Lawrence Krauss

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Further praise for *The Physics of Star Trek:*

'Always enlightening . . . this book is fun, and Mr Krauss has a nice touch with a tough subject . . . Krauss is smart, but speaks and writes the common tongue.'

JAMES GORMAN, *New York Times Book Review*

'Entertaining and fascinating.' *Manchester Evening News*

'A brilliant book'

STEVE FARRAR, *Cambridge Evening News*

'Highly recommended' M. j. SIMPSON, *SFX*

'Delightful. . . *The Physics of Star Trek* is an excellent guide to the *Star Trek* universe for an amateur scientist.'

JOSEPH SILK, *Times Higher*

"But I canna change the laws of physics, Captain!"

(Scotty, to Kirk, innumerable times)

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FOREWORD Stephen Hawking

I was very pleased that Data decided to call Newton, Einstein, and me for a game of poker aboard the *Enterprise.* Here was my chance to turn the tables on the two great men of gravity, particularly Einstein, who didn't believe in chance or in God playing dice. Unfortunately, I never collected my winnings because the game had to be abandoned on account of a red alert. I contacted Paramount studios afterward to cash in my chips, but they didn't know the exchange rate.

Science fiction like Star Trek is not only good fun but it also serves a serious purpose, that of expanding the human imagination. We may not yet be able to boldly go where no man (or woman) has gone before, but at least we can do it in the mind. We can explore how the human spirit might respond to future developments in science and we can speculate on what those developments might be. There is a two-way trade between science fiction and science. Science fiction suggests ideas that scientists incorporate into their theories, but sometimes science turns up notions that are stranger than any science fiction. Black holes are an example, greatly assisted by the inspired name that the physicist John Archibald Wheeler gave them. Had they continued with their original names of "frozen stars" or "gravitationally completely collapsed objects," there wouldn't have been half so much written about them.

One thing that Star Trek and other science fiction have focused attention on is travel faster than light. Indeed, it is absolutely essential to Star Trek's story line. If the *Enterprise* were restricted to flying just under the speed of light, it might seem to the crew that the round trip to the center of the galaxy took only a few years, but 80,000 years would have elapsed on Earth before the spaceship's return. So much for going back to see your family!

Fortunately, Einstein's general theory of relativity allows the possibility for a way around this difficulty: one might be able to warp spacetime and create a shortcut between the places one wanted to visit. Although there are problems of negative energy, it seems that such warping might be within our capabilities in the future. There has not been much serious scientific research along these lines, however, partly, I think, because it sounds too much like science fiction. One of the consequences of rapid interstellar travel would be that one could also travel back in time. Imagine the outcry about the waste of taxpayers' money if it were known that the National Science Foundation were supporting research on time travel. For this reason, scientists working in this field have to disguise their real interest by using technical terms like "closed timelike curves" that are code for time travel. Nevertheless, today's science fiction is often tomorrow's science fact. The physics that underlies Star Trek is surely worth investigating. To confine our attention to terrestrial matters would be to limit the human spirit.

PREFACE

Why the physics of Star Trek? Gene Roddenberry's creation is, after all, science fiction, not science fact. Many of the technical wonders in the series therefore inevitably rest on notions that may be ill defined or otherwise at odds with our current understanding of the universe. I did not want to write a book that ended up merely outlining where the Star Trek writers went wrong.

Yet I found that I could not get the idea of this book out of my head. I confess that it was really the transporter that seduced me. Thinking about the challenges that would have to be faced in devising such a fictional technology forces one to ponder topics ranging from computers and the information superhighway to particle physics, quantum mechanics, nuclear energy, telescope building, biological complexity, and even the possible existence of the human soul! Compound this with ideas such as warped space and time travel and the whole subject became irresistible.

I soon realized that what made this so fascinating to me was akin to what keeps drawing fans to Star Trek today, almost thirty years after the series first aired. This is, as the omnipotent Star Trek prankster Q put it, "charting the unknown possibilities of existence." And, as I am sure Q would have agreed, it is even good fun to imagine them.

As Stephen Hawking states in the foreword to this book, science fiction like Star Trek helps expand the human imagination. Indeed, exploring the infinite possibilities the future holds—including a world where humanity has overcome its myopic international and racial tensions and ventured out to explore the universe in peace—is part of the continuing wonder of Star Trek. And, as I see this as central to the continuing wonder of modern physics, it is these possibilities that I have chosen to concentrate on here.

Based on an informal survey I carried out while walking around my university campus the other day, the number of people in the United States who would not recognize the phrase "Beam me up, Scotty" is roughly comparable to the number of people who have never heard of ketchup. When we consider that the Smithsonian Institution's exhibition on the starship *Enterprise* was the most popular display in their Air and Space Museum—more popular than the real spacecraft there—I think it is clear that Star Trek is a natural vehicle for many people's curiosity about the universe. What better context to introduce some of the more remarkable ideas at the forefront of today's physics and the threshold of tomorrow's? I hope you find the ride as enjoyable as I have.

Live long and prosper.

THE PHYSICS OF STAR TREK

SECTION ONE

A Cosmic Poker Game

In which the physics of inertial dampers and tractor beams paves the way for time travel, warp speed, deflector shields, wormholes, and other spacetime oddities

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CHAPTER ONE

NEWTON Antes

"No matter where you go, there you are."
—*From a plaque on the starship* Excelsior, *in* Star Trek VI: The Undiscovered Country,*presumably borrowed from* The Adventures of Buckaroo Banzai

You are at the helm of the starship *Defiant (NCC-1764),* currently in orbit around the planet Iconia, near the Neutral Zone. Your mission: to rendezvous with a nearby supply vessel at the other end of this solar system in order to pick up components to repair faulty transporter primary energizing coils. There is no need to achieve warp speeds; you direct the impulse drive to be set at full power for leisurely half-light-speed travel, which should bring you to your destination in a few hours, giving you time to bring the captain's log up to date. However, as you begin to pull out of orbit, you feel an intense pressure in your chest. Your hands are leaden, and you are glued to your seat. Your mouth is fixed in an evil-looking grimace, your eyes feel like they are about to burst out of their sockets, and the blood flowing through your body refuses to rise to your head. Slowly, you lose consciousness ... and within minutes you die.

