Beyond

The Frontiers

TRISPATIOCENTRISM

[rf"Egocentric." "Enthnocentric." A variety of words in the English language describe the tendency of people to get locked into a limited perspective. "Anthropocentric" is a favorite word in some circles of astronomy. It describes the tendency of scientists as well as *Star Trek* writers to conjure up alien life forms that are fundamentally similar to us, not just physically, but emotionally and socially, with our motivations, drives, and dreams. The *anthropic principle* – that the Universe is as it is because we exist – is a related idea. In the never-ending battle to expand our perspectives, I write this to call attention to the existence of another limited, rarely questioned, viewpoint that affects us all: *trispatiocentrism*. Trispatiocentrism is the attitude that the "normal" three-dimensional space of our direct perceptions is all there is and all that matters.

This word arose in my substantial writing component course at the University of Texas in Austin. We were exploring the nature of space and time with a particular emphasis on spaces of various dimensions. I wanted a word to connote the notion that our three-dimensional world view carries with it unrecognized restrictions. I came up with "trispatiocentric" and its obvious variations.

There is a serious scientific side to this. Some understanding of curved space is needed to picture how Einstein's theory of gravity works. To illustrate the basic ideas, gravitational physicists often have recourse to examples of curved two-dimensional spaces, the surfaces of spheres or of saddles or of donuts. In these examples, our familiar three-dimensional space surrounds the surface so that we can easily envisage the curvature. The trick is to try to perceive what the corresponding curvature of our own three-dimensional space is like. The goal is to understand the arcanae of Einstein's theory: black holes, worm holes, time machines and the ramifications of string theory. In this context, it is quite natural for a logical, if naive, mind to ask: if the surface of a sphere curves in a three-dimensional space, then must our three-dimensional space curve in some four-dimensional space?

For the nonnaive, these issues arise at the forefront of modern physics, the attempt to construct a "theory of everything." This theory will allow us to understand the raging singularities predicted to be at the centers of black holes and from which the Universe was born. Singularities represent the place where our current concepts of space and time, indeed all of physics, break down. The most successful current attempts to develop a new understanding of space and time are based on "string theory," where, to be self-consistent, the "strings" that constitute the fundamental elements of nature exist in a space of ten dimensions. Thus these developments have led physicists to ponder higher dimensions, perhaps ones so tightly packed we cannot perceive them directly. They speak in terms of surfaces or membranes in a space of *p*-dimensions and call them "*p*-branes." Alas, I cannot resist pointing out that all this is not for pea brains like me. It is, however, the stuff that will push back the frontiers of knowledge and along the way help to resolve famous wagers made by Stephen Hawking concerning the nature of space and time.

In our course, we read the classic old tale *Flatland* by Edwin Abbott. Here we meet the Monarch of Line Land who, in blissful ignorance, suffers his monospatiocentrism. The hero of *Flatland* is a simple square who is ripped, to his ultimate chagrin, from his bispatiocentric world view by a visitor from a three-dimensional Universe we would recognize.

Abbott, Einstein, and the work of string theorists would have us ponder a fundamental verity. We are gripped in a trispatiocentrism we rarely stop to recognize and even more rarely take the time to ponder. Why does our familiar space have three dimensions, no more, no less? Is the notion that this space is natural or even unique as archaic and limited as the notions that the Sun goes around the Earth or that the Solar System is in the center of the Universe? Is Heaven not "up" in a literal sense but in a higher dimension we cannot perceive? If so, what of Hell? When Captains Kirk, Picard, or Janeway are transported to a different dimension, why is it always so boringly and trispatiocentrically of a familiar number of dimensions? We are trapped in this three-dimensional world of our direct perceptions and scarcely know it.

Is it possible that space can be prized open with "exotic matter" leading to worm holes that reconnect time and space? Are the ten dimensional spaces of string theory the first hint of the "subspace" of *Star Trek*? The work of physicists on the vanguard of knowledge provides the first glimpses of what may exist beyond or without.

The hero of *Flatland* was imprisoned for attempting to challenge the bispatiocentrism of his peers. My students seem to have the same dismal expectations for any departures from societal norms. The stories they wrote for class of other-dimensional worlds suggested that society is likely to find unwelcome any assault on cherished "centrisms." With their stories as a guide, I should expect with this contribution to be summarily institutionalized, incarcerated, or executed. Nevertheless, the truth must be exposed.

Citizens of this three-dimensional Universe unite! You have nothing to lose but your branes!

1. Quantum Gravity

The search for quantum gravity, a theory that unites both the aspects of uncertainty from the quantum theory and the aspects of curved space from general relativity, a theory of everything, is the current frontier of physics. Black holes are at the center of the action. The current contender for this intellectual prize is what is called by physicists *string theory*. The basic notion is that the fundamental entities of the Universe are not particles, dots of matter, but strings of energy, entities with one-dimensional extent.

That seems like a simple, maybe even unnecessary, generalization of our standard picture of elementary particles, electrons, neutrinos, protons, neutrons, and quarks. The doors that have been opened by this change in viewpoint are, however, wondrous.

For perspective, let us go back to the theory of Newton. Newton gave a rigorous mathematical framework in which to understand gravity and much else of basic physics, how things move under the imposition of forces. Newton's law of gravity was based on the concept of a force between two objects. It was encapsulated in a simple formula that said that the force of gravity was proportional to the mass of two gravitating objects and inversely proportional to the square of the distance between them. This prescription was immensely successful. It is still used with great effect in most of astronomy to predict the motions of stellar objects from asteroids to the swirling of majestic galaxies. It is used to guide man-made satellites and rockets. We know now, however, that Newton's theory is wrong. It is wrong in concept and wrong in application.

A hint of the conceptual problem with Newton's theory comes by examining the law of gravity (see also Chapter 9, Section 1). Newton's version of this law tells of the dependence on the masses of the gravitating objects and the distance between them but is mute on the dependence on time. Newton knew that the speed of light was a speed limit, yet his theory demanded communication of information, the strength of gravity, at infinite speed. Another clue to problems with Newton's theory is that if you reduce the distance between two objects to zero the gravitational force between them is infinite. If one looks sufficiently closely at Newton, those errors exist. The ultimate test is comparison of theory with observation and experiment. Newton is exceedingly successful in many applications but fails in some. Newton's theory gives the wrong answer to carefully posed experimental situations.

Einstein's theory of gravity, general relativity, was based on an incredibly simple and elegant idea: that physics should behave the same independent of the motion of the experimenter. The earlier version of this idea, Einstein's special theory of relativity, arose from the young Einstein asking another simple question: what would an electromagnetic wave look like if an observer moved along with it at the speed of light? To answer that question, to show that the observer could not move at the speed of light, Einstein had to show that the speed of light was the same *independent of the motion of the observer*. This result, one of the deeply true aspects of physics, remains one of the most incredible of human insights. Einstein also proved with his special theory that the lengths and times measured by an observer depended on how the measured object was moving, not in an absolute sense, but moving with respect to the observer.

