INTRODUCTION

by Brian Greene

IN THE course of a single decade, Albert Einstein discovered special and then general relativity, and in so doing overturned the conceptions of space and time that our species had held for thousands of years. Even so, many of us, at least intuitively, still adhere to those disproved conceptions. We imagine space as an inert stage on which the events of the cosmos take place. We imagine time being recorded on a universal clock, ticking away in a identical manner here, and on Mars, and in the Andromeda galaxy, and everywhere else, regardless of differing environments and physical contexts. For most of us, the unchanging eternality of space and time is among the most basic features of existence. But to hold such beliefs is to hold to a pre-Einsteinian vision that is not only theoretically untenable but, as attested to by numerous experiments, demonstrably wrong.

As a professional physicist, it is easy to become inured to relativity. Whereas the equations of relativity were once startling statements fashioned within the language of mathematics, physicists have now written relativity into the very mathematical grammar of fundamental physics. Within this framework, properly formulated mathematical equations automatically take full account of relativity, and so by mastering a few mathematical rules one becomes technically fluent in Einstein's discoveries. Nevertheless, even though relativity has been systematized mathematically, the vast majority of physicists would say that they still don't "feel relativity in their bones." I, for one, know how easy it is to slip into familiar Newtonian thinking in which space and time are incorrectly envisioned as separate, independent, and unchanging. But I can also attest to the undiminished feeling of awe I experience each time I pay sufficient attention to details hidden within mathematics streamlined for relativistic economy, and come face to face with the true *meaning* of relativity. Space and time form the very arena of reality. The seismic shift in this arena caused by relativity is nothing short of an upheaval in our basic conception of reality.

So, what does relativity say?

In 1905, Einstein published what we now call the special theory of relativity in the German *Annalen der Physik*, with the unassuming title "On the Electrodynamics of Moving Bodies." The paper grew out of an intellectual struggle he'd been engaged with since the age of sixteen regarding the mathematical description of light's motion, which was discovered by James Clerk Maxwell in the 1860s. Briefly put, unlike what one would expect based on Newton's equations (and based on common sense), Maxwell's equations (when properly interpreted) showed that whether you run toward or away from an oncoming beam of light, its speed of approach would appear exactly as it would were you standing still—not one iota faster or slower. This apparent constancy of light's speed engaged the sharpest scientific minds of the late nineteenth and early twentieth centuries because, even though it emerged from the equations, and even though it was borne out by ever more precise experimental measurements, it just seemed to make no sense. How could the speed of light not appear faster if you run toward an approaching light beam? How could the speed of light not appear slower if you run away from it? Here's where Einstein changed everything. Speed is a measure of distance traveled divided by duration of the journey, and so is intimately bound up with the concepts of space and time. And, Einstein claimed, space and time—in contrast to Newton's intuitively sensible description—are *not* fixed and unchanging. Instead, they're fluid and malleable. Space and time, he argued, adjust themselves to keep something else—the speed of light—fixed and eternal, regardless of the motion executed by the light's source or someone observing it.

In practice, this means that if you measure the length of an object—a car, a plane, a whatever—that's in motion, the result you'll find is less than if the object were stationary. And if you observe a clock that is in motion, you'll find that its rate of ticking is less than an identical clock that's stationary. Roughly speaking, spatial separations shrink and time slows for an object in motion. These spectacular features of space and time remained fully hidden until 1905 because although the effects are real, they're miniscule except when the speeds involved approach that of light. It took the genius of Einstein to see beyond everyday perception and reveal the true character of space and time.

The discovery of general relativity grew out of special relativity, but took Einstein ten more years to complete. Once again, a major impetus for Einstein was a blatant conflict he found when closely examining some of Newton's earlier insights. In this case, the focal point was the force of gravity and, in particular, how quickly gravity can exert its influence. According to special relativity, nothing—no object, no signal, no information—can travel from one point in the universe to another at a speed greater than the speed of light. Yet, as Einstein realized, according to Newton's universal law of gravity, a massive body like the sun exerts a gravitational pull on other massive bodies, such as the planets, which is instantaneous. According to Newton, were the sun to somehow change its mass or its position, we would immediately become aware of the change because the sun's gravitational pull on the earth would immediately change. And an immediate change is one that far exceeds the speed limit set by light. Einstein's motivation to seek a new theory of gravity thus came not from a conflict between Newton's equations and experimental data, but from a conflict between Newton's description of gravity and Einstein's own special relativity. To a theorist like Einstein, theoretical inconsistency can be as important as dissonance derived from experimental observations.