What happened? It is not the first signs of spatial "interphase" drift, which will later overwhelm the ship, or an attack from a previously cloaked Romulan vessel. Rather, you have fallen prey to something far more powerful. The ingenious writers of Star Trek, on whom you depend, have not yet invented inertial dampers, which they will introduce sometime later in the series. You have been defeated by nothing more exotic than Isaac Newton's laws of motion—the very first things one can forget about high school physics.

OK, I know some trekkers out there are saying to themselves, "How lame! Don't give me Newton. Tell me things I really want to know, like 'How does warp drive work?' or 'What is the flash before going to warp speed—is it like a sonic boom?' or 'What is a dilithium crystal anyway?'" All I can say is that we will get there eventually. Travel in the Star Trek universe involves some of the most exotic concepts in physics. But many different aspects come together before we can really address everyone's most fundamental question about Star Trek: "Is any of this *really* possible, and if so, *how?"*

To go where no one has gone before—indeed, before we even get out of Starfleet Headquarters—we first have to confront the same peculiarities that Galileo and Newton did over three hundred years ago. The ultimate motivation will be the truly cosmic question which was at the heart of Gene Roddenberry's vision of Star Trek and which, to me, makes this whole subject worth thinking about: *"What does modem science allow us to imagine about our possible future as a civilization?"*

Anyone who has ever been in an airplane or a fast car knows the feeling of being pushed back into the seat as the vehicle accelerates from a standstill. This phenomenon works with a vengeance aboard a starship. The fusion reactions in the impulse drive produce huge pressures, which push gases and radiation backward away from the ship at high velocity. It is the backreaction force on the engines—from the escaping gas and radiation—that causes the engines to "recoil" forward. The ship, being anchored to the engines, also recoils forward. At the helm, you are pushed forward too, by the force of the captain's seat on your body. In turn, your body pushes back on the seat.

Now, here's the catch. Just as a hammer driven at high velocity toward your head will produce a force on your skull which can easily be lethal, the captain's seat will kill you if the force it applies to you is too great. Jet pilots and NASA have a name for the force exerted on your body while you undergo high accelerations (as in a plane or during a space launch): G-forces. I can describe these by recourse to my aching back: As I am sitting at my computer terminal busily typing, I feel the ever-present pressure of my office chair on my buttocks—a pressure that I have learned to live with (yet, I might add, that my buttocks are slowly reacting to in a very noncosmetic way). The force on my buttocks results from the pull of gravity, which if given free rein would accelerate me downward into the Earth. What stops me from accelerating—indeed, from moving beyond my seat—is the ground exerting an opposite upward force on my house's concrete and steel frame, which exerts an upward force on the wood floor of my second-floor study, which exerts a force on my chair, which in turn exerts a force on the part of my body in contact with it. If the Earth were twice as massive but had the same diameter, the pressure on my buttocks would be twice as great. The upward forces would have to compensate for the force of gravity by being twice as strong.

The same factors must be taken into account in space travel. If you are in the captain's seat and you issue a command for the ship to accelerate, you must take into account the force with which the seat will push you forward. If you request an acceleration twice as great, the force on you from the seat will be twice as great. The greater the acceleration, the greater the push. The only problem is that nothing can withstand the kind of force needed to accelerate to impulse speed quickly—certainly not your body.

By the way, this same problem crops up in different contexts throughout Star Trek—even on Earth. At the beginning of *Star Trek V: The Final Frontier,* James Kirk is free-climbing while on vacation in Yosemite when he slips and falls. Spock, who has on his rocket boots, speeds to the rescue, aborting the captain's fall within a foot or two of the ground. Unfortunately, this is a case where the solution can be as bad as the problem. It is the process of stopping over a distance of a few inches which can kill you, whether or not it is the ground that does the stopping or Spock's Vulcan grip.

Well before the reaction forces that will physically tear or break your body occur, other severe physiological problems set in. First and foremost, it becomes impossible for your heart to pump strongly enough to force the blood up to your head. This is why fighter pilots sometimes black out when they perform maneuvers involving rapid acceleration. Special suits have been created to force the blood up from pilots' legs to keep them conscious during acceleration. This physiological reaction remains one of the limiting factors in determining how fast the acceleration of present-day spacecraft can be, and it is why NASA, unlike Jules Verne in his classic *From the Earth to the Moon,* has never launched three men into orbit from a giant cannon.

If I want to accelerate from rest to, say, 150,000 km/sec, or about half the speed of light, I have to do it gradually, so that my body will not be torn apart in the process. In order not to be pushed back into my seat with a force greater than 3G, my acceleration must be no more than three times the downward acceleration of falling objects on Earth. At this rate of acceleration, it would take some 5 million seconds, or about *2 1/2* months, to reach half light speed! This would not make for an exciting episode.

To resolve this dilemma, sometime after the production of the first Constitution Class starship—the *Enterprise (NCC-1701)*—the Star Trek writers had to develop a response to the criticism that the accelerations aboard a starship would instantly turn the crew into "chunky salsa."[1] They came up with "inertial dampers," a kind of cosmic shock absorber and an ingenious plot device designed to get around this sticky little problem.

