome sections, all five translations might leave you dumbfounded and only the master text will be intelligible. This is much closer to the situation with the five string theories. Theorists have found that for certain questions, one of the five may give a transparent description of the physical implications, while the descriptions given by the other four are too mathematically complex to be useful. And therein lies the power of Witten's discovery. Prior to his breakthrough, string theory researchers who encountered intractably difficult equations would be stuck. But Witten's work showed that each such question admits four mathematical translations—four mathematical reformulations—and sometimes one of the reformulated questions proves far simpler to answer. Thus, *the dictionary for translating between the five theories can sometimes provide a means for translating impossibly difficult questions into comparatively simple ones.*

It's not foolproof. Just as all five translations of certain passages in that master text might be equally incomprehensible, sometimes the mathematical descriptions given by all five string theories are equally difficult to understand. In such cases, just as we would need to consult the original text itself, we would need full comprehension of the elusive M-theory to make progress. Even so, in a wealth of circumstances, Witten's dictionary has provided a powerful new tool for analyzing string theory.

Hence, just as each translation of a complex text serves an important purpose, each string formulation does too. By combining insights gained from the perspective of each, we are able to answer questions and reveal features that are completely beyond the reach of any single string formulation. Witten's discovery thus gave theorists five times the firepower for advancing string theory's front line. And that, in large part, is why it sparked a revolution.

Eleven Dimensions

So, with our newfound power to analyze string theory, what insights have emerged? There have been many. I will focus on those that have had the greatest impact on the story of space and time.

Of primary importance, Witten's work revealed that the approximate string theory equations used in the 1970s and 1980s to conclude that the universe must have nine space dimensions *missed the true number by one.* The exact answer, his analysis showed, is that the universe according to M-theory has ten space dimensions, that is, eleven spacetime dimensions. Much as Kaluza found that a universe with five spacetime dimensions

provided a framework for unifying electromagnetism and gravity, and much as string theorists found that a universe with ten spacetime dimensions provided a framework for unifying quantum mechanics and general relativity, Witten found that a universe with eleven spacetime dimensions provided a framework for unifying all string theories. Like five villages that appear, viewed from ground level, to be completely separate but, when viewed from a mountaintop—making use of an additional, vertical dimension—are seen to be connected by a web of paths and roadways, the additional space dimension emerging from Witten's analysis was crucial to his finding connections between all five string theories.

While Witten's discovery surely fit the historical pattern of achieving unity through more dimensions, when he announced the result at the annual international string theory conference in 1995, it shook the foundations of the field. Researchers, including me, had thought long and hard about the approximate equations being used, and everyone was confident that the analyses had given the final word on the number of dimensions. But Witten revealed something startling.

He showed that all of the previous analyses had made a mathematical simplification tantamount to *assuming* that a hitherto unrecognized tenth spatial dimension would be extremely small, much smaller than all others. So small, in fact, that the approximate string theory equations that all researchers were using lacked the resolving power to reveal even a mathematical hint of the dimension's existence. And that led everyone to conclude that string theory had only nine space dimensions. But with the new insights of the unified M-theoretic framework, Witten was able to go beyond the approximate equations, probe more finely, and demonstrate that one space dimension had been overlooked all along. Thus, Witten showed that the five ten-dimensional frameworks that string theorists had developed for more than a decade were actually five approximate descriptions of a single, underlying eleven-dimensional theory.

You might wonder whether this unexpected realization invalidated previous work in string theory. By and large, it didn't. The newfound tenth spatial dimension added an unanticipated feature to the theory, but if string/M-theory is correct, and should the tenth spatial dimension turn out to be much smaller than all others—as, for a long time, had been unwittingly assumed—previous work would remain valid. However, because the known equations are still unable to nail down the sizes or shapes of extra dimensions, string theorists have expended much effort over the last few years investigating the new possibility of a not-so-small tenth spatial dimension. Among other things, the wide-ranging results of these studies have put the schematic illustration of the unifying power of M-theory, Figure 13.1, on a firm mathematical foundation.

I suspect that the updating from ten to eleven dimensions—regardless of its great importance to the mathematical structure of string/M-theory—doesn't substantially alter your mind's-eye picture of the theory. To all but the cognoscenti, trying to imagine seven curled-up dimensions is an exercise that's pretty much the same as trying to imagine six.

But a second and closely related insight from the second superstring revolution does alter the basic intuitive picture of string theory. The collective insights of a number of researchers—Witten, Duff, Hull, Townsend, and many others—established that *string theory is not just a theory of strings.*

Branes

A natural question, which may have occurred to you in the last chapter, is *Why strings?* Why are one-dimensional ingredients so special? In reconciling quantum mechanics and general relativity, we found it crucial that strings are not dots, that they have nonzero size. But that requirement can be met with two-dimensional ingredients shaped like miniature disks or Frisbees, or by three-dimensional bloblike ingredients, shaped like baseballs or lumps of clay. Or, since the theory has such an abundance of space dimensions, we can even imagine blobs with more dimensions still. Why don't these ingredients play any role in our fundamental theories?

In the 1980s and early 1990s, most string theorists had what seemed like a convincing answer. They argued that there *had* been attempts to formulate a fundamental theory of matter based on bloblike constituents by, among others, such icons of twentieth-century physics as Werner Heisenberg and Paul Dirac. But their work, as well as many subsequent studies, showed that it was extremely difficult to develop a theory based on tiny blobs that met the most basic of physical requirements—for example, ensuring that all quantum mechanical probabilities lie between 0 and 1 (no sense can be made of negative probabilities or of probabilities greater than 1), and debarring faster-than-light communication. For point particles, a half-century of research initiated in the 1920s showed that these conditions could be met (as long as gravity was ignored). And, by the 1980s, more than a decade of investigation by Schwarz, Scherk, Green,

and others established, to the surprise of most researchers, that the conditions could also be met for one-dimensional ingredients, strings (which necessarily *included* gravity). But it seemed impossible to proceed to fundamental ingredients with two or more spatial dimensions. The reason, briefly put, is that the number of symmetries respected by the equations peaks enormously for one-dimensional objects (strings) and drops off precipitously thereafter. The symmetries in question are more abstract than the ones discussed in Chapter 8 (they have to do with how equations change if, while studying the motion of a string or a higher dimensional ingredient, we were to zoom in or out, suddenly and arbitrarily changing the resolution of our observations). These transformations prove critical to formulating a physically sensible set of equations, and beyond strings it seemed that the required fecundity of symmetries was absent.[1]

It was thus another shock to most string theorists when Witten's paper and an avalanche of subsequent results[2] led to the realization that string theory, and the M-theoretic framework to which it now belongs, *does* contain ingredients besides strings. The analyses showed that there are two-dimensional objects called, naturally enough, *membranes* (another possible meaning for the "M" in M-theory) or—in deference to systematically naming their higher-dimensional cousins—*two-branes.* There are objects with three spatial dimensions called *three-branes.* And, although increasingly difficult to visualize, the analyses showed that there are also objects with p spatial dimensions, where p can be any whole number less than 10, known—with no derogation intended—as *p-branes.* Thus, strings are but one ingredient in string theory, not *the* ingredient.