Einstein's general theory took another step and asked about observers not in uniform motion, the subject of special relativity, but observers in accelerated motion. He realized that an observer freely falling in a gravitational field would measure physical effects and find them identical to an observer moving at uniform speed far from any gravitating object, but that an observer in an accelerating frame would feel exactly the same as one feeling the effects of gravity. This notion has been enshrined as Einstein's *equivalence principle*, that an acceleration gives the same effects as being at rest in a gravitational field. If you sat in a chair in a lecture hall that accelerated at a uniform rate, the floor would push on your feet and the seat would push on your rear end, exactly the same forces you feel sitting in your chair reading this book. The equivalence principle is elegantly simple to state. To put it into a self-consistent mathematical framework, Einstein found that he had to introduce the notions of curved space and a complex set of tensor equations to describe it. Our sense of the nature of space has never been the same.

Einstein's theory of gravity has passed every test put to it. It gets the right answers for the shift of Mercury's orbit and the deflection of light, and has passed numerous other tests to the limit of our current ability to devise those tests. This makes general relativity a better theory of gravity than Newton's. General relativity also becomes identical to Newton's theory, mathematically, and hence in its precise predictions, when gravity is weak, distances are large, and motion is small. It must do so in order to reproduce Newton's manifest success of predictability in those regimes. To accomplish this great success, Einstein had to abandon, not just the mathematical structure adopted by Newton, but the fundamental concept behind gravity. Einstein abandoned the notion of a “force” of gravity, and replaced it with the notion of curved space and warped time. Space is curved, and that tells matter how to move, how to orbit, how to fall. Gravity is geometry, the geometry of curved space. The change in conception wrought by Einstein was deeply profound. General relativity is, however, wrong.

So far we only know that general relativity is wrong because of conceptual problems. We have not been able to devise a test sensitive enough to display the fact. The conceptual problem is in the prediction of the singularity. General relativity predicts that, right at the center of a black hole, a region of infinitesimal size, with infinite space-time curvature and infinite tidal forces, must form. Essentially identical conditions are predicted at the beginning of the Universe, a singularity from which all arose. Those predictions of infinity are the undoing of general relativity. To be specific, the prediction of singularities flatly violates the fundamental tenet of quantum theory, the uncertainty principle (see Chapter 1, Section 2.4), which states that one cannot specify the position of anything exactly, including a “singularity.” As a predictive theory, general relativity is marvelous in the regimes where it works, just as Newton's theory was in its own regime. General relativity does everything that Newton's theory could do and more, including predictions of black holes and event horizons. Deep in its heart, however, general relativity contradicts quantum theory.

On the other side, quantum theory basically assumes that the underlying space in which particles are rendered uncertain is flat, or at least, not too curved. General relativity predicts conditions not as extreme as the singularity where its results should still be valid, but where the curvature of space is “smaller” than the size of a quantum-smeared particle. In this sense, the quantum theory breaks down at conditions where general relativity still rules. Each of these great theories of 20th century physics contradict one another at a fundamental level. We need a 21st century theory to encompass and embrace both, but that also works where they fail.

A theory of everything must take its place in this hierarchy. It must incorporate everything that Newton accurately predicted. It must also incorporate everything that Einstein consumed so elegantly. Then it must also answer the question: what is this amazing thing called a singularity? The theory must tell us what happens to space and time under conditions where quantum uncertainty dictates that the very notions of “front,” “back,” “here,” “there,” “before,” and “after” lose their meaning. There must be space without space as we know it and time without time as we know it. Is there any wonder that physicists since Einstein have labored against immense conceptual problems in attempting to cross this barrier?

2. When the Singularity Is Not a Singularity

The singularity of Einstein's theory cannot exist. Something else must happen to space and time “there.” In the absence of the full development of quantum gravity, physicists are left to grope. When physicists grope, startling ideas emerge.

We know the scale on which Einstein's theory must break down even if we do not fully understand what must replace it. This scale can be estimated from the simple idea of asking about the conditions where quantum uncertainty must be as important as the space-time curvature of gravity. The fundamental constants of quantum gravity are the strength of gravity as measured by Newton's constant from the world of the large, the degree of quantum uncertainty as measured by Planck's constant from the world of the small, and nature's speed limit, the speed of light from the world of the very fast. With values for these constants of nature in some set of units, English or metric, it does not matter, one can estimate the scale where Einstein's theory, and ordinary quantum theory, fail. This scale, of length, time, density, is called the *Planck scale*. Newton's constant has units of length cubed, time squared, and the inverse of mass. Planck's constant has units of mass, length squared, and the inverse of time. The speed of light has units of length over time. There is only one way we can combine these three fundamental constants with their individual units to produce a quantity of only length, only one other way to produce a time, and only a single third way to produce a mass. This exercise is a simple one of sorting out units, but it has profound implications because the building blocks are the fundamental constants that tell us how space curves, the degree of quantum uncertainty, and how fast things can move. Their combination implicitly tells us where space gets so curved that a quantum wave cannot exist and simultaneously where quantum uncertainty is so large that speaking of a given curvature makes no sense. We learn the conditions where the two great theories of 20^{th} century physics butt heads and contradict one another, the conditions that call for a new theory of physics.

The resulting value of the length, the Planck length, is about 10^{-33} centimeters. This is an incredibly small value, much smaller than the size of a proton, but it is not zero! This is roughly how large the singularity must be. At this level, space and time break down into something else, and Einstein's prediction of a singularity goes awry. The corresponding Planck time is about 10^{-43} seconds. This is again an incredibly short time, but not zero. Time as we know it probably does not exist at shorter intervals so that asking what happened when the Universe was younger than 10^{-43} seconds or before the big bang may not make sense, at least not in the traditional way. The Planck mass is about 10^{-5} grams. This is a small number, but not incredibly small. It is vastly bigger than any elementary particle we know. One can also work out the Planck density, the Planck mass divided by the cube of the Planck length. The answer is about 10^{93} grams per cubic centimeter. This is a gigantic density, but it is not infinite. In some average way, this must be the density of a singularity, the density from which our Universe expanded in the big bang, the density to which all is compressed in the centers of black holes.

One way to think about the singularity is as a bubbling sea of Planck masses, each a Planck length in extent winking in and out of existence for intervals of a Planck time. This quantum-bubbling mess has been called a *quantum foam*, another bit of etymological brilliance from John A. Wheeler. This term is a picturesque name intended to describe something we do not understand, yet to capture the flavor of the idea that it is not ordinary space and time. In the quantum foam, one could not speak of front and back because space itself would be so quantum uncertain that such concepts are invalid. The same is true for the ideas of before and after, with time also a quantum froth.

Even in the absence of a full theory, if we picture the singularity not as a point of zero size and infinite density but a dollop of quantum foam, then other ideas begin to emerge. The Universe was not born from a point of infinite density but emerged as a bubble of ordinary space and time from this quantum foam. This bubble was highly energetic and expanded to become everything we see. As we discussed in Chapter 12, the expansion is pictured in the sense that all points of space move away from all other points of space, not an explosion of stuff into a preexisting three-dimensional space. Also, as three-dimensional physicists, we do not have to address the issue of what the three-dimensional Universe is expanding into, as much as that question seems to intrude.

That the Universe emerges from the quantum foam already gives some predictability to the nature of the Universe. There must have been quantum fluctuations in the density and temperature of the very young, hot big bang as it emerged from the quantum foam 10^{-33} centimeters across and 10^{-43} seconds old. These unavoidable fluctuations can be calculated from the quantum theory with some assumptions, and they later cause the tiny irregularities in temperature detected by *COBE* and *WMAP* that after billions of years grow to form all the structure we see – stars, galaxies, clusters of galaxies (Chapter 12, Section 5).