The inertial dampers are most notable in their absence. For example, the *Enterprise* was nearly destroyed after losing control of the inertial dampers when the microchip life-forms known as Nanites, as part of their evolutionary process, started munching on the ship's central-computer-core memory. Indeed, almost every time the *Enterprise* is destroyed (usually in some renegade timeline), the destruction is preceded by loss of the inertial dampers. The results of a similar loss of control in a Romulan Warbird provided us with an explicit demonstration that Romulans bleed green.

Alas, as with much of the technology in the Star Trek universe, it is much easier to describe the problem the inertial dampers address than it is to explain exactly how they might do it. The First Law of Star Trek physics surely must state that the more basic the problem to be circumvented, the more challenging the required solution must be. For the reason we have come this far, and the reason we can even postulate a Star Trek future, is that physics is a field that builds on itself. A Star Trek fix must circumvent not merely some problem in physics but every bit of physical knowledge that has been built upon this problem. Physics progresses not by revolutions, which do away with ail that went before, but rather by evolutions, which exploit the best about what is already understood. Newton's laws will continue to be as true a million years from now as they are today, no matter what we discover at the frontiers of science. If we drop a ball on Earth, it will always fall. If I sit at this desk and write from here to eternity, my buttocks will always suffer the same consequences.

Be that as it may, it would be unfair simply to leave the inertial dampers hanging without at least some concrete description of how they would have to operate. From what I have argued, they must create an artificial world inside a starship in which the reaction force that responds to the accelerating force is canceled. The objects inside the ship are "tricked" into acting as though they were not accelerating. I have described how accelerating gives you the same feeling as being pulled at by gravity. This connection, which was the basis of Einstein's general theory of relativity, is much more intimate than it may at first seem. Thus there is only one choice for the modus operandi of these gadgets: they must set up an artificial gravitational field inside the ship which "pulls" in the opposite direction to the reaction force, thereby canceling it out.

Even if you buy such a possibility, other practical issues must be dealt with. For one thing, it takes some time for the inertial dampers to kick in when unexpected impulses arise. For example, when the *Enterprise* was bumped into a causality loop by the *Bozeman* as the latter vessel emerged from a temporal distortion, the crew was thrown all about the bridge (even before the breach in the warp core and the failure of the dampers). I have read in the *Enterprise's* technical specifications that the response time for the inertial dampers is about 60 milliseconds.[2] Short as this may seem, it would be long enough to kill you if the same delay occurred during programmed periods of acceleration. To convince yourself, think how long it takes for a hammer to smash your head open, or how long it takes for the ground to kill you if you hit it after falling off of a cliff in Yosemite. Just remember that a collision at 10 miles per hour is equivalent to running full speed into a brick wall! The inertial dampers had better be pretty quick to respond. More than one trekker I know has remarked that whenever the ship *is* buffeted, no one ever gets thrown more than a few feet.

Before leaving the familiar world of classical physics, I can't help mentioning another technological marvel that must confront Newton's laws in order to operate: the *Enterprise's* tractor beam—highlighted in the rescue of the Genome colony on Moab IV, when it deflected an approaching stellar core fragment, and in a similar (but failed) attempt to save Bre'el IV by pushing an asteroidal moon back into its orbit. On the face of it, the tractor beam seems simple enough—more or less like an invisible rope or rod—even if the force exerted may be exotic. Indeed, just like a strong rope, the tractor beam often does a fine job of pulling in a shuttle craft, towing another ship, or inhibiting the escape of an enemy spacecraft. The only problem is that when we pull something with a rope, we must be anchored to the ground or to something else heavy. Anyone who has ever been skating knows what happens if you are on the ice and you try to push someone away from you. You do manage to separate, but at your own expense. Without any firm grounding, you are a helpless victim of your own inertia.

It was this very principle that prompted Captain Jean-Luc Picard to order Lieutenant Riker to turn off the tractor beam in the episode "The Battle"; Picard pointed out that the ship they were towing would be carried along beside them by its own momentum—its inertia. By the same token, if the *Enterprise* were to attempt to use the tractor beam to ward off the *Stargazer,* the resulting force would push the *Enterprise* backward as effectively as it would push the *Stargazer* forward.

This phenomenon has already dramatically affected the way we work in space at present. Say, for example, that you are an astronaut assigned to tighten a bolt on the Hubble Space Telescope. If you take an electric screwdriver with you to do the job, you are in for a rude awakening after you drift over to the offending bolt. When you switch on the screwdriver as it is pressed against the bolt, you are as likely to start spinning around as the bolt is to turn. This is because the Hubble Telescope is a lot heavier than you are. When the screwdriver applies a force to the bolt, the reaction force you feel may more easily turn you than the bolt, especially if the bolt is still fairly tightly secured to the frame. Of course, if you are lucky enough, like the assassins of Chancellor Gorkon, to have gravity boots that secure you snugly to whatever you are standing on, then you can move about as efficiently as we are used to on Earth.

Likewise, you can see what will happen if the *Enterprise* tries to pull another spacecraft toward it. Unless the *Enterprise* is very much heavier, it will move toward the other object when the tractor beam turns on, rather than vice versa. In the depths of space, this distinction is a meaningless semantic one. With no reference system nearby, who is to say who is pulling whom? However, if you are on a hapless planet like Moab IV in the path of a renegade star, it makes a great deal of difference whether the *Enterprise* pushes the star aside or the star pushes the *Enterprise* aside!