These other ingredients escaped earlier theoretical investigation for much the same reason the tenth space dimension did: the approximate string equations proved too coarse to reveal them. In the theoretical contexts that string researchers had investigated mathematically, it turns out that all p-branes are significantly heavier than strings. And the more massive something is, the more energy is required to produce it. But a limitation of the approximate string equations—a limitation embedded in the equations and well known to all string theorists—is that they become less and less accurate when describing entities and processes involving more and more energy. At the extreme energies relevant for p-branes, the approximate equations lacked the precision to expose the branes lurking in the shadows, and that's why decades passed without their presence being noticed in the mathematics. But with the various rephrasings and new approaches provided by the unified M-theoretic framework, researchers were able to skirt some of the previous technical obstacles, and there, in full mathematical view, they found a whole panoply of higher-dimensional ingredients.[3]

The revelation that there are other ingredients besides strings in string theory does not invalidate or make obsolete earlier work any more than the discovery of the tenth spatial dimension did. Research shows that if the higher-dimensional branes are much more massive than strings—as had been unknowingly assumed in previous studies—they have minimal impact on a wide range of theoretical calculations. But just as the tenth space dimension does not have to be much smaller than all others, so the higher-dimensional branes do not have to be much heavier. There are a variety of circumstances, still hypothetical, in which the mass of a higher-dimensional brane can be on a par with the lowest-mass string vibrational patterns, and in such cases the brane *does* have a significant impact on the resulting physics. For example, my own work with Andrew Strominger and David Morrison showed that a brane can wrap itself around a spherical portion of a Calabi-Yau shape, much like plastic wrap vacuum-sealed around a grapefruit; should that portion of space shrink, the wrapped brane would also shrink, causing its mass to decrease. This decrease in mass, we were able to show, allows the portion of space to collapse fully and tear open—space itself can rip apart—while the wrapped brane ensures that there are no catastrophic physical consequences. I discussed this development in detail in *The Elegant Universe* and will briefly return to it when we discuss time travel in Chapter 15, so I won't elaborate further here. But this snippet makes clear how higher-dimensional branes can have a significant effect on the physics of string theory.

For our current focus, though, there is another profound way that branes impact the view of the universe according to string/M-theory. The grand expanse of the cosmos—the entirety of the spacetime of which we are aware—may itself be nothing but an enormous brane. Ours may be a braneworld.

Braneworlds

Testing string theory is a challenge because strings are ultrasmall. But remember the physics that determined the string's size. The messenger particle of gravity—the graviton—is among the lowest-energy string vibrational patterns, and the strength of the gravitational force it communicates is proportional to the length of the string. Since gravity is such a weak force, the string's length must be tiny; calculations show that it must be within a factor of a hundred or so of the Planck length for the string's graviton vibrational pattern to communicate a gravitational force with the observed strength.

Given this explanation, we see that a highly energetic string is not constrained to be tiny, since it no longer has any direct connection to the graviton particle (the graviton is a *low*-energy, zero-mass vibrational pattern). In fact, as more and more energy is pumped into a string, at first it will vibrate more and more frantically. But after a certain point, additional energy will have a different effect: it will cause the string's length to increase, and there's no limit to how long it can grow. By pumping enough energy into a string, you could even make it grow to macroscopic size. With today's technology we couldn't come anywhere near achieving this, but it's possible that in the searingly hot, extremely energetic aftermath of the big bang, long strings were produced. If some have managed to survive until today, they could very well stretch clear across the sky. Although a long shot, it's even possible that such long strings could leave tiny but detectable imprints on the data we receive from space, perhaps allowing string theory to be confirmed one day through astronomical observations.

Higher-dimensional *p*-branes need not be tiny, either, and because they have more dimensions than strings do, a qualitatively new possibility opens up. When we picture a long—perhaps infinitely long—string, we envision a long one-dimensional object that exists within the three large space dimensions of everyday life. A power line stretched as far as the eye can see provides a reasonable image. Similarly, if we picture a large—perhaps infinitely large—two-brane, we envision a large two-dimensional surface that exists within the three large space dimensions of common experience. I don't know of a realistic analogy, but a ridiculously huge drive-in movie screen, extremely thin but as high and as wide as the eye can see, offers a visual image to latch on to. When it comes to a large three-brane, though, we find ourselves in a qualitatively new situation. A three-brane has three dimensions, so if it were large—perhaps infinitely large—it would *fill* all three big spatial dimensions. Whereas a one-brane and a two-brane, like the power line and movie screen, are objects that exist *within* our three large space dimensions, a large three-brane would occupy all the space of which we're aware.

This raises an intriguing possibility. Might we, right now, be living within a three-brane? Like Snow White, whose world exists within a two-dimensional movie screen—a two-brane—that itself resides within a higher-dimensional universe (the three space dimensions of the movie theater), might everything we know exist within a three-dimensional screen—a three-brane—that itself resides within the higher-dimensional universe of string/M-theory? Could it be that what Newton, Leibniz, Mach, and Einstein called three-dimensional space is actually a particular three-dimensional entity in string/M-theory? Or, in more relativistic language, could it be that the four-dimensional spacetime developed by Minkowski and Einstein is actually the wake of a three-brane as it evolves through time? In short, might the universe as we know it be a brane?[4]

The possibility that we are living within a three-brane—the so-called *braneworld scenario*—is the latest twist in string/M-theory's story. As we will see, it provides a qualitatively new way of thinking about string/M-theory, with numerous and far-reaching ramifications. The essential physics is that branes are rather like cosmic Velcro; in a particular way we'll now discuss, they are very sticky.

Sticky Branes and Vibrating Strings

One of the motivations for introducing the term "M-theory" is that we now realize that "string theory" highlights but one of the theory's many ingredients. Theoretical studies revealed one-dimensional strings decades before more refined analyses discovered the higher-dimensional branes, so "string theory" is something of an historical artifact. But, even though M-theory exhibits a democracy in which extended objects of a variety of dimensions are represented, strings still play a central role in our current formulation. In one way this is immediately clear. When all the higher-dimensional p-branes are much heavier than strings, they can be ignored, as researchers had done unknowingly since the 1970s. But there is another, more general way in which strings are first among equals.

In 1995, shortly after Witten announced his breakthrough, Joe Polchinski of the University of California at Santa Barbara got to thinking. Years earlier, in a paper he had written with Robert Leigh and Jin Dai, Polchinski had discovered an interesting though fairly obscure feature of string theory. Polchinski's motivation and reasoning were somewhat technical and the details are not essential to our discussion, but his results are. He found that in certain situations the endpoints of open strings—remember, these are string segments with two loose ends—would not be able to move with complete freedom. Instead, just as a bead on a wire is free to move, but must follow the wire's contour, and just as a pinball is free to move, but must follow the contours of the pinball table's surface, the endpoints of an open string would be free to move but would be restricted to particular shapes or contours in space. While the string would still be free to vibrate, Polchinski and his collaborators showed that its endpoints would be "stuck" or "trapped" within certain regions.

In some situations, the region might be one-dimensional, in which case the string's endpoints would be like two beads sliding on a wire, with the string itself being like a cord connecting them. In other situations, the region might be two-dimensional, in which case the endpoints of the string would be very much like two pinballs connected by a cord, rolling around a pinball table. In yet other situations, the region might have three, four, or any other number of spatial dimensions less than ten. These results, as shown by Polchinski and also by Petr Hořava and Michael Green, helped resolve a long-standing puzzle in the comparison of open and closed strings, but over the years, the work attracted limited attention.[5] In October 1995, when Polchinski finished rethinking these earlier insights in light of Witten's new discoveries, that changed.

A question that Polchinski's earlier paper left without a complete answer is one that may have occurred to you while reading the last paragraph: If the endpoints of open strings are stuck within a particular region of space, *what is it that they are stuck to*? Wires and pinball machines have a tangible existence independent of the beads or balls that are constrained to move along them. What about the regions of space to which the endpoints of open strings are constrained? Are they filled with some independent and fundamental ingredient of string theory, one that jealously clutches open string endpoints? Prior to 1995, when string theory was thought to be a theory of strings only, there didn't seem to be any candidate for the job. But after Witten's breakthrough and the torrent of results it inspired, the answer became obvious to Polchinski: if the endpoints of open strings are restricted to move within some p-dimensional region of space, then that region of space must be occupied by a p-brane.* His calculations showed that the newly discovered p-branes had exactly the right properties to be the objects that exert an unbreakable grip on open string

*The more precise name for these sticky entities is *Dirichlet-p-branes*, or *D-p-branes* for short. We will stick with the shorter *p-brane*.

endpoints, constraining them to move within the p-dimensional region of space they fill.