The resolution of this conflict was not short in coming. In 1912, after some five years of contemplation, Einstein wrote to his friend Arnold Sommerfeld that "compared with understanding gravity, the special theory of relativity was mere child's play." Nevertheless, Einstein resolutely kept at it. His line of attack was to understand the mechanism by which gravity operates—after all, how *does* the sun, some 93 million miles distant, influence the earth's motion? The sun never touches the earth, so how is the force we commonly call gravity communicated over such vast distances of largely empty space? This is a mystery Newton himself was well aware of, noting in his *Principia* that he had been unable to figure out the means by which gravitational influence is transmitted—and that, henceforth, he was leaving that problem to the "consideration of the reader." No doubt, many a reader read that challenge and read on, but Einstein was different. He was willing to take on this two-hundred-year-old challenge in the hopes that if he understood how gravity really works, he might resolve the conflict between Newton's description of gravity and the speed limit set by special relativity.

Einstein's hope proved well founded. By 1915, Einstein came up with the general theory of relativity in which he identified the very fabric of spacetime as the medium that transmits the force of gravity. Einstein argued that much as a large rock sitting on a trampoline causes the canvas to curve—and in that way affects the motion of a marble rolling on the trampoline's surface—a large astrophysical body (the sun, the earth, a neutron star) immersed within spacetime causes the fabric of the *cosmos* to curve—and in that way affects the motion of other bodies moving nearby. As the earth orbits the sun, according to general relativity, it rolls along a valley in the warped spacetime fabric caused by the sun's presence.

This is a stunning proposal. With special relativity, Einstein had shown that the cosmic scaffolding could not be dismantled into rigid, universally agreed upon struts of space and time. Now, with general relativity, he argued that the shape of the cosmic scaffolding *responds* to the presence of matter or energy—and, in turn, the shape of spacetime affects how other objects move. Space and time, according to Einstein, are participants in the evolution of the universe.

A proposal that so dramatically challenges previous conceptions requires dramatic experimental support. Through its underlying mathematical formulation, which owes much to the nineteenth-century geometrical insights of Bernhard Reimann, general relativity makes detailed predictions for how objects move under the force of gravity (i.e., how the curvature of spacetime affects the motion of objects). When these predictions and those of Newton's theory of gravity are compared with experimental observations, Einstein's are always at least a little more accurate, vindicating general relativity's claim to supplant Newton's theory. And of prime importance, when Einstein calculated the speed by which warps and curves travel through space—the speed of gravity in his new formulation—the answer he came to was thoroughly gratifying. Unlike in Newton's theory in which gravity supposedly exerts its force instantaneously over any distance, in general relativity gravity travels at exactly the *speed of light*, fully in keeping with the central dictum of the special theory of relativity that nothing can exceed light speed.

Einstein published the general theory of relativity in 1916, arguably the most important year in our understanding of space and time. Within general relativity, the special theory was seen to be a special case—the case in which one considers space and time in the absence of a background distribution of matter and energy, i.e., space and time in the absence of gravity. Adding gravity, Einstein discovered, breathes a wholly unexpected fluidity and flexibility into spacetime.

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In the century since relativity's discovery, Einstein's breakthroughs have been understood more deeply and their implications for the cosmos appreciated more fully. Here are five highlights.