One trekker I know claims that the way around this problem is already stated indirectly in at least one episode: if the *Enterprise* were to use its impulse engines at the same time that it turned its tractor beam on, it could, by applying an opposing force with its own engines, compensate for any recoil it might feel when it pushed or pulled on something. This trekker claims that somewhere it is stated that the tractor beam requires the impulse drive to be operational in order to work. I, however, have never noticed any instructions from Kirk or Picard to turn on the impulse engines at the same time the tractor beam is used. And in fact, for a society capable of designing and building inertial dampers, I don't think such a brute force solution would be necessary. Reminded of Geordi LaForge's need for a warp field to attempt to push back the moon at Bre'el IV, I think a careful, if presently unattainable, manipulation of space and time would do the trick equally well. To understand why, we need to engage the inertial dampers and accelerate to the modern world of curved space and time.

CHAPTER TWO
EINSTEIN Raises

There once was a lady named Bright, Who traveled much faster than light. She departed one day, in a relative way, And returned on the previous night.
—*Anonymous*

"Time, the final frontier"—or so, perhaps, each Star Trek episode should begin. Thirty years ago, in the classic episode "Tomorrow Is Yesterday," the round-trip time travels of the *Enterprise* began. (Actually, at the end of an earlier episode, "The Naked Time," the *Enterprise* is thrown back in time three days—*but* it is only a one-way trip.) The starship is kicked back to twentieth-century Earth as a result of a close encounter with a "black star" (the term "black hole" having not yet permeated the popular culture). Nowadays exotica like wormholes and "quantum singularities" regularly spice up episodes of *Star Trek: Voyager,* the latest series. Thanks to Albert Einstein and those who have followed in his footsteps, the very fabric of spacetime is filled with drama.

While every one of us is a time traveler, the cosmic pathos that elevates human history to the level of tragedy arises precisely because we seem doomed to travel in only one direction—into the future. What wouldn't any of us give to travel into the past, relive glories, correct wrongs, meet our heroes, perhaps even avert disasters, or simply revisit youth with the wisdom of age? The possibilities of space travel beckon us every time we gaze up at the stars, yet we seem to be permanent captives in the present. The question that motivates not only dramatic license but a surprising amount of modern theoretical physics research can be simply put: Are we or are we not prisoners on a cosmic temporal freight train that cannot jump the tracks?

The origins of the modern genre we call science fiction are closely tied to the issue of time travel. Mark Twain's early classic *A Connecticut Yankee in King Arthur's Court* is more a work of fiction than science fiction, in spite of the fact that the whole piece revolves around the time-travel adventures of a hapless American in medieval England. (Perhaps Twain did not dwell longer on the scientific aspects of time travel because of the promise he made to Picard aboard the *Enterprise* not to reveal his glimpse of the future once he returned to the nineteenth century by jumping through a temporal rift on Devidia II, in the episode "Time's Arrow.") But H. G. Wells's remarkable work *The Time Machine* completed the transition to the paradigm that Star Trek has followed. Wells was a graduate of the Imperial College of Science and Technology, in London, and scientific language permeates his discussions, as it does the discussions of the *Enterprise* crew.

Surely among the most creative and compelling episodes in the Star Trek series are those involving time travel. I have counted no less than twenty-two episodes in the first two series which deal with this theme, and so do three of the Star Trek movies and a number of the episodes of *Voyager* and *Deep Space Nine* that have appeared as of this writing.

Perhaps the most fascinating aspect of time travel as far as Star Trek is concerned is that there is no stronger potential for violation of the Prime Directive. The crews of Starfleet are admonished not to interfere with the present normal historical development of any alien society they visit. Yet by traveling back in time it is possible to remove the present altogether. Indeed, it is possible to remove history altogether!

A famous paradox is to be found in both science fiction and physics: What happens if you go back in time and kill your mother before you were born? You must then cease to exist. But if you cease to exist, you could not have gone back and killed your mother. But if you didn't kill your mother, then you have not ceased to exist. Put another way: if you exist, then you cannot exist, while if you don't exist, you must exist.

There are other, less obvious but equally dramatic and perplexing questions that crop up the moment you think about time travel. For example, at the resolution of "Time's Arrow," Picard ingeniously sends a message from the nineteenth to the twenty-fourth century by tapping binary code into Data's severed head, which he knows will be discovered almost five hundred years later and reattached to Data's body. As we watch, he taps the message, and then we cut to LaForge in the twenty-fourth century, as he succeeds in reattaching Data's head. To the viewer these events seem contemporaneous, but they are not; once Picard has tapped the message into Data's head, it lies there for half a millennium. But if I were carefully examining Data's head in the twenty-fourth century and Picard had not yet traveled back in time to change the future, would I see such a message? One might argue that if Picard hasn't traveled back in time yet, there can have been no effect on Data's head. Yet the actions that change Data's programming were performed in the nineteenth century regardless of when Picard traveled back in time to perform them. Thus they have already happened, even if Picard has not yet left! In this way, a cause in the nineteenth century (Picard tapping) can produce an effect in the twenty-fourth century (Data's circuitry change) before the cause in the twenty-fourth century (Picard leaving the ship) produces the effect in the nineteenth century (Picard's arrival in the cave where Data's head is located) which allowed the original cause (Picard tapping) to take place at all.

Actually, if the above plot line is confusing, it is nothing compared to the Mother of all time paradoxes, which arises in the final episode of *Star Trek: The Next Generation,* when Picard sets off a chain of events that will travel back in time and destroy not just his own ancestry but all life on Earth. Specifically, a "subspace temporal distortion" involving "antitime" threatens to grow backward in time, eventually engulfing the amino acid protoplasm on the nascent Earth before the first proteins, which will be the building blocks of life, can form. This is the ultimate case of an effect producing a cause. The temporal distortion is apparently created in the future. If, in the distant past, the subspace temporal distortion was able to destroy the first life on Earth, then life on Earth could never have evolved to establish a civilization capable of creating the distortion in the future!