To get a better sense for what this means, look at Figure 13.2. In (a), we see a couple of two-branes with a slew of open strings moving around and vibrating, all with their endpoints restricted to motion along their respective branes. Although it is increasingly difficult to draw, the situation with higher-dimensional branes is identical. Open string endpoints can move freely on and within the p-brane, but they can't leave the brane itself. When it comes to the possibility of motion off a brane, branes are the stickiest things imaginable. It's also possible for one end of an open string to be stuck to one p-brane and its other end to be stuck to a different p-brane, one that may have the same dimension as the first (Figure 13.2b) or may not (Figure 13.2c).

To Witten's discovery of the connection between the various string theories, Polchinski's new paper provided a companion manifesto for the second superstring revolution. While some of the great minds of twentieth-century theoretical physics had struggled and failed to formulate a theory containing fundamental ingredients with more dimensions than dots (zero dimensions) or strings (one dimension), the results of Witten and Polchinski, together with important insights of many of today's leading researchers, revealed the path to progress. Not only did these physicists establish that string/M-theory contains higher-dimensional ingredients,

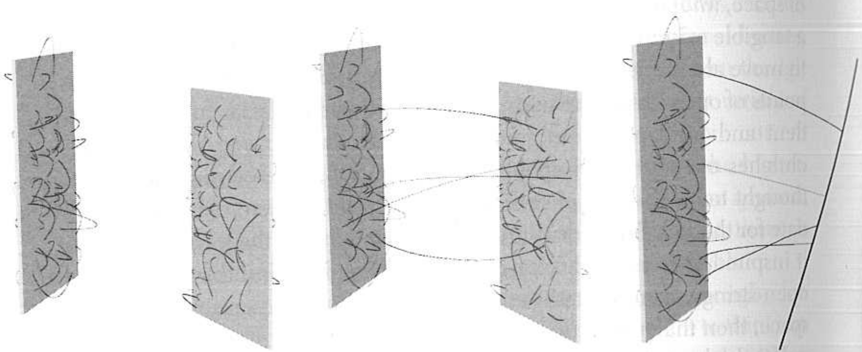


Figure 13.2 **(a)** Open strings with endpoints attached to two-dimensional branes, or two-branes. **(b)** Strings stretching from one two-brane to another. **(c)** Strings stretching from a two-brane to a one-brane.

but Polchinski's insights in particular provided a means for analyzing their detailed physical properties theoretically (should they prove to exist). The properties of a brane, Polchinski argued, are to a large extent captured by the properties of the vibrating open strings whose endpoints it contains. Just as you can learn a lot about a carpet by running your hand through its pile—the snippets of wool whose endpoints are attached to the carpet backing—many qualities of a brane can be determined by studying the strings whose endpoints it clutches.

That was a paramount result. It showed that decades of research that produced sharp mathematical methods to study one-dimensional objects—strings—could be used to study higher-dimensional objects, p-branes. Wonderfully, then, Polchinski revealed that the analysis of higher-dimensional objects was reduced, to a large degree, to the thoroughly familiar, if still hypothetical, analysis of strings. It's in this sense that strings are special among equals. If you understand the behavior of strings, you're a long way toward understanding the behavior of p-branes.

With these insights, let's now return to the braneworld scenario—the possibility that we're all living out our lives within a three-brane.

Our Universe as a Brane

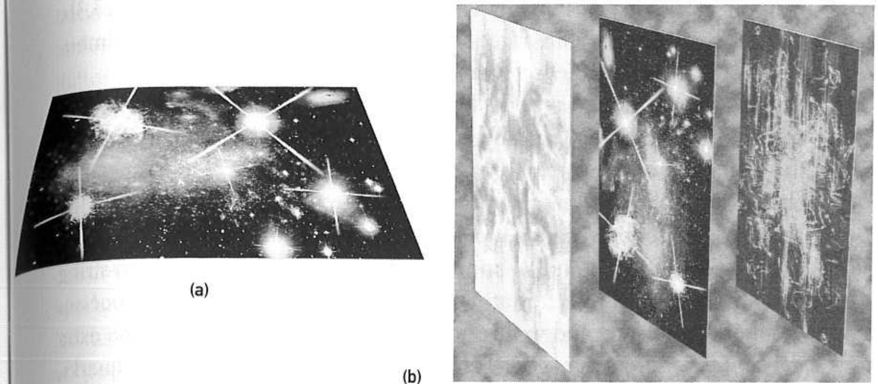
If we are living within a three-brane—if our four-dimensional spacetime is nothing but the history swept out by a three-brane through time—then the venerable question of whether spacetime is a something would be cast in a brilliant new light. Familiar four-dimensional spacetime would arise from a real physical entity in string/M-theory, a three-brane, not from some vague or abstract idea. In this approach, the reality of our four-dimensional spacetime would be on a par with the reality of an electron or a quark. (Of course, you could still ask whether the larger spacetime within which strings and branes exist—the eleven dimensions of string/M-theory—is itself an entity; the reality of the spacetime arena we directly experience, though, would be rendered obvious.) But if the universe we're aware of really is a three-brane, wouldn't even a casual glance reveal that we are immersed within something—within the three-brane interior?

Well, we've already learned of things within which modern physics suggests we may be immersed—a Higgs ocean; space filled with dark energy; myriad quantum field fluctuations—none of which make themselves directly apparent to unaided human perceptions. So it shouldn't be a shock to learn that string/M-theory adds another candidate to the list of invisible things that may fill "empty" space. But let's not get cavalier. For each of the previous possibilities, we understand its impact on physics and how we might establish that it truly exists. Indeed, for two of the three—dark energy and quantum fluctuations—we've seen that strong evidence supporting their existence has already been gathered; evidence for the Higgs field is being sought at current and future accelerators. So what is the corresponding situation for life within a three-brane? If the braneworld scenario is correct, why don't we see the three-brane, and how would we establish that it exists?

The answer highlights how the physical implications of string/M-theory in the braneworld context differ radically from the earlier "brane-free" (or, as they're sometimes affectionately called, no-braner) scenarios. Consider, as an important example, the motion of light—the motion of photons. In string theory, a photon, as you now know, is a particular string vibrational pattern. More specifically, mathematical studies have shown that in the braneworld scenario, only open string vibrations, not closed ones, produce photons, and this makes a big difference. Open string endpoints are constrained to move within the three-brane, but are otherwise completely free. This implies that photons (open strings executing the photon mode of vibration) would travel without any constraint or obstruction throughout our three-brane. And that would make the brane appear *completely transparent—completely invisible*—thus preventing us from seeing that we are immersed within it.

Of equal importance, because open string endpoints cannot leave a brane, they are unable to move into the extra dimensions. Just as the wire constrains its beads and the pinball machine constrains its balls, our sticky three-brane would permit photons to move *only* within our three spatial dimensions. Since photons are the messenger particles for electromagnetism, this implies that the electromagnetic force—light—would be trapped within our three dimensions, as illustrated (in two dimensions so we can draw it) in Figure 13.3.

That's an intense realization with important consequences. Earlier, we required the extra dimensions of string/M-theory to be tightly curled up. The reason, clearly, is that we don't see the extra dimensions and so they must be hidden away. And one way to hide them is to make them smaller than we or our equipment can detect. But let's now reexamine



(a) (b)

Figure 13.3 (**a**) In the braneworld scenario, photons are open strings with endpoints trapped within the brane, so they—light—cannot leave the brane itself. (**b**) Our braneworld could be floating in a grand expanse of additional dimensions that remain invisible to us, because the light we see cannot leave our brane. There might also be other braneworlds floating nearby.

this issue in the braneworld scenario. How do we detect things? Well, when we use our eyes, we use the electromagnetic force; when we use powerful instruments like electron microscopes, we also use the electromagnetic force; when we use atom smashers, one of the forces we use to probe the ultrasmall is, once again, the electromagnetic force. But if the electromagnetic force is confined to our three-brane, our three space dimensions, it is *unable* to probe the extra dimensions, regardless of their size. Photons cannot escape our dimensions, enter the extra dimensions, and then travel back to our eyes or equipment allowing us to detect the extra dimensions, *even if they were as large as the familiar space dimensions.*

So, if we live in a three-brane, there is an alternative explanation for why we're not aware of the extra dimensions. It is not necessarily that the extra dimensions are extremely small. They could be big. We don't see them because of the *way* we see. We see by using the electromagnetic force, which is unable to access any dimensions beyond the three we know about. Like an ant walking along a lily pad, completely unaware of the deep waters lying just beneath the visible surface, we could be floating within a grand, expansive, higher-dimensional space, as in Figure 13.3b, but the electromagnetic force—eternally trapped within our dimensions—would be unable to reveal this.