First, much has happened on the experimental front. The initial experimental tests of relativity were somewhat indirect. General relativity's prediction for the bending of starlight passing by the sun, which was confirmed by two teams of astronomers during the solar eclipse of 1919, is rightly heralded as the observation that convinced the world that Einstein's new theory was correct. However, with relativity's yielding bizarre predictions such as motion and gravity being able to affect the rate of time's passage, one can't help longing to see direct verification. The observational fact that short-lived muon particles produced in the upper atmosphere by cosmic ray collisions are able to survive the long journey to Earth's surface (by moving quickly, the muons' internal clocks slow relative to ours, and hence the moving muons live longer than their stationary counterparts, allowing them to complete the journey to the surface of the earth) is a step closer to direct confirmation, but the disconnect between a muon's millionth-of-a-second lifespan and time as experienced in everyday life can still make this confirmation of relativity seem remote and theoretical. In 1971, an experiment carried out by Joseph Haefle and Richard Keating went a long way toward bridging this gap. They strapped a clock (albeit an atomic clock) into a passenger seat in a Pan Am jet, and closely monitored it as the plane flew around the earth. Because the plane was in motion, and also because it experienced a slightly weaker gravitational field due to its increased distance from Earth's center, relativity predicts that by the end of the journey, the onboard clock should differ from Earthbound stationary clocks by a few billionths of a second. Indeed, this is just what the experimenters found, thus providing a direct confirmation of relativity's conclusion that the passage of time—real time, the kind of time measured by clocks—is affected by motion and by gravity.

Second, and relatedly, new experiments are currently underway to test some of the more subtle implications of relativity. Gravity Probe B, a satellite hovering hundreds of miles above Earth's surface, is trying to give the first direct confirmation of relativity's claim that not only does a massive body warp the spacetime fabric, but when it turns it drags spacetime into a whirlpool-like spin. By pointing the most accurate gyroscopes ever fabricated at a chosen distant star, the experimenters hope to observe relativity's prediction that, over the course of a year, the earth's rotation will drag spacetime enough to cause the onboard gyroscopes' axes to turn by about a hundred-thousandth of a degree. Measuring such a tiny turning angle is a significant challenge, but after some forty years of development, the experimenters believe they have the technological fidelity to do so. Another difficult but tremendously exciting experiment is the search for gravitational waves. According to general relativity, when a massive object moves it can cause the fabric of space to undulate, somewhat like the surface of a pond into which a pebble has been tossed. Were such a wave of undulating space to roll by Earth, all material objects would be stretched one way, and then the other, as the wave of distorted space passed. The challenge in detecting these gravitational waves is that those produced by ordinary phenomena (dropping a cup, two cars colliding, setting off an explosive, etc.) are too tiny to be seen, while those produced by cataclysmic astrophysical events (stars going supernovae, black holes colliding, etc.) are larger but their strength diminishes rapidly as they spread during their long journey to Earth. Scientists have used general relativity to calculate that gravitational waves produced by the most violent of astrophysical events, at typical astronomical distances, would stretch a one-meter-long rod here on Earth by less than a millionth of a billionth of a centimeter, making detection enormously difficult. Nevertheless, in the United States two gravitational wave detectors are now in operation (and around the world, a number of others are planned or in operation) which, at least in principle, have the capacity to measure such a tiny stretching of matter. This experiment is particularly important because successfully detecting a gravitational wave would be more than just confirming a remaining prediction of the general theory of relativity. Because of the intrinsic weakness of the gravitational force, gravitational waves can penetrate realms that are opaque to visible light and electromagnetic radiation more generally. Thus, the detection of gravitational waves could very well open up a new field of gravitational wave–based astronomy in which the cosmos is studied via gravitational—not electromagnetic—radiation. Some physicists are even hopeful that gravitational waves may one day allow us to peer back to the big bang itself.

A third development stems from the work of Karl Schwarzchild, a Russian physicist, who shortly after Einstein published general relativity solved Einstein's equations to puzzling effect. Schwarzchild found that if enough matter were crushed into a small enough volume (e.g., were the entire earth crushed into a one-inch diameter ball), the resulting warpage of spacetime would become so severe that nothing—not even light—would be able to escape the resulting powerful gravitational pull. Einstein was surprised by this solution, and felt that the extreme conditions Schwarzchild was envisioning would never be attained in the real world. But today, observations using powerful Earth- and space-based telescopes have revealed regions suffused with intense gravitational fields in which downward-spiraling matter heats up and gives off a spectrum of x-rays that is precisely in keeping with those expected from matter just before heading over the edge of one of Schwarzchild's "dark stars" (later christened "black holes" by the eminent physicist John Wheeler). Such data leaves little doubt that black holes are real, and perhaps even ubiquitous. Astronomers now believe that many galaxies have a giant black hole sitting at their center. For example, there is observational evidence that even our own Milky Way galaxy, at its core, has a black hole weighing more than *three million* times as much as the sun. An important problem, which has resisted resolution for more than twenty-five years, is to determine what happens in the deep interior of a black hole. General relativity seems to suggest that time comes to an end at the black hole's center, but as yet no one has figured out what that really means or whether quantum mechanical considerations might justify the conclusion. Coming to grips with this problem will likely give deep insights into the fundamental nature of space and time.