The standard resolution of these paradoxes, at least among many physicists, is to argue a priori that such possibilities must not be allowed in a sensible universe, such as the one we presumably live in. However, the problem is that Einstein's equations of general relativity not only do not directly forbid such possibilities, they encourage them.

Within thirty years of the development of the equations of general relativity, an explicit solution in which time travel could occur was developed by the famous mathematician Kurt Gödel, who worked at the Institute for Advanced Study in Princeton along with Einstein. In Star Trek language, this solution allowed the creation of a "temporal causality loop," such as the one the *Enterprise* got caught in after being hit by the *Bozeman.* The dryer terminology of modern physics labels this a "closed timelike curve." In either case, what it implies is that you can travel on a round-trip and return to your starting point in both space *and* time! Gödel's solution involved a universe that, unlike the one we happen to live in, is not expanding but instead is spinning uniformly. In such a universe, it turns out that one could in principle go back in time merely by traveling in a large circle in space. While such a hypothetical universe is dramatically different than the one in which we live, the mere fact that this solution exists at all indicates clearly that time travel is possible within the context of general relativity.

There is a maxim about the universe which I always tell my students: That which is not explicitly forbidden is guaranteed to occur. Or, as Data said in the episode "Parallels," referring to the laws of quantum mechanics, "All things which can occur, do occur." This is the spirit with which I think one should approach the physics of Star Trek. We must consider the distinction not between what is practical and what is not, but between what is possible and what is not.

This fact was not, of course, lost on Einstein himself, who wrote, "Kurt Gödel's [time machine solution raises] the problem [that] disturbed me already at the time of the building up of the general theory of relativity, without my having succeeded in clarifying it.... It will be interesting to weigh whether these [solutions] are not to be excluded on physical grounds."[1]

The challenge to physicists ever since has been to determine what if any "physical grounds" exist that would rule out the possibility of time travel, which the form of the equations of general relativity appears to foreshadow. To discuss such things will require us to travel beyond the classical world of general relativity to a murky domain where quantum mechanics must affect even the nature of space and time. On the way, we, like the *Enterprise,* will encounter black holes and wormholes. But first we ourselves must travel back in time to the latter half of the nineteenth century.

The marriage of space and time that heralded the modern era began with the marriage, in 1864, of electricity and magnetism. This remarkable intellectual achievement, based on the cumulative efforts of great physicists such as André-Marie Ampère, Charles-Augustin de Coulomb, and Michael Faraday, was capped by the brilliant British physicist James Clerk Maxwell. He discovered that the laws of electricity and magnetism not only displayed an intimate relationship with one another but together implied the existence of "electromagnetic waves," which should travel throughout space at a speed that one could calculate based on the known properties of electricity and magnetism. The speed turned out to be identical to the speed of light, which had previously been measured.

Now, since the time of Newton there had been a debate about whether light was a wave—that is, a traveling disturbance in some background medium—or a particle, which travels regardless of the presence of a background medium. The observation of Maxwell that electromagnetic waves must exist and that their speed was identical to that of light ended the debate: light was an electromagnetic wave.

Any wave is just a traveling disturbance. Well, if light is an electromagnetic disturbance, then what is the medium that is being disturbed as the wave travels? This became the hot topic for investigation at the end of the nineteenth century. The proposed medium had had a name since Aristotle. It was called the aether, and had thus far escaped any attempts at direct detection. In 1887, however, Albert A. Michelson and Edward Morley, working at the institutions that later merged in 1967 to form my present home, Case Western Reserve University, performed an experiment guaranteed to detect not the aether but the aether's effects: Since the aether was presumed to fill all of space, the Earth was presumed to be in motion through it. Light traveling in different directions with respect to the Earth's motion through the aether ought therefore to show variations in speed. This experiment has since become recognized as one of the most significant of the last century, even though Michelson and Morley never observed the effect they were searching for. In fact, it is precisely because they failed to observe the effect of the Earth's motion through the aether that we remember their names today. (A. A. Michelson actually went on to become the first American Nobel laureate in physics for his experimental investigations into the speed of light, and I feel privileged to hold a position today which he held more than a hundred years ago. Edward Morley continued as a renowned chemist and determined the atomic weight of helium, among other things.)

The nondiscovery of the aether did send minor ripples of shock throughout the physics community, but, like many watershed discoveries, its implications were fully appreciated only by a few individuals who had already begun to recognize several paradoxes associated with the theory of electromagnetism. Around this time, a young high school student who had been eight years old at the time of the Michelson-Morley experiment independently began to try to confront these paradoxes directly. By the time he was twenty-six, in the year 1905, Albert Einstein had solved the problem. But as also often occurs whenever great leaps are made in physics, Einstein's results created more questions than they answered.