Okay, you might say, but the electromagnetic force is only one of nature's four forces. What about the other three? Can they probe into the extra dimensions, thus enabling us to reveal their existence? For the strong and weak nuclear forces, the answer is, again, no. In the braneworld scenario, calculations show that the messenger particles for these forces—gluons and W and Z particles—also arise from open-string vibrational patterns, so they are just as trapped as photons, and processes involving the strong and weak nuclear forces are just as blind to the extra dimensions. The same goes for particles of matter. Electrons, quarks, and all other particle species also arise from the vibrations of open strings with trapped endpoints. *Thus, in the braneworld scenario, you and I and everything we've ever seen are permanently imprisoned within our three-brane.* Taking account of time, everything is trapped within our four-dimensional slice of spacetime.

Well, almost everything. For the force of gravity, the situation is different. Mathematical analyses of the braneworld scenario have shown that gravitons arise from the vibrational pattern of closed strings, much as they do in the previously discussed no-braner scenarios. And closed strings—strings with no endpoints—are not trapped by branes. They are as free to leave a brane as they are to roam on or through it. So, if we were living in a brane, we would not be completely cut off from the extra dimensions. Through the gravitational force, we could both influence and be influenced by the extra dimensions. Gravity, in such a scenario, would provide our sole means for interacting beyond our three space dimensions.

How big could the extra dimensions be before we'd become aware of them through the gravitational force? This is an interesting and critical question, so let's take a look.

Gravity and Large Extra Dimensions

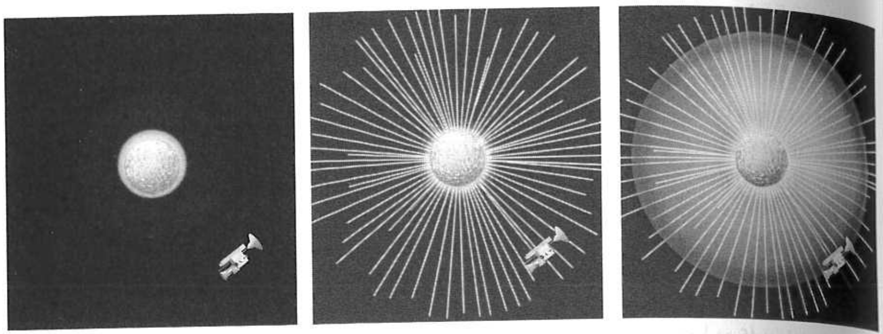
Back in 1687, when Newton proposed his universal law of gravity, he was actually making a strong statement about the number of space dimensions. Newton didn't just say that the force of attraction between two objects gets weaker as the distance between them gets larger. He proposed a formula, the *inverse square law*, which describes precisely how the grav-

itational attraction will diminish as two objects are separated. According to this formula, if you double the distance between the objects, their gravitational attraction will fall by a factor of 4 (2^2); if you triple the distance, it will fall by a factor of 9 (3^2); if you quadruple the distance, it will fall by a factor of 16 (4^2); and more generally, the gravitational force drops in proportion to the square of the separation. As has become abundantly evident over the last few hundred years, this formula works.

But *why* does the force depend on the square of the distance? Why doesn't the force drop like the cube of the separation (so that if you double the distance, the force diminishes by a factor of 8) or the fourth power (so that if you double the distance, the force diminishes by a factor of 16), or perhaps, even more simply, why doesn't the gravitational force between two objects drop in direct proportion to the separation (so that if you double the distance, the force diminishes by a factor of 2)? The answer is tied directly to the number of dimensions of space.

One way to see this is to think about how the number of gravitons emitted and absorbed by the two objects depends on their separation, or by thinking about how the curvature of spacetime that each object experiences diminishes as the distance between them increases. But let's take a simpler, more old-fashioned approach, which gets us quickly and intuitively to the correct answer. Let's draw a figure (Figure 13.4a) that schematically illustrates the gravitational field produced by a massive object—let's say the sun—much as Figure 3.1 schematically illustrates the magnetic field produced by a bar magnet. Whereas magnetic field lines sweep around from the magnet's north pole to its south pole, notice that gravitational field lines emanate radially outward in all directions and just keep on going. The strength of the gravitational pull another object—imagine it's an orbiting satellite—would feel at a given distance is proportional to the density of field lines at that location. The more field lines penetrate the satellite, as in Figure 13.4b, the greater the gravitational pull to which it is subject.

We can now explain the origin of Newton's inverse square law. An imaginary sphere centered on the sun and passing through the satellite's location, as in Figure 13.4c, has a surface area that—like the surface of any sphere in three-dimensional space—is proportional to the *square* of its radius, which in this case is the *square* of the distance between the sun and the satellite. This means that the density of field lines passing through the sphere—the total number of field lines divided by the sphere's area—decreases as the square of sun-satellite separation. If you double the dis-



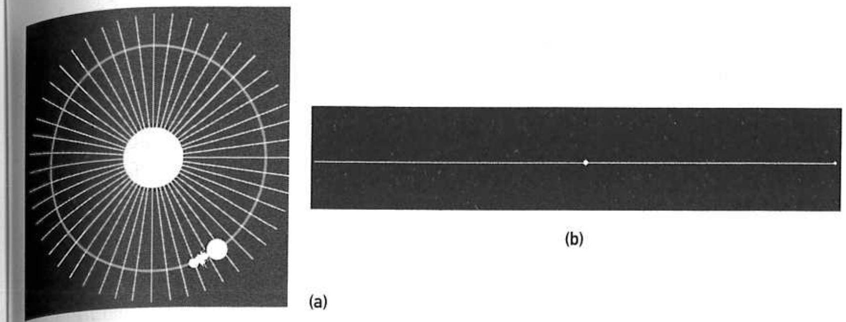
(a) (b) (c)

Figure 13.4 **(a)** The gravitational force exerted by the sun on an object, such as a satellite, is inversely proportional to the square of the distance between them. The reason is that the sun's gravitational field lines spread out uniformly as in **(b)** and hence have a density at a distance d that is inversely proportional to the area of an imaginary sphere of radius d—schematically drawn in **(c)**—an area which basic geometry shows to be proportional to d^2.

tance, the same number of field lines are now uniformly spread out on a sphere with four times the surface area, and hence the gravitational pull at that distance will drop by a factor of four. Newton's inverse square law for gravity is thus a reflection of a geometrical property of spheres in three space dimensions.

By contrast, if the universe had two or even just one space dimension, how would Newton's formula change? Well, Figure 13.5a shows a two-dimensional version of the sun and its orbiting satellite. As you can see, at any given distance the sun's gravitational field lines uniformly spread out on a circle, the analog of a sphere in one lower dimension. Since the circle's circumference is proportional to its radius (not to the square of its radius), if you double the sun–satellite separation, the density of field lines will decrease by a factor of 2 (not 4) and so the strength of the sun's gravitational pull will drop only by a factor of 2 (not 4). If the universe had only two space dimensions, then, gravitational pull would be inversely proportional to separation, not the square of separation.

If the universe had only one space dimension, as in Figure 13.5b, the law of gravity would be simpler still. Gravitational field lines would have no room to spread out, and so the force of gravity would not decrease with separation. If you were to double the distance between the sun and the



(a) (b)

Figure 13.5 **(a)** In a universe with only two spatial dimensions, the gravitational force drops in proportion to separation, because gravitational field lines uniformly spread on a circle whose circumference is proportional to its radius. **(b)** In a universe with one space dimension, gravitational field lines do not have any room to spread, so the gravitational force is constant, regardless of separation.

satellite (assuming that versions of such objects could exist in such a universe), the same number of field lines would penetrate the satellite and hence the force of gravity acting between them would not change at all.