The notion of a quantum foam also plays a role in the thinking about worm holes (Chapter 13) and shows again that we cannot pursue the physics of worm holes without a theory of the quantum foam, a theory of the singularity, a quantum-gravity theory of everything. One way to picture the quantum foam is as quantum-connected fragments of space and time, connecting different places and different times willy-nilly in a probabilistic way. These connections, although dominated by quantum uncertainty, are essentially tiny quantum worm holes. One can imagine making a worm hole by taking a little quantum loop of space and time and blowing it up to become a worm hole big enough to travel through.

Another way to imagine making a worm hole leads to similar issues of the quantum nature of space and time. If you start from ordinary space and want to make a black hole, you have to stretch and distort the space, but you do not have to rip or tear it (at least not until you get to that nasty singularity). That is not true for a worm hole. To make a worm hole, you have to tear and reconnect space. You have to change not just the curvature of space but its connectedness, its topology. If you think about it, a tea cup with a nice handle and a donut are the same basic thing in terms of how they are connected. They are both solid objects with one hole through them. You could make both from the same lump of clay by just molding a side of the donut shape to be the cup and shape the clay around the hole to be the handle. You would not have to tear the clay or reattach it at any point. You cannot, however, make a solid lump of clay into either a donut or tea cup without tearing a hole in the clay.

Think of how you could connect space on a large scale to make a worm hole. It helps to imagine this in two dimensions. Picture a balloon. Push two fingers inward from opposite sides until your fingers almost touch, separated only by the thin rubber of the balloon. You have almost made a worm hole. If the connection could be made there in the center of the balloon, there would be a way to travel on a shortcut through the center of the balloon, rather than taking the long way around on the surface. The balloon serves as a two-dimensional analog of our three-dimensional space, so all motion is confined to the rubber of the surface. Now think of what you need to do to make the connection between your fingers. You would have to cut the rubber and attach the ends of the two cones; but cutting the rubber is the analogy of cutting the very fabric of space. That would be the issue in our real three-dimensional space in order to make a three-dimensional worm hole. The cutting and reattaching of space would amount to, at least temporarily, introducing an end to space, a singularity, before the reattachment is made. To make a worm hole or a worm-hole time machine in this way, we have to bring in the operation of introducing a tear in space-time, a tear in the quantum foam. We will not know whether such an operation even makes sense until we have a theory of quantum gravity that tells how space and time behave if such a rent is threatened. Once again, we cannot think constructively about worm holes or time machines without a theory of quantum gravity to guide us.

If the Universe were born not from a singularity of infinite density, but from a spot of quantum foam, then the inverse is true. When a star collapses to make a black hole, the matter of the star does not disappear into a singularity of zero volume but is crushed into a froth of quantum foam of a Planck density. One of the most dramatic ideas to emerge in the last few years was to ask, if a black hole leads back to the quantum foam from which the Universe arose, why cannot the cycle repeat? This idea was first put forth by Andre Linde, a Russian physicist, now at Stanford University. Linde was striving for some new idea to present at a conference to which he had been invited. He was ill and contemplating skipping the meeting, when this notion came to him. He worked out the basic mathematical and physical picture and presented it at the meeting.

The idea is that the quantum foam that forms at the center of the black hole is identical to that from which the big bang, our whole Universe, arose. This means, Linde argued, that a new Universe can arise from the quantum foam of the black hole. The dramatic implication is that the chain could be endless. A universe forms; it expands to form stars. Some of the stars collapse to make black holes. From the singularities of those black holes, new universes can be born elsewhere in hyperspace. Here, perhaps, is a way to answer the question of what came before and what comes after the big bang – endless universes forming endless black holes.

Like many grand ideas of physics, this one must be poked and pummeled and analyzed. How do you prove such a startling conjecture? We cannot travel to other universes to see how they work. We are stuck in this one but empowered with our imaginations and our mathematics and physics. Physicists are already at work generalizing the old cosmologies to see how these ideas could fit in. The easiest way to picture a bubble being blown in the quantum foam to become our Universe is to picture a literal bubble being blown. Such a bubble, basically a sphere, is a two-dimensional analog, an embedding diagram, for a closed three-dimensional universe. Such a universe would have a finite lifetime and would have to recollapse (neglecting the effects of Dark Energy). The results reported in Chapter 12 suggest that our Universe is not closed and “spherical.” It might be flat, but accelerating. Physicists and cosmologists are working now to develop models of inflating universes that are consistent with infinite expansion. Such universes, can, of course, make black holes as they expand, and that is enough to raise Linde's conjecture of new universes being constantly created.

These ideas have been taken one more dramatic step by Lee Smolin, now at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, in his book, *The Life of the Cosmos*. Smolin addresses the deepest issue that drives both physicists and theologians. Why are *we* here? What is it about our Universe that gave rise to life, to us. Smolin may not have the answer, but he has put the issues in an especially thought-provoking way by combining these ideas from physics with the basic ideas of biology, the power of natural selection. Smolin notes the amazing coincidences of numbers and physical conditions that are required to give rise to life as we know it. What if, Smolin wonders, each new universe had different numbers, for instance different values of the fundamental constants, Newton's constant of gravity, Planck's constant, the speed of light, and other physical constants of nature. Most of those universes would fail. Some would not get out of the quantum foam or would quickly fall back. Others would expand so rapidly that stars did not have a chance to form, so there would be no black holes. In either case, those universes would be barren, unable to produce progeny, new universes with new properties. Smolin makes a natural selection argument that after countless trials, the universes that survive would be those that maximize the production of black holes so that maximum progeny are ensured. Smolin argues that physicists may have to give up on a purely reductionist approach to science wherein the constants of nature have set values that theory and experiment can reveal and accept that our Universe has arisen from a process of trial and error, a result of probabilities, not certainty. To be fruitful, such a universe would have to expand about as fast as ours, make stars like ours, produce heavy elements like ours to control the heating and cooling of the interstellar gas to keep star formation going for billions of years. Such a universe, Smolin deduces, must have the properties of our Universe, and such a universe naturally gives rise to life to contemplate and make sense of it. Now that is a grand vision.

For all its inventiveness, Smolin's picture does not really address the fundamental issue. Given that there are infinite universes experimenting with all possible forms, how did it all arise in the first place? Was there a beginning to this process? Is there an end? James Gott of Princeton has put another wrinkle on the game by combining the self-reproduction of universes through black holes with the notions of time machines. If new universes emerge from the quantum foam of a black hole singularity, can they emerge in the past? If that were possible, Gott conjectures, then the universe that emerges from a black hole could be the one that made the black hole from which it emerged, or a universe somewhere back in the chain of universes that Linde and Smolin contemplate. Recall from Chapter 13 that the Novikov consistency conjecture does not rule out time travel, it only demands self-consistency. Could it be that the Universe or a complex web of universes gave rise to itself in a closed but self-consistent time loop? Could it be that there is no "beginning" and no "end" but just an infinite closed loop? As Gott asks, could the Universe have created itself?

All these issues loom, but we cannot address them without a theory of quantum gravity. Fortunately, we have a candidate for that theory. Before forging into that area, a review of hyperspace notions is relevant.