Einstein's solution, forming the heart of his special theory of relativity, was based on a simple but apparently impossible fact: the only way in which Maxwell's theory of electromagnetism could be self-consistent would be if the observed speed of light was independent of the observer's speed relative to the light. The problem, however, is that this completely defies common sense. If a probe is released from the *Enterprise* when the latter is traveling at impulse speed, an observer on a planet below will see the probe whiz past at a much higher speed than would a crew member looking out an observation window on the *Enterprise.* However, Einstein recognized that Maxwell's theory would be self-consistent only if light waves behaved differently—that is, if their speed as measured by both observers remained identical, independent of the relative motion of the observers. Thus, if I shoot a phaser beam out the front of the *Enterprise,* and it travels away from the ship at the speed of light toward the bridge of a Romulan Warbird, which itself is approaching the *Enterprise* at an impulse speed of 3/4 the speed of light, those on the enemy bridge will observe the beam to be heading toward them just at the speed of light and not at 13/4 times the speed of light. This sort of thing has confused some trekkers, who imagine that if the *Enterprise* is moving at near light speed and another ship is moving in the opposite direction at near light speed, the light from the *Enterprise* will never catch up with the other ship (and therefore the *Enterprise* will not be visible to it). Instead, those on the other ship will see the light from the *Enterprise* approaching at the speed of light.

This realization alone was not what made Einstein's a household name. More important was the fact that he was willing to explore the implications of this realization, all of which on the surface seem absurd. In our normal experience, it is time and space that are absolute, while speed is a relative thing: how fast something is perceived to be moving depends upon how fast you yourself are moving. But as one approaches light speed, it is speed that becomes an absolute quantity, and therefore *space and time must become relative!*

This comes about because speed is literally defined as distance traveled during some specific time. Thus, the only way observers in relative motion can measure a single light ray to traverse the same distance—say, 300 million meters—relative to each of them in, say, one second is if each of their "seconds" is different or each of their "meters" is different! It turns out that in special relativity, the "worst of both worlds" happens—that is, seconds and meters both become relative quantities.

From the simple fact that the speed of light is measured to be the same for all observers, regardless of their relative motion, Einstein obtained the four following consequences for space, time, and matter:

(a) Events that occur for one observer *at the same time in two different places* need not be simultaneous to another observer moving with respect to the first. *Each person's "now" is unique to themselves. "Before" and "after" are relative for distant events.*

(b) All clocks on starships that are moving relative to me will appear to me to be ticking more slowly than my clock. *Time is measured to slow down for objects in motion.*

(c) All yardsticks on starships that are moving relative to me will appear shorter than they would if they were standing still in my frame. *Objects, including starships, are measured to contract if they are moving.*

(d)All massive objects get heavier the faster they travel. As they approach the speed of light, they become infinitely heavy. *Thus, only massless objects, like light, can actually travel at the speed of light.*

This is not the place to review all of the wonderful apparent paradoxes that relativity introduces into the world. Suffice it to say that, like it or not, consequences (a) through (d) are true—that is, they have been tested. Atomic clocks have been carried aloft in high-speed aircraft and have been observed to be behind their terrestrial counterparts upon their return. In high-energy physics laboratories around the world, the consequences of the special theory of relativity are the daily bread and butter of experiment. Unstable elementary particles are made to move near the speed of light, and their lifetimes are measured to increase by huge factors. When electrons, which at rest are 2000 times less massive than protons, are accelerated to near light speed, they are measured to carry a momentum equivalent to that of their heavier cousins. Indeed, an electron accelerated to . 9999999999999999999999999999999999999999999999999 99999999 times the speed of light would hit you with the same impact as a Mack truck traveling at normal speed.

Of course, the reason all these implications of the relativity of space and time are so hard for us to accept at face value is that we happen to live and move at speeds far smaller than the speed of light. Each of the above effects becomes noticeable only when one is moving at "rel-ativistic" speeds. For example, even at half the speed of light, clocks would slow and yardsticks would shrink by only about 15 percent. On NASA's space shuttle, which moves at about 5 miles per second around the Earth, clocks tick less than one ten-millionth of a percent slower than their counterparts on Earth.

However, in the high-speed world of the *Enterprise* or any other starship, relativity would have to be confronted on a daily basis. Indeed, in managing a Federation, one can imagine the difficulties of synchronizing clocks across a large segment of the galaxy when a great many of these clocks are moving at close to light speed. As a result, Starfleet apparently has a rule that normal impulse operations for starships are to be limited to a velocity of 0.25 *c*—that is, 1/4 light speed, or a mere 75,000 km/sec.[2]

Even with such a rule, clocks on ships traveling at this speed will slow by slightly over 3 percent compared with clocks at Starfleet Command. This means that in a month of travel, clocks will have slowed by almost one day. If the *Enterprise* were to return to Starfleet Command after such a trip, it would be Friday on the ship but Saturday back home. I suppose the inconvenience would not be any worse than resetting your clocks after crossing the international date line when traveling to the Orient, except in this case the crew would *actually be* one. day younger after the round-trip, whereas on a round-trip to the Orient you gain one day going in one direction and lose one going in the other.

You can now see how important warp drive is to the *Enterprise.* Not only is it designed to avoid the ultimate speed limit—the speed of light—and so allow practical travel across the galaxy, but it is also designed to avoid the problems of time dilation, which result when the ship is traveling close to light speed.

I cannot overemphasize how significant these facts are. The fact that clocks slow down as one approaches the speed of light has been taken by science fiction writers (and indeed by all those who have dreamed of traveling to the stars) as opening the possibility that one might cross the vast distances between the stars in a human lifetime—at least a human lifetime for those aboard the spaceship. At close to the speed of light, a journey to, say, the center of our galaxy would take more than 25,000 years of Earth time. For those aboard the spaceship, if it were moving sufficiently close to light speed, the trip might take less than 10 years—a long time, but not impossibly so. Nevertheless, while this might make individual voyages of discovery possible, it would make the task of running a Federation of civilizations scattered throughout the galaxy impossible. As the writers of Star Trek have correctly surmised, the fact that a 10-year journey for the *Enterprise* would correspond to a 25,000-year period for Starfleet Command would wreak havoc on any command operation that hoped to organize and control the movements of many such craft. Thus it is absolutely essential that (a) light speed be avoided, in order not to put the Federation out of synchronization, *and* (b) faster-than-light speed be realized, in order to move practically about the galaxy.