Although it is impossible to draw, the pattern illustrated by Figures 13.4 and 13.5 extends directly to a universe with four or five or six or any number of space dimensions. The more space dimensions there are, the more room gravitational lines of force have to spread out. And the more they spread out, the more precipitously the force of gravity drops with increasing separation. In four space dimensions, Newton's law would be an inverse cube law (double the separation, force drops by a factor of 8); in five space dimensions, it would be an inverse fourth-power law (double the separation, force drops by a factor of 16); in six space dimensions, it would be an inverse fifth-power law (double the separation, force drops by a factor of 32); and so on for ever higher-dimensional universes.

You might think that the success of the inverse square version of Newton's law in explaining a wealth of data—from the motion of planets to the paths of comets—confirms that we live in a universe with precisely three space dimensions. But that conclusion would be hasty. We know that the inverse square law works on astronomical scales,[6] and we know that it works on terrestrial scales, and that jibes well with the fact that on such scales we see three space dimensions. But do we know that it works on smaller scales? How far down into the microcosmos has gravity's inverse square law been tested? As it turns out, experimenters have confirmed it down to only about a tenth of a millimeter; if two objects are brought to within a separation of a tenth of a millimeter, the data verify that the strength of their gravitational attraction follows the predictions of the inverse square law. But so far, it has proven a significant technical challenge to test the inverse square law on shorter scales (quantum effects and the weakness of gravity complicate the experiments). This is a critical issue, because deviations from the inverse square law would be a convincing signal of extra dimensions.

To see this explicitly, let's work with a lower-dimensional toy example that we can easily draw and analyze. Imagine we lived in a universe with one space dimension—or so we thought, because only one space dimension was visible and, moreover, centuries of experiments had shown that the force of gravity does not vary with the separation between objects. But also imagine that in all those years experimenters had been able only to test the law of gravity down to distances of about a tenth of a millimeter. For distances shorter than that, no one had any data. Now, imagine further that, unbeknownst to everyone but a handful of fringe theoretical physicists, the universe actually had a second, curled-up space dimension making its shape like the surface of Philippe Petit's tightrope, as in Figure 12.5. How would this affect future, more refined gravitational tests? We can deduce the answer by looking at Figure 13.6. As two tiny objects are brought close enough together—much closer than the circumference of the curled-up dimension—the two-dimensional character of space would become apparent immediately, because on those scales gravitational field lines *would* have room to spread out (Figure 13.6a). Rather than being

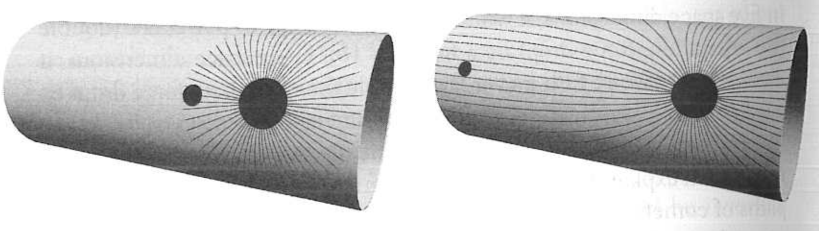


Figure 13.6 (a) When objects are close, the gravitational pull varies as it does in two space dimensions. (b) When objects are farther apart, the gravitational pull behaves as it does in one space dimension—it is constant.

independent of distance, the force of gravity would vary *inversely* with separation when objects were close enough together.

Thus, if you were an experimenter in this universe, and you developed exquisitely accurate methods for measuring gravitational attraction, here's what you would find. When two objects were extremely close, much closer than the size of the curled-up dimension, their gravitational attraction would diminish in proportion to their separation, just as you expect for a universe with two space dimensions. But then, when the objects were about as far apart as the circumference of the curled-up dimension, things would change. Beyond this distance, the gravitational field lines would be unable to spread any further. They would have spilled out as far as they could into the second curled-up dimension—they would have saturated that dimension—and so from this distance onward the gravitational force would no longer diminish, as illustrated in Figure 13.6b. You can compare this saturation with the plumbing in an old house. If someone opens the faucet in the kitchen sink when you're just about to rinse the shampoo out of your hair, the water pressure can drop because the water spreads between the two outlets. The pressure will diminish yet again should someone open the faucet in the laundry room, since the water will spread even more. But once all the faucets in the house are open, the pressure will remain constant. Although it might not provide the relaxing, high-water-pressure experience you'd anticipated, the pressure in the shower will not drop any further once the water has completely spread throughout all "extra" outlets. Similarly, once the gravitational field has completely spread throughout the extra curled-up dimension, it will not diminish with further separation.

From your data you would deduce two things. First, from the fact that the gravitational force diminished in proportion to distance when objects are very close, you'd realize that the universe has *two* space dimensions, not one. Second, from the crossover to a gravitational force that is constant—the result known from hundreds of years of previous experiments—you'd conclude that one of these dimensions is curled up, with a size about equal to the distance at which the crossover takes place. And with this result, you'd overturn centuries, if not millennia, of belief regarding something so basic, the number of space dimensions, that it seemed almost beyond questioning.

Although I set this story in a lower-dimensional universe, for visual ease, our situation could be much the same. Hundreds of years of experiments have confirmed that gravity varies inversely with the square of distance, giving strong evidence that there are three space dimensions. But as of 1998, no experiment had ever probed gravity's strength on separations smaller than a millimeter (today, as mentioned, this has been pushed to a tenth of a millimeter). This led Savas Dimopoulos, of Stanford, Nima Arkani-Hamed, now of Harvard, and Gia Dvali, of New York University, to propose that *in the braneworld scenario extra dimensions could be as large as a millimeter and would still have been undetected.* This radical suggestion inspired a number of experimental groups to initiate a study of gravity at submillimeter distances in hopes of finding violations of the inverse square law; so far, none have been found, down to a tenth of a millimeter. Thus, even with today's state-of-the-art gravity experiments, *if we are living within a three-brane, the extra dimensions could be as large as a tenth of a millimeter, and yet we wouldn't know it.*

This is one of the most striking realizations of the last decade. Using the three nongravitational forces, we can probe down to about a billionth of a billionth (10^{-18}) of a meter, and no one has found any evidence of extra dimensions. But in the braneworld scenario, the nongravitational forces are impotent in searching for extra dimensions since they are trapped on the brane itself. Only gravity can give insight into the nature of the extra dimensions, and, as of today, the extra dimensions could be as thick as a human hair and yet they'd be completely invisible to our most sophisticated instruments. Right now, right next to you, right next to me, and right next to everyone else, there could be another spatial dimension—a dimension beyond left/right, back/forth, and up/down, a dimension that's curled up but still large enough to swallow something as thick as this page—that remains beyond our grasp.*

Large Extra Dimensions and Large Strings

By trapping three of the four forces, the braneworld scenario significantly relaxes experimental constraints on how big the extra dimensions can be, but the extra dimensions aren't the only thing this approach allows to get bigger. Drawing on insights of Witten, Joe Lykken, Constantin Bachas, and others, Ignatios Antoniadis, together with Arkani-Hamed, Dimopoulos, and Dvali, realized that in the braneworld scenario even unexcited, low-energy strings can be *much* larger than previously thought. In fact, the two scales—the size of extra dimensions and the size of strings—are closely related.

*There is even a proposal, from Lisa Randall, of Harvard, and Raman Sundrum, of Johns Hopkins, in which gravity too can be trapped, not by a sticky brane, but by extra dimensions that curve in just the right way, relaxing even further the constraints on their size.