3. Hyperspace Perspectives

To illustrate black holes and curved space, we have had recourse to embedding diagrams that reduce the fullness of the curved three-dimensional space to two so that we, as three-dimensional creatures, can view these warped spaces from our higher-dimensional perspective (Chapter 9, Section 5; Chapter 12, Section 2; Figure 13.2). From this perspective, it is clear to us that, even though there is no two-dimensional outside to the two-dimensional space, there is a very natural "outside" to the two-dimensional space, the very three-dimensional "hyperspace" that we occupy. This naturally leads one to wonder whether there is a "real" fourth spatial dimension that we, as three-dimensional creatures, cannot perceive, into which our three-dimensional Universe curves. This hyperspace would be where worm holes go when they go.

The issue of a fourth spatial dimension has been around for a long time, even pre-dating Einstein. When Georg Reimann and Nikolai Ivanovich Lobachevsky laid the foundations for the mathematics of curved space in the mid 19th century, people already began to wonder to where might curved space curve. Notions of a four-dimensional hyperspace actually affected art and culture around the beginning of the 20th century as explored by my colleague, art historian Linda Henderson in her book *The Fourth Dimension and Non-Euclidean Geometry in Modern Art*.

People explored simple four-dimensional shapes like tesseracts, the four-dimensional extension of a cube, and more complex shapes. Some founded religions and philosophies based on this hyperspace perspective.

It was in this context that Abbott's marvelous *Flatland* was written, misogyny and all. As Abbott described, an imagined two-dimensional creature could "see" (whether electromagnetic radiation could propagate in a two-dimensional space is another issue) the front of another denizen of two-dimensional space. From three-dimensions, however, we could see the front, back, sides, and *insides* of such a creature simultaneously. Likewise, when we greet a friend in our three-dimensional space, we perceive their smiling visage, but cannot simultaneously see their backsides, never mind the state of their heart and lungs. If there were a hypothetical four-dimensional creature who could look "down" on us as we look "down" on a two-dimensional creature sketched on a sheet of paper, that 4D creature could simultaneously perceive our front, back, sides, all our 2D surface, but also all of our 3D volume, all of our guts and plumbing, all with one glance.

A 3D creature passing through a 2D "universe" would first penetrate it at a point, then would "fill" a two-dimensional area, then would recede back to a point as the creature proceeded on into its own 3D "hyperspace" and no longer intercepted any part of the 2D "universe." Likewise a 4D creature passing through our 3D space would first appear at a point, then expand to "fill" what we perceive as a 3D volume, but which would be a mere cross section to the 4D creature, then shrink back to a point and then vanish from our perspective as the creature proceeded on its 4D way.

These ideas floated through the salons of late 19^{th} century and early 20^{th} century Paris. A case can be made that cubism arose in part out of an attempt to portray objects from different aspects and different times simultaneously (but not that Picasso influenced Einstein's thinking), in somewhat the manner that a hyperspace perspective invites. This cultural phenomenon of pondering a spatial four-dimensional hyperspace faded with Einstein and the powerful notion that the fourth dimension was time, but it has never quite vanished from the cultural landscape. The cross depicted in Salvadore Dali's famous *Crucifixion* is actually a representation of a 4D tesseract unfolded into 3D, each "side" of the tesseract itself being a 3D cube. The full title of the painting is *Crucifixion (Corpus Hypercubus)*. Even today modern artists like the Brazilian Marcos Novak invent fantastic four-dimensional shapes and then represent them as they would be projected in our 3D space as they partially penetrated it. Some of these ideas are even woven into Steve Martin's witty play, *Picasso at the Lapin Agile*.

Despite the intuitively natural sense that invokes this sort of higher dimension when one talks about curved space around black holes or the possibility that the entire Universe is the three-dimensional analog of the two-dimensional curved surface of a sphere, throughout most of the 20^{th} century, a true large four-dimensional hyperspace was not part of physics. Physicists can construct mathematical models of curved three-dimensional spaces and universes, even worm holes, completely within the confines of that three-dimensional space. There was no need, or means, to invoke any extensive higher dimension, no way to measure it, no way to do physics with it. Not until string theory, anyway.

4. String Theory

Work on string theories is beginning to penetrate the barriers that separate Einstein's theory from the standard quantum theory and to bring a whole new perspective to hyperspace. The previous summary of the history of this area in Section 3 gives some preparation for what is necessary. Whereas Einstein overthrew the concept of gravity as a force between two objects, the quantum gravity theory of everything is likely to bring with it entirely new ways to think about gravity and, indeed, about space and time. In the appropriate regime, one can still think of curved space as the origin of gravity, just as for weak gravity it is still useful to think of a force of gravity and to use Newton's theory in appropriate circumstances. One of the steps that energized string theory was the understanding that within the full mathematics of the theory, a subset described exactly Einstein's theory of general relativity. Just as Einstein's theory "contains" Newton's theory of gravity in the limit of weak gravity, string theory "contains" Einstein's theory.

String theory, however, holds a lot more. The underlying concepts of a theory of everything may require a shift in conceptual basis as profound as that from a force of gravity to gravity as curved space. The notion that the fundamental entities from which everything is constructed are strings is such a conceptual shift. Recent developments point strongly to the conclusion that, at a sufficiently small scale physics will be very different than Newton, Einstein, or the founders of quantum theory envisaged.

To see how this idea has arisen, a sketch of string theory is necessary. An excellent introduction is given by Brian Green in his book *The Elegant Universe* and the PBS series of the same name. The roots of string theory go back to the 1960's when physicists were exploring the fundamental forces. In classic (non-stringy) quantum theory, the fundamental forces (Chapter 1, Section 2.1) have a very different cause than curved space or Newton's action at a distance. The strong and weak nuclear forces and the electromagnetic force arise from an exchange of particles between two interacting entities. This quantum exchange can yield either attractive or repulsive forces depending on circumstances. For the electromagnetic force, the exchange particles are photons, the fundamental entities of electromagnetic radiation. For the strong nuclear force, the exchanged particles are pi mesons and gluons. For the weak nuclear force, the particles are three special ones that can be charged either positively or negatively or not at all. In the 1960's physicists realized that the equations that described the strong nuclear force by this sort of exchange also described entities that could stretch and wiggle, entities with the properties of dynamic strings of energy.

The basic notion is that particles, mathematical points, are too simple to contain the wonders of nature. True point particles have no inner structure, no richness. A string, on the other hand, by adding only one more dimension to the structure, can vibrate in many modes. You can't make music with four grains of sand, but with four violin strings you can have Mozart! In the view of string theory, different modes of vibrations of the string represent different particles, just as one string on a violin can give different notes depending on where the violinist's finger is placed.

Unlike violin strings, the strings that represent the fundamental entities in this theory do not exist only in our ordinary three-dimensional space. To make a mathematically self-consistent picture, one free of infinities and other inconsistencies, the space through which the strings thread must be of much higher dimension. The currently most viable versions of the theory have ten spatial dimensions plus one of time. Hyperspace, a notion that has floated through much of this book, is not a mere abstraction to string theory; hyperspace is absolutely intrinsic to the structure of string theory.