The kicker is that, in the context of special relativity alone, the latter possibility *cannot be realized.* Physics becomes full of impossibilities if super light speed is allowed. Not least among the problems is that because objects get more massive as they approach the speed of light, it takes progressively more and more energy to accelerate them by a smaller and smaller amount. As in the myth of the Greek hero Sisyphus, who was condemned to push a boulder uphill for all eternity only to be continually thwarted near the very top, all the energy in the universe would not be sufficient to allow us to push even a speck of dust, much less a starship, past this ultimate speed limit.

By the same token, not just light but all massless radiation *must* travel at the speed of light. This means that the many types of beings of "pure energy" encountered by the *Enterprise,* and later by the *Voyager,* would have difficulty existing as shown. In the first place, they wouldn't be able to sit still. Light cannot be slowed down, let alone stopped in empty space. In the second place, any form of intelligent-energy being (such as the "photonic" energy beings in the *Voyager* series; the energy beings in the Beta Renna cloud, in *The Next Generation;* the Zetarians, in the original series; and the Dal'Rok, in *Deep Space Nine),* which is constrained to travel at the speed of light, would have clocks that are infinitely slowed compared to our own. The entire history of the universe would pass by in a single instant. If energy beings could experience anything, they would experience everything at once! Needless to say, before they could actually interact with corporeal beings the corporeal beings would be long dead.

Speaking of time, I think it is time to introduce the Picard Maneuver. Jean-Luc became famous for introducing this tactic while stationed aboard the *Stargazer.* Even though it involves warp travel, or super light speed, which I have argued is impossible in the context of special relativity alone, it does so for just an instant and it fits in nicely with the discussions here. In the Picard Maneuver, in order to confuse an attacking enemy vessel, one's own ship is accelerated to warp speed for an instant. It then appears to be in two places at once. This is because, traveling faster than the speed of light for a moment, it *overtakes* the light rays that left it the instant before the warp drive was initiated. While this is a brilliant stategy—and it appears to be completely consistent as far as it goes (that is, ignoring the issue of whether it is possible to achieve warp speed)—I think you can see that it opens a veritable Pandora's can of worms. In the first place, it begs a question that has been raised by many trekkers over the years: How can the *Enterprise* bridge crew "see" objects approaching them at warp speed? Just as surely as the *Stargazer* overtook its own image, so too will all objects traveling at warp speed; one shouldn't be able to see the moving image of a warp-speed object until long after it has arrived. One can only assume that when Kirk, Picard, or Janeway orders up an image on the viewscreen, the result is an image assembled by some sort of long-range "subspace" (that is, super-light-speed communication) sensors. Even ignoring this apparent oversight, the Star Trek universe would be an interesting and a barely navigable one, full of ghost images of objects that long ago arrived where they were going at warp speed.

Moving back to the sub-light-speed world: We are not through with Einstein yet. His famous relation between mass and energy, $E=mc^2$, which is a consequence of special relativity, presents a further challenge to space travel at impulse speeds. As I have described it in chapter 1, a rocket is a device that propels material backward in order to move forward. As you might imagine, the faster the material is propelled backward, the larger will be the forward impulse the rocket will receive. Material cannot be propelled backward any faster than the speed of light. Even propelling it at light speed is not so easy: the only way to get propellant moving backward at light speed is to make the fuel out of matter and antimatter, which (as I describe in a later chapter) can completely annihilate to produce pure radiation moving at the speed of light.

However, while the warp drive aboard the *Enterprise* uses such fuel, the impulse drive does not. It is powered instead by nuclear fusion—the same nuclear reaction that powers the Sun by turning hydrogen into helium. In fusion reactions, about 1 percent of the available mass is converted into energy. With this much available energy, the helium atoms that are produced can come streaming out the back of the rocket at about an eighth of the speed of light. Using this exhaust velocity for the propellant, we then can calculate the amount of fuel the *Enterprise* needs in order to accelerate to, say, half the speed of light. The calculation is not difficult, but I will just give the answer here. It may surprise you. Each time the *Enterprise* accelerates to half the speed of light, it must burn 81 *TIMES ITS ENTIRE MASS* in hydrogen fuel. Given that a Galaxy Class starship such as Picard's *Enterprise-D* would weigh in excess of 4 million metric tons,[3] this means that over 300 million metric tons of fuel would need to be used each time the impulse drive is used to accelerate the ship to half light speed! If one used a matter-antimatter propulsion system for the impulse drive, things would be a little better. In this case, one would have to burn merely *twice* the entire mass of the *Enterprise* in fuel for each such acceleration.

It gets worse. The calculation I described above is correct for a single acceleration. To bring the ship to a stop at its destination would require the same factor of 81 times its mass in fuel. This means that just to go somewhere at half light speed and stop again would require fuel in the amount of 81x81= 6561 TIMES *THE ENTIRE SHIP'S MASS!* Moreover, say that one wanted to achieve the acceleration to half the speed of light in a few hours (we will assume, of course, that the inertial dampers are doing their job of shielding the crew and ship from the tremendous G-forces that would otherwise ensue). The power radiated as propellant by the engines would then be about 10^{22} watts—or about a billion times the total average power presently produced and used by all human activities on Earth!