Remember from the previous chapter that the basic size of string is determined by requiring that its graviton vibrational pattern communicate a gravitational force of the observed strength. The weakness of gravity translates into the string's being very short, about the Planck length (10^{-33} centimeters). But this conclusion is highly dependent on the size of the extra dimensions. The reason is that in string/M-theory, the strength of the gravitational force we observe in our three extended dimensions represents an interplay between two factors. One factor is the intrinsic, fundamental strength of the gravitational force. The second factor is the size of the extra dimensions. The larger the extra dimensions, the more gravity can spill into them and the weaker its force will *appear* in the familiar dimensions. Just as larger pipes yield weaker water pressure because they allow water more room to spread out, so larger extra dimensions yield weaker gravity, because they give gravity more room to spread out.

The original calculations that determined the string's length assumed that the extra dimensions were so tiny, on the order of the Planck length, that gravity couldn't spill into them at all. Under this assumption, gravity appears weak because it *is* weak. But now, if we work in the braneworld scenario and allow the extra dimensions to be much larger than had previously been considered, the observed feebleness of gravity no longer means that it's intrinsically weak. Instead, gravity could be a relatively powerful force that appears weak only because the relatively large extra dimensions, like large pipes, dilute its intrinsic strength. Following this line of reasoning, if gravity is much stronger than once thought, the strings can be much longer than once thought, too.

As of today, the question of exactly how long doesn't have a unique, definite answer. With the newfound freedom to vary both the size of strings and the size of the extra dimensions over a much wider range than previously envisioned, there are a number of possibilities. Dimopoulos and his collaborators have argued that existing experimental results, both from particle physics and from astrophysics, show that unexcited strings can't be larger than about a billionth of a billionth of a meter (10^{-18} meters). While small by everyday standards, this is about a hundred million billion (10^{17}) times larger than the Planck length—*nearly a hundred* *million billion times larger than previously thought.* As we'll now see, that would be large enough that signs of strings could be detected by the next generation of particle accelerators.

String Theory Confronts Experiment?

The possibility that we are living within a large three-brane is, of course, just that: a possibility. And, within the braneworld scenario, the possibility that the extra dimensions could be much larger than once thought—and the related possibility that strings could also be much larger than once thought—are also just that: possibilities. *But they are tremendously exciting possibilities.* True, even if the braneworld scenario is right, the extra dimensions and the string size could still be Planckian. But the possibility within string/M-theory for strings and the extra dimensions to be much larger—to be just beyond the reach of today's technology—is fantastic. It means that there is at least a chance that in the next few years, string/M-theory will make contact with observable physics and become an experimental science.

How big a chance? I don't know, and nor does anyone else. My intuition tells me it's unlikely, but my intuition is informed by a decade and a half of working within the conventional framework of Planck-sized strings and Planck-sized extra dimensions. Perhaps my instincts are old-fashioned. Thankfully, the question will be settled without the slightest concern for anyone's intuition. If the strings are big, or if some of the extra dimensions are big, the implications for upcoming experiments are spectacular.

In the next chapter, we'll consider a variety of experiments that will test, among other things, the possibilities of comparatively large strings and large extra dimensions, so here I will just whet your appetite. If strings are as large as a billionth of a billionth (10^{-18}) of a meter, the particles corresponding to the higher harmonic vibrations in Figure 12.4 will not have enormous masses, in excess of the Planck mass, as in the standard scenario. Instead, their masses will be only a thousand to a few thousand times that of a proton, and that's low enough to be within reach of the Large Hadron Collider now being built at CERN. If these string vibrations were to be excited through high-energy collisions, the accelerator's detectors would light up like the Times Square crystal ball on New Year's Eve. A whole host of never-before-seen particles would be produced, and their masses would be related to one another's much as the various harmonics are related on a cello. String theory's signature would be etched across the data with a flourish that would have impressed John Hancock. Researchers wouldn't be able to miss it, even without their glasses.

Moreover, in the braneworld scenario, high-energy collisions might even produce—get this—miniature black holes. Although we normally think of black holes as gargantuan structures out in deep space, it's been known since the early days of general relativity that if you crammed enough matter together in the palm of your hand, you'd create a tiny black hole. This doesn't happen because no one's grip—and no mechanical device—is even remotely strong enough to exert a sufficient compression force. Instead, the only accepted mechanism for black hole production involves the gravitational pull of an enormously massive star's overcoming the outward pressure normally exerted by the star's nuclear fusion processes, causing the star to collapse in on itself. But if gravity's intrinsic strength on small scales is far greater than previously thought, tiny black holes could be produced with significantly less compression force than previously believed. Calculations show that the Large Hadron Collider may have just enough squeezing power to create a cornucopia of microscopic black holes through high-energy collisions between protons.[7] Think about how amazing that would be. The Large Hadron Collider might turn out to be a factory for producing microscopic black holes! These black holes would be so small and would last for such a short time that they wouldn't pose us the slightest threat (years ago, Stephen Hawking showed that all black holes disintegrate via quantum processes—big ones very slowly, tiny ones very quickly), but their production would provide confirmation of some of the most exotic ideas ever contemplated.

Braneworld Cosmology

A primary goal of current research, one that is being hotly pursued by scientists worldwide (including me), is to formulate an understanding of cosmology that incorporates the new insights of string/M-theory. The reason is clear: not only does cosmology grapple with the big, gulp-in-the-throat questions, and not only have we come to realize that aspects of familiar experience—such as the arrow of time—are bound up with conditions at the universe's birth, but cosmology also provides a theorist with what New York provided Sinatra: a proving ground par excellence. If a theory can make it in the extreme conditions characteristic of the universe's earliest moments, it can make it anywhere.

As of today, cosmology according to string/M-theory is a work in progress, with researchers heading down two main pathways. The first and more conventional approach imagines that just as inflation provided a brief but profound front end to the standard big bang theory, string/M-theory provides a yet earlier and perhaps yet more profound front end to inflation. The vision is that string/M-theory will unfuzz the fuzzy patch we've used to denote our ignorance of the universe's earliest moments, and after that, the cosmological drama will unfold according to inflationary theory's remarkably successful script, recounted in earlier chapters.

While there has been progress on specific details required by this vision (such as trying to understand why only three of the universe's spatial dimensions underwent expansion, as well as developing mathematical methods that may prove relevant to analyzing the spaceless/timeless realm that may precede inflation), the eureka moments have yet to occur. The intuition is that whereas inflationary cosmology imagines the observable universe getting ever smaller at ever earlier times—and hence being ever hotter, denser, and energetic—string/M-theory tames this unruly (in physics-speak, "singular") behavior by introducing a minimal size (as in our discussion on pages 350–351) below which new and less singular physical quantities become relevant. This reasoning lies at the heart of string/M-theory's successful merger of general relativity and quantum mechanics, and many researchers expect that we will shortly determine how to apply the same reasoning in the context of cosmology. But, as of now, the fuzzy patch still looks fuzzy, and it's anybody's guess when clarity will be achieved.

The second approach employs the braneworld scenario, and in its most radical incarnation posits a completely new cosmological framework. It is far from clear whether this approach will survive detailed mathematical scrutiny, but it does provide a good example of how breakthroughs in fundamental theory can suggest novel trails through well-trodden territory. The proposal is called the *cyclic model.*

Cyclic Cosmology

From the standpoint of time, ordinary experience confronts us with two types of phenomena: those that have a clearly delineated beginning, middle, and end (this book, a baseball game, a human life) and those that are cyclic, happening over and over again (the changing seasons, the rising and setting of the sun, Larry King's weddings). Of course, on closer scrutiny we learn that cyclic phenomena also have a beginning and end, since cycles do not generally go on forever. The sun has been rising and setting—that is, the earth has been spinning on its axis while revolving around the sun—every day for some 5 billion years. But before that, the sun and the solar system had yet to form. And one day, some 5 billion years from now, the sun will turn into a red giant star, engulfing the inner planets, including earth, and there will no longer even be a notion of a rising and setting sun, at least not here.