The nature of these multidimensional loops of energy is that they have a characteristic length or scale, roughly the distance "along" the loop. The exact size of this scale is not known;

it is fantastically smaller than the size of an ordinary particle like a proton or neutron, but somewhat bigger than the Planck scale by perhaps a factor of a thousand. Concepts relating to black holes are woven throughout discussions of string theory. Here is an example. The way physicists have proceeded to explore ever more fundamental entities is to go to smaller scales: molecules to atoms to nuclei to protons to quarks. Experimentally, one probes these smaller scales by invoking ever higher energies. This is related to the fact that, in quantum theory where everything has a wavelike character, higher energy is associated with shorter wavelengths and hence, smaller length scales. Basically, one needs higher energy to probe smaller volumes and that is why physicists hunger for ever larger, more energetic "atom smashers" or particle accelerators in modern parlance. We know, though, that if one packs too much energy into a small volume, you make a black hole. We also know that black holes behave such that the more mass/energy you add to them the *bigger* they are, in terms of their event horizons, not smaller. The very nature of black holes thus suggests that there is a minimum size scale physicists can probe before they lose information inside event horizons. That length scale might be the string scale, or something related to it. The issue of information and black holes will come back again in a very profound way in Section 6. There is also an issue of how "thick" the strings are. By the same tenets of quantum uncertainty that limit the thickness of the ring singularity in a rotating black hole, strings cannot really be of zero thickness. Physicists assume for working purposes that they are of roughly a Planck size thick. One should not take the image of small rubber bands too literally; the strings are intrinsically quantum entities with all the wave-like uncertainty that entails.

With this string perspective, the "singularities" of Einstein, are probably not of the Planck scale, but regions roughly the size of the string scale. Exactly what physics looks like, how space and time behave on the string scale, remains to be fully elucidated, but because they have finite length, strings smooth out physics on this string scale and remove the troublesome infinities that otherwise pop up in the mathematics.

Through much of its development, the higher dimensions invoked by string theorists were all "compact." To picture a compact space, start again with a two-dimensional analog, a sheet of paper. As shown in Figure 14.1, roll the paper up into a tight roll. From a distance, the resulting object looks like a straight line, a string of length of perceptible extent, but no width. Imagine rolling the paper up laterally so you have a tiny ball. Now from a distance, the whole original sheet of paper resembles a point, a particle of no extent. A string in that original sheet of paper could still exist and vibrate away in that compact space that we could not directly perceive. We could, however, deduce that the higher dimensions exist because the nature of particles in our Universe demands it!

The last few years have seen some immense advances in string theory that have given great hope that it is the basis for the theory of everything. One step has been to prove that what looked like five or six different string theories are all versions of the same underlying theory, the full shape of which has not yet been elucidated. These connections were established by what physicists have called *duality*, a connection between the properties of the theories. In one version of the theory, a parameter could be small, and, as the parameter got large, the mathematics of the theory broke down. In another string theory, the dual to the first, there would be a parameter that was just the inverse of the first. In that second theory, as the first parameter got large, the inverse parameter got small, and the mathematics in that theory was well behaved. The middle ground is unknown, but this duality yields a signpost for how to link the disparate theories and show that they are deeply connected, that they are aspects of the same thing. This grand string theory that is taking shape is called *M theory, M* for matrix, or mystery, or an upside down W for Ed Witten of the Institute for Advanced Study, who developed it.

One of the concepts that has emerged from string theory is that there are not only strings threading the ten dimensions of the string theory hyperspace but also surfaces. These surfaces can be canted in hyperspace in just the same way that a sheet of paper can be oriented in all sorts of ways in our ordinary three-dimensional space. A more general word for a surface is a membrane, a term that also connotes a certain elasticity, a property that these surfaces have. These membranes can vibrate just as the strings can vibrate, and their modes of motion are also important to the behavior that emerges as ordinary physics in our ordinary space time. To classify the membranes in spaces of various dimensions, they are referred to as p-branes, where p is a symbol denoting the dimension of the membrane; $p = 2$ for a two-dimensional surface, $p = 3$ for three-dimensions, $p = 9$ for nine dimensions. The surfaces must have at least one dimension less than the full dimensionality of the space they occupy. In a sense, strings themselves are 1-branes.

An important development of string theory in recent years has been the recognition of the critical nature of the interaction of strings with p-branes. The ends of the string can attach to the p-branes or snap off to form closed rings. Some of the seminal work on branes was done by Joe Polchinski at the University of California at Santa Barbara but many others are contributing to the fevered pace of development.

A striking feat that followed the development of the theory of p-branes and their interactions with strings has been the capacity to construct simple models of black holes. These black holes are not the creatures of the curved space-time of Einstein, but simpler versions in two dimensions constructed from the entities of p-branes and strings. Nevertheless, because string theory contains Einstein's theory, objects that exert gravitational pull and that have event horizons can be constructed. The difference is that string theorists can count the numbers of modes and vibrations of the strings within the black holes they have constructed and tell exactly what the temperature and entropy should be. They get precisely the same answer as Hawking did in predicting Hawking radiation (Chapter 9), even though the mathematics and, indeed, the conceptual framework they use, is completely different. This striking concordance is the sort of development that tells physicists that they are getting close to a universal truth and that string theory has deep lessons to reveal.

String theory has also brought new insight into another problem that arises from thinking about the nature of black holes. This is called the *information crisis*. Information, the bits and bytes of computers, is about as fundamental as you can get. The problem is that black holes seem to destroy information, and that bugs physicists. The idea was already there in our previous discussions of the nature of black holes in Chapter 9 and captured in John Wheeler's phrase "black holes have no hair." You can throw stars, cars, people, and protons into a black hole, and all the information that described that ordinary stuff vanishes inside the event horizon. The only properties of a black hole that can be measured from the outside are its mass, spin, and electrical charge. Now Stephen Hawking enters the game. Black holes can evaporate, giving off Hawking radiation. Given enough time, the black hole will just disappear, leaving pure radiation with very little information content, essentially pure randomness. This process conserves energy, the energy equivalent of all the stuff that went down the black hole eventually emerges as the energy in the radiation. What happened to the information that defined that stars, the cars, the people, and the protons that went down the hole? Physicists have been debating this fundamental problem since the implications of Hawking's ideas of black hole evaporation were first assimilated.

One can sense a possible wrinkle in this argument. Hawking's theory was designed to work for ordinary-size black holes where the event horizon was well separated from the singularity at the center of the black hole. When a black hole evaporates down to the last of its essence, one needs a theory that can simultaneously treat the event horizon and the singularity and that probably requires a quantum gravity, a theory of everything. In the absence of that theory, it is not clear that one can use Hawking's original theory to account for the final moments. String theory gives a different possibility. It suggests that the black hole cannot evaporate entirely, but that, as the process runs away, one is left with a string vibrating intensely somewhere in its eleven-dimensional space-time. In those vibrations could be the epitaph of all that entered the black hole, all that original information, the size of the stars, the bumper stickers on the cars, the personalities of the people, the number of protons. On the other hand, Hawking has proclaimed that the information might reside in the radiation emitted; that the radiation is not so simple as that of an object of a single, well-defined temperature, and hence only one “bit” of information. This issue remains on the forefront.

Einstein wrote down a full and self-consistent set of equations to describe gravity (in the absence of quantum effects) in 1916. Those equations have yet to be fully solved. String theory is like that, only more so. The full mathematical structure of string theory is very complex, and only a few solutions have been wrested from it. Those solutions have been tremendously encouraging. Exactly what theory of space and time will emerge from string theory is thus not yet clear. One can see that, because string theory is a theory of quantum fields and forces, the fundamental concept of gravity will again be a force, but a quantum force, not that of Newton. Away from any singularity, this “force” of gravity will act just as in Einstein's theory. One will be able to speak in the language of curved space and time and dream of the construction of worm-hole time machines.