Fourth, gravity is the dominant force when considering the physics of large agglomerations of matter such as stars and galaxies. Hence, the grandest possible arena for applying general relativity is the largest such agglomeration: the entirety of the universe itself. Cosmology is the name given to the study of the origin and evolution of the universe and is a field, not surprisingly, that general relativity has revolutionized. Before 1916, there had been no shortage of cosmologies proposed by various of the world's theologians and natural philosophers. But with the discovery of general relativity, cosmology entered the realm of rigorous science. In fact, within just a couple of years, Einstein realized that the cosmology implied by general relativity was thoroughly unexpected. The fabric of space, according to Einstein's equations, cannot be static: the universe can expand or contract, but it can't stay put. Even Einstein, maverick thinker that he was, found this conclusion too outlandish to accept. "Clearly" the universe, on the largest of scales, is fixed and unchanging. Thus, in 1917, to remedy this problematic implication of general relativity, Einstein modified his equations by introducing the so-called cosmological constant—a uniform energy throughout space that could exert an outward push and hence balance the inward pull of gravity, yielding a static cosmos. Some of Einstein's contemporaries—most notably, the Belgian priest Georges Lemaitre and the Russian mathematician and meteorologist Alexander Friedmann—were less certain that the universe really was unchanging, and so during the 1920s they investigated a number of possible cosmologies emerging from the equations of general relativity, both with and without the cosmological constant. All of these theoretical studies came to a head in the watershed year for cosmology—1929. In that year, Edwin Hubble, using the 100-inch telescope at Mount Wilson Observatory, concluded that distant galaxies are rushing away from us with a speed proportional to their distance, in perfect consonance with the general relativistic cosmologies—without a cosmological constant—that Lemaitre and Friedmann had developed mathematically. The fabric of space *is* stretching with time. Had Einstein been willing to accept the implication of his own general theory of relativity at face value, he would have *pre-*

dicted the expansion of the universe a dozen years before it was observed. Today, cosmology continues to be one of the most active areas of theoretical and observational research, with refined versions of Lemaitre's and Friedmann's works being developed worldwide, all founded on the equations of general relativity. Such research has led to what many physicists consider the most significant surprise of the last decade, which is the fifth of our highlights.

With Hubble's observations, and much follow-up research that confirmed his conclusions, the community of physicists became convinced that the universe is expanding. But because gravity is an attractive force—a force that pulls things together—most everyone was also convinced that the pull of gravity was causing the rate of expansion to slow with time. An interesting research problem, then, was to determine how quickly the expansion was slowing, as this would give insight into how much matter the universe contains (more matter implies greater gravitational pull and hence larger slow-down rate). In the mid 1990s, two teams set out to make this measurement: Saul Perlmutter and his collaborators in the Supernova Cosmology Project, and Brian Schmidt and his collaborators in the High-Z Supernova Search program. By the late 1990s, both groups reached the same astonishing conclusion: the expansion of space is not slowing down. Instead, their observations of distant supernovae showed that for the last seven billion years, the expansion of space has been *speeding up*. How could this be? This is a question researchers are still struggling to answer, but one favored explanation takes us full circle, right back to 1917. If the universe were to have a cosmological constant of just the right value, then up until about seven billion years ago its outward push would have been overshadowed by the more powerful inward pull of matter's ordinary gravitational attraction. Then, as the universe expanded and matter got spread more thinly throughout space, gravitational attraction would steadily drop and at the seven-billion-year mark the repulsive push of the cosmological constant would become dominant. From that point on, the rate of expansion of space would increase—the expansion of space would accelerate, in agreement with the recent observations.

In short, Einstein's "blunder" of 1917, his introduction of an outward-pushing cosmological constant, may actually be correct. If these results hold up, Einstein would thus have gotten the value of the cosmological constant wrong (since he wanted it to precisely balance the inward pull of gravity rather than become stronger), but the concept itself would be confirmed. To date, examination of the rate by which the expansion of space is increasing has led researchers to conclude that the cosmological constant accounts for about 70 percent of the energy of the entire universe—and so the *majority* of the universe's energy budget may well be stored in this still mysterious, invisible entity. Many researchers agree that understanding fully the nature of this invisible energy is one of the most important issues in physics and cosmology.