But these are modern scientific recognitions. To the ancients, cyclic phenomena seemed eternally cyclic. And to many, the cyclic phenomena, running their course and continuously returning to begin anew, were the primary phenomena. The cycles of days and seasons set the rhythm of work and life, so it is no wonder that some of the oldest recorded cosmologies envisioned the unfolding of the world as a cyclical process. Rather than positing a beginning, a middle, and an end, a cyclic cosmology imagines that the world changes through time much as the moon changes through phases: after it has passed through a complete sequence, conditions are ripe for everything to start afresh and initiate yet another cycle.

Since the discovery of general relativity, a number of cyclic cosmological models have been proposed; the best-known was developed in the 1930s by Richard Tolman of the California Institute of Technology. Tolman suggested that the observed expansion of the universe might slow down, someday stop, and then be followed by a period of contraction in which the universe got ever smaller. But instead of reaching a fiery finale in which it implodes on itself and comes to an end, the universe might, Tolman proposed, undergo a *bounce:* space might shrink down to some small size and then rebound, initiating a new cycle of expansion followed once again by contraction. A universe eternally repeating this cycle—expansion, contraction, bounce, expansion again—would elegantly avoid the thorny issues of origin: in such a scenario, the very concept of origin would be inapplicable since the universe always was and would always be.

But Tolman realized that looking back in time from today, the cycles could have repeated for a while, but not indefinitely. The reason is that during each cycle, the second law of thermodynamics dictates that entropy would, on average, rise.[8] And according to general relativity, the amount of entropy at the beginning of each new cycle determines how long that cycle will last. More entropy means a longer period of expansion before the outward motion grinds to a halt and the inward motion takes over. Each successive cycle would therefore last much longer than its predecessor; equivalently, earlier cycles would be shorter and shorter. When analyzed mathematically, the constant shortening of the cycles implies that they cannot stretch infinitely far into the past. Even in Tolman's cyclic framework, the universe would have a beginning.

Tolman's proposal invoked a spherical universe, which, as we've seen, has been ruled out by observations. But a radically new incarnation of cyclic cosmology, involving a flat universe, has recently been developed within string/M-theory. The idea comes from Paul Steinhardt and his collaborator Neil Turok of Cambridge University (with heavy use of results discovered in their collaborations with Burt Ovrut, Nathan Seiberg, and Justin Khoury) and proposes a new mechanism for driving cosmic evolution.[9] Briefly put, they suggest that we are living within a three-brane that violently collides every few trillion years with another nearby, parallel three-brane. And the "bang" from the collision initiates each new cosmological cycle.

The basic setup of the proposal is illustrated in Figure 13.7 and was suggested some years ago by Hořava and Witten in a noncosmological

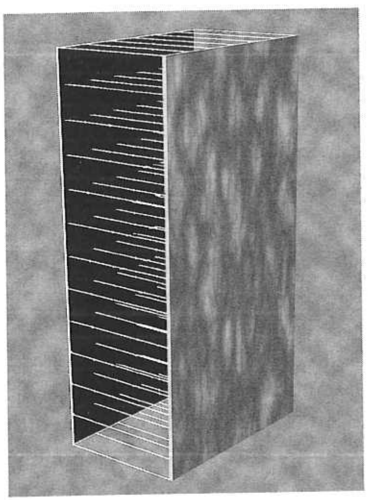


Figure 13.7 Two three-branes, separated by a short interval.

context. Hořava and Witten were trying to complete Witten's proposed unity among all five string theories and found that if one of the seven extra dimensions in M-theory had a very simple shape—not a circle, as in Figure 12.7, but a little segment of a straight line, as in Figure 13.7—and was bounded by so-called end-of-the-world branes attached like bookends, then a direct connection could be made between the Heterotic-E string theory and all others. The details of how they drew this connection are neither obvious nor of the essence (if you are interested, see, for example, *The Elegant Universe*, Chapter 12); what matters here is that it's a starting point that naturally emerges from the theory itself. Steinhardt and Turok enlisted it for their cosmological proposal.

Specifically, Steinhardt and Turok imagine that each brane in Figure 13.7 has three space dimensions, with the line segment between them providing a fourth space dimension. The remaining six space dimensions are curled up into a Calabi-Yau space (not shown in the figure) that has the right shape for string vibrational patterns to account for the known particle species.[10] The universe of which we are directly aware corresponds to one of these three-branes; if you like, you can think of the second three-brane as another universe, whose inhabitants, if any, would also be aware of only three space dimensions, assuming that their experimental technology and expertise did not greatly exceed ours. In this setup, then, another three-brane—another universe—is right next door. It's hovering no more than a fraction of a millimeter away (the separation being in the fourth spatial dimension, as in Figure 13.7), but because our three-brane is so sticky and the gravity we experience so weak, we have no direct evidence of its existence, nor its hypothetical inhabitants any evidence of ours.

But, according to the cyclic cosmological model of Steinhardt and Turok, Figure 13.7 isn't how it's always been or how it will always be. Instead, in their approach, the two three-branes are attracted to each other—almost as though connected by tiny rubber bands—and this implies that each drives the cosmological evolution of the other: the branes engage in an endless cycle of collision, rebound, and collision once again, eternally regenerating their expanding three-dimensional worlds. To see how this goes, look at Figure 13.8, which illustrates one complete cycle, step by step.

At Stage 1, the two three-branes have just rushed toward each other and slammed together, and are now rebounding. The tremendous energy of the collision deposits a significant amount of high-temperature radiation and matter on each of the rebounding three-branes, and—this is

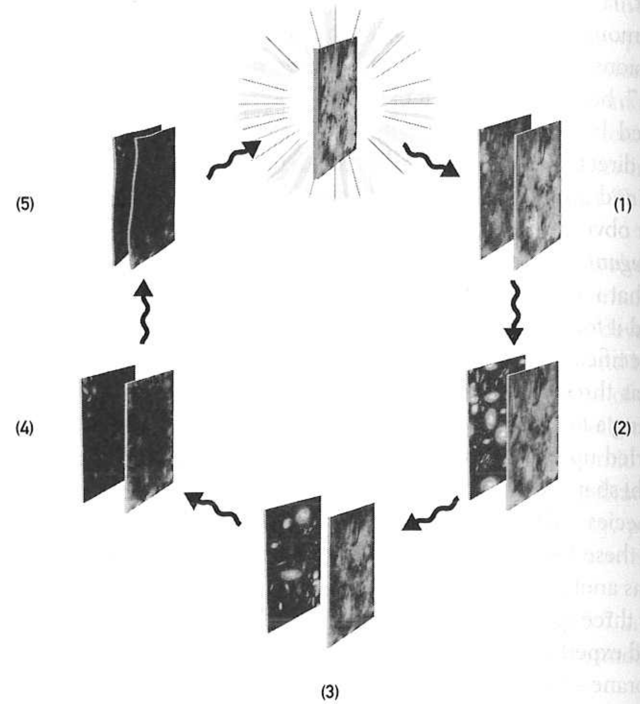


Figure 13.8 Various stages in the cyclic braneworld cosmological model.

key—Steinhardt and Turok argue that *the detailed properties of this matter and radiation have a nearly identical profile to what's produced in the inflationary model.* Although there is still some controversy on this point, Steinhardt and Turok therefore claim that the collision between the two three-branes results in physical conditions extremely close to what they'd be a moment after the burst of inflationary expansion in the more conventional approach discussed in Chapter 10. Not surprisingly, then, to a hypothetical observer within our three-brane, the next few stages in the cyclic cosmological model are essentially the same as those in the standard approach as illustrated in Figure 9.2 (where that figure is now interpreted as depicting evolution on one of the three-branes). Namely, as our three-brane rebounds from the collision, it expands and cools, and cosmic structures such as stars and galaxies gradually coalesce from the primordial plasma, as you can see in Stage 2. Then, inspired by the recent supernova observations discussed in Chapter 10, Steinhardt and Turok configure their model so that about 7 billion years into the cycle—Stage 3—the energy in ordinary matter and radiation becomes sufficiently diluted by the expansion of the brane so that a dark energy component gains the upper hand and, through its negative pressure, drives an era of accelerated expansion. (This requires an arbitrary tuning of details, but it allows the model to match observation, and so, the cyclic model's proponents argue, is well motivated.) About 7 billion years later, we humans find ourselves here on earth, at least in the current cycle, experiencing the early stages of the accelerated phase. Then, for roughly the next *trillion* years, not much new happens beyond our three-brane's continued accelerated expansion. That's long enough for our three-dimensional space to have stretched by such a colossal factor that matter and radiation are diluted almost completely away, leaving the braneworld looking almost completely empty and completely uniform: Stage 4.