On the microscopic scale, however, the new concepts of string theory will lead to different pictures, pictures that are only just now beginning to take hazy conceptual form. One can see that gravity will be represented by the familiar terms of Einstein's gravity plus “something else” that comes in ever more strongly as one approaches, intellectually at least, the string scale. At the string scale itself, Einstein's theory will be completely inapplicable, as Newton's theory is within the event horizon of a black hole. The point singularity of Einstein with infinite density and infinite tidal forces will not exist in this framework, but what will replace it is not entirely clear.

While string theory struggles to understand what physics is like at the string scale, the growing understanding of the properties of strings and branes led to a revolution in our perspective of the Universe on the largest scales.

5. Brane Worlds

As outlined above, branes are surfaces that slice through multidimensional space. They must be of a dimension less than the full dimensionality of the space that contains them. In a 10-dimensional space, the largest dimension brane would be a 9-brane. The space "surrounding" a brane has come to be called the *bulk*. The bulk is effectively the hyperspace "volume" in which the brane is immersed. An example would again be a sheet of paper (or the two-dimensional surface of any ordinary object) in our normal three-dimensional space. In that case, the sheet of paper would represent the brane and the three-dimensional space above, below and around it would be the bulk in which it resides. From the notion of strings, branes, and bulk, came a new view of the hyperspace that may envelop our Universe.

Recall from Section 3 the discussion of four-dimensional hyperspace, the space into which three-dimensional curved space might curve. Physicists did not merely ignore such a possibility. There was a very basic reason why physicists rejected the notion that such a hyperspace existed and why they insisted, in the development of string theory, that any higher dimensions must be tightly wrapped. The reasoning would have made sense to Newton.

In our common experience, the brightness of a light (the detected intensity of a distant supernova as discussed in Chapter 12), the electrical force due to a single electrical charge, or the effect of a star's gravity on an orbiting planet, all decrease like one over the distance squared. There is a very basic reason for that, and it is deeply connected with the dimensionality of our perceptions. For any of these three examples (for weak, Newtonian gravity and light that shines equally in all directions, unlike gamma-ray bursts, Chapter 11), the effect of the light, the electrical charge, or the gravity spreads out through larger volumes of space as one gets more distant from the source. Specifically, the effect is spread over a larger and larger area at greater distance and that results in a dilution of the apparent brightness or electrical or gravitational "force." The dilution factor is precisely the area through which the influence must flood at a given distance. If the area is bigger, most of the influence is "wasted" in other directions from the direction where the detection or measurement occurs. The area is just $4\pi D^2$ where D is the distance of the observer or detector from the source of the light, or the electrical force, or the gravity. The effect at a distance is thus diluted by a factor of one over the area spanned at that distance and this, in turn, means one over the distance squared. The key point here is that the area goes like the distance squared only in a three dimensional space where volumes scale as the size or distance cubed. The "2" that appears in the inverse distance squared law is exactly and precisely a factor of 1 less than the full dimensionality of the space, namely 3.

We can, in principle, extend this argument to hypothetical higher dimensions. Suppose we consider the possibility of a true, large, extended fourth spatial dimension, as some people did in the late 19th century. Setting aside for now the issue of how light or electrical force might penetrate that void, let's focus on gravity. Gravity is an entity of space. Gravity curves space. Gravity can send ripples though space. If there is an extended fourth spatial dimension, gravity ought to be able to go there. With a fourth dimension, however, "volumes" scale as length raised to the fourth power and "areas" scale like one power less, namely as length or size or distance raised to the third power; exactly and precisely a factor of 1 less than the full dimensionality of the space, namely 4.

If this were the case, then, physicists argued, the existence of an extended fourth spatial dimension would require that the strength of gravity would fall off like one over the distance *cubed*. Even Newton knew that was wrong! Planetary orbits would be completely bonkers and could not even exist if gravity worked that way. The best empirical attempts to measure the strength of gravity show that it does decrease like one over the distance squared.

The implication was, it was long thought, that if there were a fourth, or higher, spatial dimension, it must be tightly wrapped up. To the extent that gravity tried to "go" into this higher dimensional space, there would be very little "volume" or "surface" to dilute it, and so the inverse distance squared law would continue to work in the three-dimensional space of our perceptions, just as we observe it to do.

Various models of this wrapped up space have been considered. One that seemed particularly amenable to the needs of physics and string theory was the six-dimensional Calabi-Yau space. The idea was that at each and every point in our three-dimensional space there were six other mutually perpendicular directions, each bending around in a tightly curved, complex, but systematic way to end up at exactly the same beginning point in three-dimensional space.

That perception that any higher dimensional spaces must be tightly wrapped changed dramatically in 1999. Lisa Randall, now at Harvard, and Raman Sundrum, now at Johns Hopkins, realized that there was a technical flaw in this argument. The tacit assumption had been made that gravity must flood into a large fourth dimension with the same ease that it penetrates the three dimensions of our perceptions. Randall and Sundrum concluded that while that could be true, it was not necessarily true. Within a reasonable mathematical framework, there could be a large four-dimensional hyperspace and gravity would still go there only a little; there would be little effective "area" associated with this space, and gravity would still decrease very nearly as one over the distance squared. This idea opened the floodgates.

Within the framework that Randall and Sundrum revealed, our three-dimensional Universe would be a 3-brane immersed in this four-dimensional bulk. The bulk would represent a real, large (infinite) four-dimensional hyperspace in which our three-dimensional Universe is embedded. With this new vision, a number of deep issues of physics, quantum theory, gravity, and string theory fell into place.

In this picture, the ordinary forces - electromagnetism, nuclear forces - correspond to "open" strings that are not closed loops, but have open ends. These ends are not free to wiggle about, however; they must be anchored to a brane. In this case, the brane is the 3-brane of our Universe. This leads to an insight into why we cannot "see" higher dimensions. We "see" by receiving photons of electromagnetic radiation. In this view, photons are represented by certain vibrations of strings that themselves are locked onto the brane. The string cannot leave the 3-brane, the photons cannot leave the 3-brane, and so we cannot receive photons from, or send photons to, the bulk. It may also still very well be true that yet other higher dimensions are tightly wrapped up, so there is very little "there" to perceive even if photons could get there, which they cannot.

Even in this framework, gravity remains a different beast. The strings representing gravity, quanta of gravitational exchange "particles" called gravitons, are "closed" loops of strings. They are not attached to branes, and they can leave the brane to pervade the bulk. As for the pool-ball crisis of Chapter 13, an analogy is again the game of pool. Under normal circumstances the balls roll around on the table, confined to the two-dimensional flat plane. In this case, however, there is something that is *never* confined to the flat plane, and that is the *sound* of the pool balls as they click together. The sound pervades the room, an intimate and intrinsic characteristic of the game. In our world, the electroweak force and the strong nuclear force (presumably all part of one grand unified force, Chapter 1) are represented by strings that cannot leave the brane, like the pool balls restricted to the green felt. Gravity carried by closed strings can leak out into the bulk as the sound of clicking pool balls can be heard throughout the bar. In the bar, the sound weakens as one over the distance squared, but, as Randall and Sundrum showed, gravity, while not completely restricted to our 3-brane, does not penetrate far into the bulk, so it also weakens very nearly like one over the distance squared even with the hypothesized immense bulk "surrounding" us.