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After Einstein succeeded with special relativity in merging space and time into the unified whole of spacetime, and after he succeeded with general relativity in demonstrating that the force of gravity is nothing but the warping and curving of spacetime, he wondered whether he might go even further and bring the other force known at that time—the electromagnetic force—into the geometrical framework he had developed. It was a bold vision. Einstein imagined a single theory, perhaps expressed by a single principle or equation, which might describe all of nature's forces. For the last thirty years of his life, Einstein sought this so-called unified theory with unrelenting passion, and even though there were reports that he had succeeded (one of which was a cover story in the *New York Times*), every time he closely examined the results, Einstein concluded that he hadn't reached the goal. Nevertheless, these failures did not diminish his belief in unification. In fact, in 1955 as he lay dying in Princeton Hospital, he asked for a pad of paper on which he had been scribbling equations in the desperate hope that in his final moments the unified theory would come to him. It didn't.

For many years after Einstein died, it seemed like the dream of unification had died with him. By the late 1960s and early 1970s, however, this changed. Through the combined efforts of Sheldon Glashow, Steven Weinberg, and Abdus Salam, the weak nuclear force (a force Einstein was hardly aware of, but which is now understood to underlie radioactivity) and the electromagnetic force were unified into the electroweak force—a theory that was confirmed experimentally by the end of the 1970s. In 1974, Glashow, together with his colleague Howard Georgi, took the next step by developing a "grand unified theory," which merged the electroweak force and the strong nuclear force (the force now known to hold atomic nuclei together) into a single mathematical structure. Although their particular model has since been experimentally ruled out, many physicists believe that it is just a matter of time before some version of grand unification is confirmed. But even with these concrete steps toward Einstein's dream of unification, one force has been conspicuously left out. For decades, all attempts to incorporate gravity, the force closest to Einstein's heart, into a unified theory proved theoretically inconsistent.

The problem is that quantum mechanics, which underlies the description of nature's three nongravitational forces, proves to be fundamentally at odds with Einstein's description of gravity. The reason, briefly put, is that the Einsteinian image of space as a gently curving geometrical shape runs headlong into the core idea of quantum theory: the uncertainty principle. In 1927, Werner Heisenberg discovered that quantum mechanics entails an unavoidable uncertainty that limits how sharply various complementary physical features (such as a particle's position and its velocity) can be delineated. This uncertainty results in what physicists call "quantum fluctuations": particles, roughly speaking, unavoidably jitter this way and that as their positions and velocities fluctuate within the window set by quantum uncertainty. These particle fluctuations have been much studied experimentally, and Heisenberg's uncertainty principle has been confirmed to high precision. Where things get more troublesome, though, is when the uncertainty principle is applied not to ordinary particles but to the force of gravity. Since gravity, in Einstein's description, is nothing but the curvature of spacetime, quantum fluctuations in the gravitational force are fluctuations in the spacetime fabric itself. When physicists studied this incarnation of quantum uncertainty mathematically, they found that over small distance and time scales quantum gravitational fluctuations would become so severe that spacetime would not resemble the nice, gently curving geometry on which Einstein based general relativity. Instead, spacetime would resemble a frothing, boiling cauldron in which space violently heaved to and fro in a manner that caused Einstein's equations to break down.

For many years, researchers tried to resolve this incompatibility between general relativity and quantum mechanics, but it wasn't until the discovery and development of superstring theory in the 1970s and, most notably, in the 1980s that theorists found a viable direction to pursue. Superstring theory claims that the traditional conception that the fundamental particles of nature are points of vanishingly small size is wrong. In its place, the theory posits that the most fundamental entities making up matter are tiny one-dimensional filaments of energy that, if magnified sufficiently, would look like little vibrating strings. "Sufficiently" here means by a factor many billions of times more than we can achieve even with our most sophisticated instruments, and that's why, according to superstring theory, physicists have long thought that the elementary particles were dots.

Now, this change from point-particles to strings that are so small they look like points might not sound like it would accomplish much. But it does.