By this point, our three-brane has completed its rebound from the initial collision and has started to approach the second three-brane once again. As we get closer and closer to another collision, quantum jitters of the strings attached to our brane overlie its uniform emptiness with tiny ripples, Stage 5. As we continue to pick up speed, the ripples continue to grow; then, in a cataclysmic collision, we smack into the second three-brane, we bounce off, and the cycle starts anew. The quantum ripples imprint tiny inhomogeneities in the radiation and matter produced during the collision and, much as in the inflationary scenario, these deviations from perfect uniformity grow into clumps that ultimately generate stars and galaxies.

These are the major stages in the cyclic model (also known tenderly as the *big splat*). Its premise—colliding braneworlds—is very different from that of the successful inflationary theory, but there are, nevertheless, significant points of contact between the two approaches. That both rely on quantum agitation to generate initial nonuniformities is one essential similarity. In fact, Steinhardt and Turok argue that the equations governing the quantum ripples in the cyclic model are nearly identical to those in the inflationary picture, so the resulting nonuniformities predicted by the two theories are nearly identical as well.[11] Moreover, while there isn't an inflationary burst in the cyclic model, there is a trillion-year period (beginning at Stage 3) of milder accelerated expansion. But it's really just a matter of haste versus patience; what the inflationary model accomplishes in a flash, the cyclic model accomplishes in a comparative eternity. Since the collision in the cyclic model is not the beginning of the universe, there is the luxury of slowly resolving cosmological issues (like the flatness and horizon problems) during the final trillion years of each *previous* cycle. Eons of gentle but steady accelerated expansion at the end of each cycle stretch our three-brane nice and flat, and, except for tiny but important quantum fluctuations, make it thoroughly uniform. And so the long, final stage of each cycle, followed by the splat at the beginning of the next cycle, yields an environment very close to that produced by the short surge of expansion in the inflationary approach.

A Brief Assessment

At their present levels of development, both the inflationary and the cyclic models provide insightful cosmological frameworks, but neither offers a complete theory. Ignorance of the prevailing conditions during the universe's earliest moments forces proponents of inflationary cosmology to simply assume, without theoretical justification, that the conditions required for initiating inflation arose. If they did, the theory resolves numerous cosmological conundrums and launches time's arrow. But such successes hinge on inflation's happening in the first place. What's more, inflationary cosmology has not been seamlessly embedded within string theory and so is not yet part of a consistent merger of quantum mechanics and general relativity.

The cyclic model has its own share of shortcomings. As with Tolman's model, consideration of entropy buildup (and also of quantum mechanics[12]) ensures that the cyclic model's cycles could not have gone on forever. Instead, the cycles began at some definite time in the past, and so, as with inflation, we need an explanation of how the first cycle got started. If it did, then the theory, also like inflation, resolves the key cosmological problems and sets time's arrow pointing from each low-entropy splat forward through the ensuing stages of Figure 13.8. But, as it's currently conceived, the cyclic model offers no explanation of how or why the universe finds itself in the necessary configuration of Figure 13.8. Why, for instance, do six dimensions curl themselves up into a particular Calabi-Yau shape while one of the extra dimensions dutifully takes the shape of a spatial segment separating two three-branes? How is it that the two end-of-the-world three-branes line up so perfectly and attract each other with just the right force so that the stages in Figure 13.8 proceed as we've described? And, of critical importance, what actually happens when the two three-branes collide in the cyclic model's version of a bang?

On this last question, there is hope that the cyclic model's splat is less problematic than the singularity encountered at time zero in inflationary cosmology. Instead of all of space being infinitely compressed, in the cyclic approach only the single dimension between the branes gets squeezed down; the branes themselves experience overall expansion, not contraction, during each cycle. And this, Steinhardt, Turok, and their collaborators have argued, implies *finite* temperature and *finite* densities on the branes themselves. But this is a highly tentative conclusion because, so far, no one has been able to get the better of the equations and figure out what would happen should branes slam together. In fact, the analyses so far completed point toward the splat being subject to the same problem that afflicts the inflationary theory at time zero: the mathematics breaks down. Thus, cosmology is still in need of a rigorous resolution of its singular start—be it the true start of the universe, or the start of our current cycle.

The most compelling feature of the cyclic model is the way it incorporates dark energy and the observed accelerated expansion. In 1998, when it was discovered that the universe is undergoing accelerated expansion, it was quite a surprise to most physicists and astronomers. While it can be incorporated into the inflationary cosmological picture by assuming that the universe contains precisely the right amount of dark energy, accelerated expansion seems like a clumsy add-on. In the cyclic model, by contrast, dark energy's role is natural and pivotal. The trillion-year period of slow but steadily accelerated expansion is crucial for wiping the slate clean, for diluting the observable universe to near nothingness, and for resetting conditions in preparation for the next cycle. From this point of view, both the inflationary model and the cyclic model rely on accelerated expansion—the inflationary model near its beginning and the cyclic model at the end of each of its cycles—but only the latter has direct observational support. (Remember, the cyclic approach is designed so that we are just entering the trillion-year phase of accelerated expansion, and such expansion has been recently observed.) That's a tick in the cyclic model's column, but it also means that should accelerated expansion fail to be confirmed by future observations, the inflationary model could survive (although the puzzle of the missing 70 percent of the universe's energy budget would emerge anew) but the cyclic model could not.

New Visions of Spacetime

The braneworld scenario and the cyclic cosmological model it spawned are both highly speculative. I have discussed them here not so much because I feel certain that they are correct, as because I want to illustrate the striking new ways of thinking about the space we inhabit and the evolution it has experienced that have been inspired by string/M-theory. If we are living within a three-brane, the centuries-old question regarding the corporeality of three-dimensional space would have its most definite answer: space would be a brane, and hence would most definitely be a something. It might also not be anything particularly special as there could be many other branes, of various dimensions, floating within string/M-theory's higher dimensional expanse. And if cosmological evolution on our three-brane is driven by repeated collisions with a nearby brane, time as we know it would span only one of the universe's many cycles, with one big bang followed by another, and then another.

To me, it's a vision that's both exciting and humbling. There may be much more to space and time than we anticipated; if there is, what we consider to be "everything" may be but a small constituent of a far richer reality.

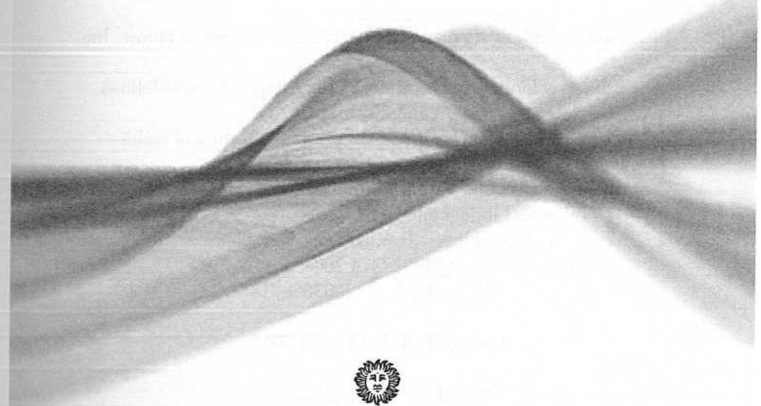
V

REALITY AND IMAGINATION

THE FABRIC OF THE COSMOS

SPACE, TIME, AND THE TEXTURE OF REALITY

BRIAN GREENE



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