Theoretical physicists and cosmologists are now on a rampage to explore all the implication of this amazing new intellectual vista. The models now flooding the literature are called *brane-worlds*. They are all built around the idea that our Universe is a 3-brane "floating" in this four-dimensional bulk. Virtually all the current models regard the other six dimensions of string theory's ten dimensional space to be "wrapped up," a Calibi-Yau space or some version of that. Whether having three "normal," one large hyperspace bulk, and all the rest of the six higher dimensions wrapped up is merely the simplest extension of the Randall/Sundrum ideas or whether this configuration is somehow required by physics and mathematics is not completely clear. Virtually all the current work in this area assumes only one large extra dimension, although it is conceivable that there could be more than one of these large extra dimensions and correspondingly less wrapped-up dimensions.

With the notion that our Universe is a 3-brane in an immensely larger bulk, one is invited to consider other complete, even infinite, three-dimensional universes immersed in this bulk, but "elsewhere" in four-dimensional hyperspace. One early theory manifesting these ideas was the Ekpyrotic Theory (from the Greek *ekpyrosis*, or conflagration) developed by Paul Steinhardt of Princeton and his colleagues. In this theory, there would be two 3-branes floating in the bulk. These 3-branes could collide, with every three-dimensional point in one universe "hitting" a three-dimensional point in the other universe, as one can picture bringing two sheets of paper (2-branes) together in a room (the 3D bulk) so that each point of one sheet contacts a corresponding point on the other sheet. In the Ekyprotic Theory, this collision would release immense energy and cause the two universes to spring apart in the bulk with an attendant expansion of their three-dimensional space. The result would be, from the perspective within the 3-brane, an expansion from a very hot, dense state, a big bang. In this case, however, the big bang would not start from Einstein's singularity, but from this collision of 3-branes in a four-dimensional hyperspace bulk. This theory has not generally gained broad support, but it did suggest that the gravitational waves generated in the collision would be distinctly different than those in the standard big bang, so there is even some prospect for a test.

Is this bulk the place where our three-dimensional space curves when it curves? That link is invited, but is not necessitated in the current framework. Is the bulk the first hint of the hyperspace travel of *Star Trek* and *Star Wars* with only engineering details to be worked out? That also is extremely premature; but still physics, not science fiction, has given this peek behind the hyperspace curtain.

One of the lessons of science is that Nature follows the tenets of mathematics; sometimes there is no correspondence between an abstract aspect of mathematics and physical reality, but at other times pure mathematics has pointed the way to deep new understanding of Nature. String theory has been so rich and challenging, that it has opened new vistas for mathematical research as well as for physics. The hard and critical question for now is whether any of this is real or just mathematical fantasy. The key will be to put these ideas to observational or experimental test.

Physicists are straining to devise such tests. One question is whether gravity does, indeed, behave a little differently than one over the distance squared. Is it possible that gravity scales like $1/D^{2.001}$ rather than $1/D^2$? Such a difference might give a hint that some higher dimension or dimensions exists. Experiments are underway now to try to measure any minute departures from the inverse distance squared behavior of gravity. Another possibility currently beyond the technical horizon, is the question of whether black holes might behave slightly differently than Einsteinian gravity right down near the event horizon. Perhaps someday that behavior could be measured with X-rays that emerge from the inner edges of accretion disks. People are exploring the idea that the Dark Energy of Chapter 12 is some manifestation of a "nearby" three-dimensional universe, another 3-brane, only a little distance from us in the four-dimensional bulk.

Black holes remain at the center of this quest. Black holes may behave differently in the presence of the bulk; in particular, small, primordial, black holes might extend into the bulk, changing their effective area and altering their Hawking temperature (Chapter 9, Section 6). Recall that while radiating black holes will emit photons most easily (no rest mass to produce), they also can, in principle, emit any kind of particle, including anti-protons. Experiments to measure the abundance of anti-protons in cosmic rays have revealed evidence for a source of anti-protons other than normal cosmic ray interactions. Katsuhiko Sato and his colleagues in Japan have explored the notion that these excess anti-protons arise in primordial black holes and that the existence of the anti-protons hints at a large extra dimension. I would not take this to the bank, but this sort of work illustrates the range of exploration going into this topic today.

The take away message is that hyperspace might be real. There will clearly be an immense amount of work on these topics in the near future. Stay tuned!

6. A Holographic Universe?

Section 4 referred to information that black holes do or do not have. That seems like an abstract and obscure topic, but thinking about it is at the frontier of modern physics. There are two key ideas that are familiar to anyone with a computer and a credit card. The information stored in a computer and whipped around the world on the Internet is digitized. It comes in patterns of bits, zeros and ones. The amount of information stored in a computer memory is then related to the number of bits that can be registered in its memory or on its hard drive. That amount of information is amazingly large in this day and age, and is destined to get larger, but it is finite. We have also learned to store information in holograms. The basic idea is to register information in the interference pattern of two lasers and to imprint that interference pattern, rather than a literal image, on a film surface. When another laser is shone upon that surface, a three-dimensional representation can be restored that seems to have depth and volume. The little "hologram" on your credit card is a basic version of this, giving at least some sense of three-dimensional depth, although you cannot walk around your credit card and see the image from all sides as you can a true reconstructed hologram. You can put these two ideas together and wonder whether there is a limit to the amount of bits one can store in a hologram, and hence the total information. If you follow that path, and recall that there is a smallest "size" to things, the Planck length, or perhaps the string length, then you find yourself contemplating deep issues of not just quantum gravity, but the nature of reality.

In 1993, Gerardus 't Hooft, who shared the 1999 Nobel Prize in physics for fundamental work on particle physics, proposed what he called the *holographic principle*. Leonard Susskind of Stanford and many other physicists have furthered the idea. The notion is that all the information about everything within a volume can be represented by a theory of the information on the surface of that volume and that each Planck area (the square of the Planck length; setting aside for the moment that the string length is larger than the Planck length) contains one "bit" of information. 't Hooft calls this "Nature's bookkeeping system."

The roots of this thinking go back to the nature of black holes. Black holes have a size, an event horizon, that increases with the mass. According to Hawking, they also have a temperature that decreases with the mass (Chapter 9, Section 6) and an *entropy* that increases with the mass. In a casual sense, entropy is a measure of the disorganization of a system. In the "game" of 52-card pickup, a deck of cards flung in the air to land scattered around a room is more disorganized than the original pack: after flinging, the cards have more entropy. Disorganization would seem to imply less information, but, in fact, just the opposite is the case. If you flipped a coin 100 times and it came up heads every time, you would conclude the coin was rigged and could predict with essentially 100% accuracy that the 101st flip would produce a head. There would be no new information content in that 101st flip. A completely organized set of events, like all heads, or a string of all 1s, or a string of all 0s, has no entropy and no information content. An honest, random coin, would provide a new bit of information, whether you won or lost a bet on the outcome, for instance, with every flip. The randomness also represents a high entropy; each coin flip has one bit of entropy, one bit of information. According to *information theory*, entropy is a measure of information. Hawking also established that the entropy, and hence the information content, of a black hole increases with its mass in direct proportion to the area of the event horizon. It was the ability of string theory to provide an identical determination of the information content of a black hole that gave an impetus to string theory as a theory of gravity (Section 4).