Superstring theory successfully merges general relativity and quantum mechanics. The full explanation for how this is accomplished is involved, but here's a rough way to understand it. By introducing strings as the fundamental ingredients, superstring theory takes the old idea of point-particles and spreads it out—stretches it out—into the new idea of tiny filaments. This spreading of points into filaments also implies that the microscopic structure of space is spread out relative to how it was envisioned (and how it was mathematically modeled in calculations) prior to superstring theory. When strings spread space at the microscopic level, the violent undulations that were the source of the theoretical conflict between quantum mechanics and general relativity, get stretched out and hence diluted. And, as detailed calculations attest, this dilution of the violent spacetime fluctuations is just enough to allow quantum mechanics and general relativity to merge into a mathematically consistent quantum theory of gravity.

Moreover, not only does superstring theory merge general relativity with quantum mechanics, but it also has the capacity to embrace—on an equal footing—the electromagnetic force, the weak force, and the strong force. Within superstring theory, each of these forces is simply associated with a different vibrational pattern of a string. And so, like a guitar chord composed of four different notes, the four forces of nature are united within the music of superstring theory. What's more, the same goes for all of matter as well. The electron, the quarks, the neutrinos, and all other particles are also described in superstring theory as strings undergoing different vibrational patterns. Thus, all matter and all forces are brought together under the same rubric of vibrating strings—and that's about as unified as a unified theory could be.

Finally, superstring theory requires that the fabric of the cosmos have more than three spatial dimensions. This may sound strange and surprising when first encountered, but it's an idea that pre-dates superstring theory and one that Einstein himself pursued for some time. Back in 1919, a German mathematician named Theodor Kaluza found that if he posited a fourth dimension of space and reformulated general relativity in this enlarged setting, the resulting set of equations contained those of Einstein's original formulation and—amazingly—also those of Maxwell's electrodynamics. A fourth dimension of space was therefore capable of bringing the equations of gravity and electromagnetism together. After a bit of hesitation, Einstein became an enthusiastic supporter of this approach to unifying these two forces, but after years of research (with important contributions by Oskar Klein) this so-called Kaluza-Klein approach to unification could not be made to work in detail (for example, it proved difficult to incorporate an electron with the known values for its mass and charge into this framework). In superstring theory, to the contrary, the Kaluza-Klein idea of extra dimensions *emerges* from the theory itself, and the problems that beset the original Kaluza-Klein attempt do not arise. What's more, the geometry of the extra dimensions—which are usually assumed to be very small in spatial extent to explain why we don't see them—has an impact on how strings vibrate (much as the geometry of a French horn affects the vibrational patterns of air streams traversing its interior, the geometry of the extra dimensions affects the vibrational patterns of strings) and hence on the physics we observe. This means that the geometry of spacetime may be bound up not only with the force of gravity, as Einstein found, but through the extra dimensions; the geometry of spacetime may also determine the masses and charges of elementary particles (these particle properties are determined by string vibrational patterns which in turn are influenced by the geometry of the extra dimensions). In short, superstring theory suggests that geometry may well explain why the universe is the way it is.

Were Einstein alive, I think there is much within superstring theory that he would find compelling and exciting. Superstring theory carries forward his quest for unification. It follows his philosophy, evidenced in general relativity, of relying heavily on geometrical ideas to describe the cosmos. And superstring theory shows how general relativity can be made compatible with quantum mechanics. Even so, Einstein would no doubt also view superstring theory with much skepticism. Shortly after they were proposed, special and general relativity could be subjected to rigorous testing, and so when these theories made outrageous claims, they had to be taken seriously because experiments had shown that the theories work. To the contrary, superstring theory does not yet have experimental support. Making two experimentally confirmed theories—general relativity and quantum mechanics—compatible is an important step. But no one will be convinced that superstring theory is right, that it is the unified theory Einstein sought but never found, until the theory is itself confirmed experimentally. With the increased power of the world's accelerators and ever more refined telescopes gathering data of unprecedented precision, such confirmation could happen within this century. If so, Einstein's theories of relativity would be seen as part of a much grander theoretical synthesis. If not, the world's physicists will no doubt carry on the search for unification down other avenues (some other approaches, such as loop quantum gravity, are already highly developed and being pursued vigorously). Einstein lit the torch of unification. Physicists that have and will continue to follow will do all they can to keep it burning.