Think, then, of a spherical volume to keep things simple. A small mass black hole with little entropy and hence little information can fit in that volume. There is a maximum mass, and hence size, and hence entropy and information, that will fit in that volume and that is when the event horizon of a black hole just fills the chosen volume. For any smaller black hole, the information content is less. This means that the maximum entropy and information of a region is related not to its volume, as one might think, but to the area surrounding that volume. This suggests that the information about the volume is somehow related to the area surrounding that volume, not to the volume, *per se*. 't Hooft followed this line of logic to conjecture that the information about any volume, not just that containing a black hole, is related to the surface and that the surface, not what goes on within the volume, is the true reality. The little image on my credit card is really a flat surface with an imprinted interferogram. The idea that there is a little bird with some depth on my platinum card is an illusion. Could it be that all the information about the nature of the Universe is actually enscribed in some fashion on its surface and all that we perceive as three-dimensional reality is an "illusion?" These ideas currently have two manifestations, one in observational cosmology and one in the structure and meaning of string theory.

Craig Hogan of the University of Washington has considered some implications of holographic ideas in the context of the nature of the Big Bang. Hogan notes that the current theory of cosmology is that Universe exploded from some hot dense state with matter/energy nearly uniform, but subject to wrinkles associated with the intrinsic quantum uncertainty of that early dense state. As the Universe expanded, those wrinkles were frozen in by the huge expansion of the inflation era; they remained the seeds of all the structure that ultimately formed in our visible Universe. Slightly overdense regions contracted under gravity to become denser and to attract surrounding matter, leaving irregularities in the temperature of the cosmic background radiation (Chapter 12, Section 5) and ultimately leading to the galaxies that litter deep *Hubble Space Telescope* images. Each patch of hotter or colder background radiation measured by the WMAP satellite (Chapter 12, Section 5) originated from a single quantum fluctuation. Hogan marvels that each such patch is at once the largest (in the current epoch) and the smallest (at the moment of the Big Bang) single entity we can image. Hogan notes that in "classical" quantum theory which assumes a continuous underlying space-time, there is no lower limit to the extent of the original perturbations, but there is in the context of holographic theory. Because no "bit" of universal information can be smaller than a Planck area, each quantum fluctuation contains a limited amount of information. An analogy, Hogan points out, is a digital photo, that looks pixilated under high resolution. Perhaps, Hogan speculates, the space-time of the Universe is fundamentally pixilated. Hogan estimates that the total amount of information that can be tiled on the surface that surrounded the causally-connected volume of the inflating Universe was remarkably finite, only about 10 Gigabits. You could store that amount of information on your personal computer! This is a quantum gravity notion; the information implied by standard quantum theory and standard gravity, Einstein's theory, considered separately would be tremendously greater, essentially infinite. From the holographic point of view, Hogan has estimated that the total number of bits in a given quantum fluctuation that grew to become a galaxy is less than a million and that future maps of the temperature fluctuations of the cosmic background radiation might have the resolution to detect the fundamental pixilation of quantum gravity space time. From such an observation might come fundamental understanding of how space and time form from conditions where space and time as we know them do not exist. That is a grand vision.

The other application of the holographic principle in physics operates in the new world of strings, branes, and the bulk. The key ideas were presented by Juan Maldecena, now of the Institute for Advanced Study, in the late 1990's. The ideas represented a conceptual breakthrough yielding new insights into both quantum gravity and the standard model of particle physics. There is a mapping, an equivalence, of the theory of quantum gravity, string theory, in the bulk and the theory of ordinary physics on the brane. The two theories that sound so different can be mathematically identical. To make this work the nature of the "bulk" must have four ordinary space dimensions plus time and be a so-called *anti-de Sitter space*, a space with an effective negative cosmological constant. Whether this mathematically-defined space has anything to do with the implicit 4D hyperspace where worm holes go when they go is not clear. Anti-de Sitter space does not correspond to the space we live in, but it is mathematically more tractable. In certain mathematical circumstances, the boundary of this anti-de Sitter space is a flat space-time of three ordinary dimensions plus time; something like our observed Universe.

Maldecena found that if one describes the physics on this boundary, our brane, in terms of certain classes of so-called supersymmetry theories of ordinary particles and forces, then the theory of gravity in the anti-de Sitter space bulk and the theory of physics on the surface brane are mathematically equivalent. In this rather subtle and sophisticated sense, the theory of physics on the brane, everything we know of physics in our 3D plus time universe, is a "hologram" of the physics of gravity in the higher-dimensional bulk. We, everything we know, *are* the "shadow."

If this is the way physics works, all the physics on Earth, from atoms to you, could be contained on a surface around the Earth. All the physics in the Universe could be contained in the surface of the Universe, as if all the information that constitutes "you" could be enscribed in your shadow. In the context of M-theory, branes and the bulk, we are the 3D shadow of the 4D bulk. How freaky is that?

There are also theories of the paranormal that label themselves as part of the "holographic universe," so if you do a web search on this, use some discrimination.

7. Coda

This is heady stuff. It is amazing that these ideas have emerged, not from science fiction, but from hard-nosed physicists wrestling to make sense of the Universe of our observations. Examining these ideas for self-consistency will yield progress, and that enterprise will go forward with great energy. The real solution, or at least the one we can contemplate today, is to develop the theory of quantum gravity, the theory of everything. Today the best bet for that appears to be string theory, M theory. So one can ask, what does string theory say about the quantum foam? Quantum foam was just a name, a place holder, until some physics came along. What exactly does string theory say about the conditions at the Planck scale? Does string theory allow new universes to be born from the conditions predicted by string theory for "not time" and "not space" at the center of a black hole constructed from strings?

Other, more speculative questions also arise. What are these higher dimensions that are forced on the string theorists by mathematical self-consistency? Do they simply dictate the properties of particles that appear in the three-dimensional Universe of our space-time, or can they be manipulated in some way? Does string theory allow worm holes and time machines? Does it prevent them?

While string theory remains the focus of intense effort, one can already glean hints that, as it stands today, it is not necessarily the theory of everything. As tantalizing and intellectually productive as it has been to study the vibrations of strings and branes in their higher dimensional spaces, one has to ask: whence those higher dimensional spaces; what of time? Einstein taught us to abandon pre-existing space, to consider space as a dynamical entity. The space in which string and branes vibrate is, however, just "there" and time is, mathematically, the same as we treat it in "normal" physics and in our everyday experience. As John A. Wheeler also said in yet another poetic summary, "time is what keeps everything from happening all at once." This is not fully satisfactory. A true theory of quantum gravity should have both space and time emerge from some aspect of the theory as emergent properties, not aspects that are assumed *ad hoc*. On a less fundamental, but still sobering, level, physicists have been able to categorize string theories in the framework of M theory. They estimate that there may be 10^{500} different string theories constituting what Leonard Susskind has called a *string landscape* in which only some might describe a Universe we could know and love. That will take a while to sort out!

Papers exploring string theory, brane worlds, and the holographic principle are rampant. Some discuss the impact of these ideas on the "real world." It is somewhat old fashioned, but my guess is that even with a theory of everything under discussion we are not about to see the end of physics.