Now, you may suggest (as a bright colleague of mine did the other day when I presented him with this argument) that there is a subtle loophole. The argument hinges on the requirement that you carry your fuel along with the rocket. What if, however, you harvest your fuel as you go along? After all, hydrogen is the most abundant element in the universe. Can you not sweep it up as you move through the galaxy? Well, the average density of matter in our galaxy is about one hydrogen atom per cubic centimeter. To sweep up just one gram of hydrogen per second, even moving at a good fraction of the speed of light, would require you to deploy collection panels with a diameter of over 25 miles. And even turning all this matter into energy for propulsion would provide only about a hundred-millionth of the needed propulsion power!

To paraphrase the words of the Nobel prizewinning physicist Edward Purcell, whose arguments I have adapted and extended here:

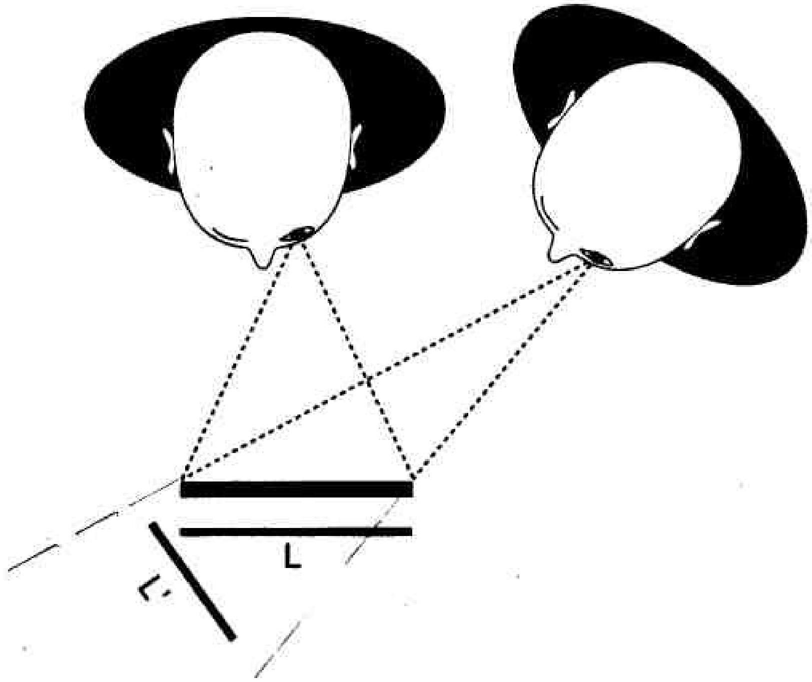
If this sounds preposterous to you, you are right. Its preposterousness follows from the elementary laws of classical mechanics and special relativity. The arguments presented here are as inescapable as the fact that a ball will fall when you drop it at the Earth's surface. Rocket-propelled space travel through the galaxy at near light speed *is not physically practical,* now or ever!

So, do I end the book here? Do we send back our Star Trek memorabilia and ask for a refund? Well, we are still not done with Einstein. His final, perhaps greatest discovery holds out a glimmer of hope after all.

Fast rewind back to 1908: Einstein's discovery of the relativity of space and time heralds one of those "Aha!" experiences that every now and then forever change our picture of the universe. It was in the fall of 1908 that the mathematical physicist Hermann Minkowski wrote these famous words: "Henceforth, space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality."

What Minkowski realized is that even though space and time are relative for observers in relative motion—your clock can tick slower than mine, and my distances can be different from yours—if space and time are instead merged as part of a four-dimensional whole (three dimensions of space and one of time), an "absolute" objective reality suddenly reappears.

The leap of insight Minkowski had can be explained by recourse to a world in which everyone has monocular vision and thus no direct depth perception. If you were to close one eye, so that your depth perception was reduced, and I were to hold a ruler up for you to see, and I then told someone else, who was observing from a different angle, to close one eye too, the ruler I was holding up would appear to the other observer to be a different length than it would appear to be to you—as the following bird's-eye view shows.



Each observer in the example above, without the direct ability to discern depth, will label "length" (L or L') to be the two-dimensional projection onto his or her plane of vision of the actual three-dimensional length of the ruler. Now, because we know that space has three dimensions, we are not fooled by this trick. We know that viewing something from a different angle does not change its real length, even if it changes its apparent length. Minkowski showed that the same idea can explain the various paradoxes of relativity, if we now instead suppose that our perception of space is merely a three-dimensional slice of what is actually a four-dimensional manifold in which space and time are joined. Two different observers in relative motion perceive *different* three-dimensional slices of the underlying four-dimensional space in much the same way that the two rotated observers pictured here view *different* two-dimensional slices of a three-dimensional space.

Minkowski imagined that the spatial distance measured by two observers in relative motion is a projection of an underlying *four-dimensional spacetime distance* onto the three-dimensional space that they can sense; and, similarly, that the temporal "distance" between two events is a projection of the four-dimensional spacetime distance onto their own timeline. Just as rotating something in three dimensions can mix up width and depth, so relative motion in four-dimensional space can mix up different observers' notions of "space" and "time." Finally, just as the length of an object does not change when we rotate it in space, the four-dimensional spacetime distance between two events is absolute—independent of how different observers in relative motion assign "spatial" and "temporal" distances.

So the crazy invariance of the speed of light for all observers provided a key clue to unravel the true nature of the four-dimensional universe of spacetime in which we actually live. *Light displays the hidden connection between space and time.* Indeed, the speed of light *defines* the connection.

It is here that Einstein returned to save the day for Star Trek. Once Minkowski had shown that spacetime in special relativity was like a four-dimensional sheet of paper, Einstein spent the better part of the next decade flexing his mathematical muscles until he was able to bend that sheet, which in turn allows us to bend the rules of the game. As you may have guessed, light was again the key.

CHAPTER
THREE

HAWKING
Shows His Hand

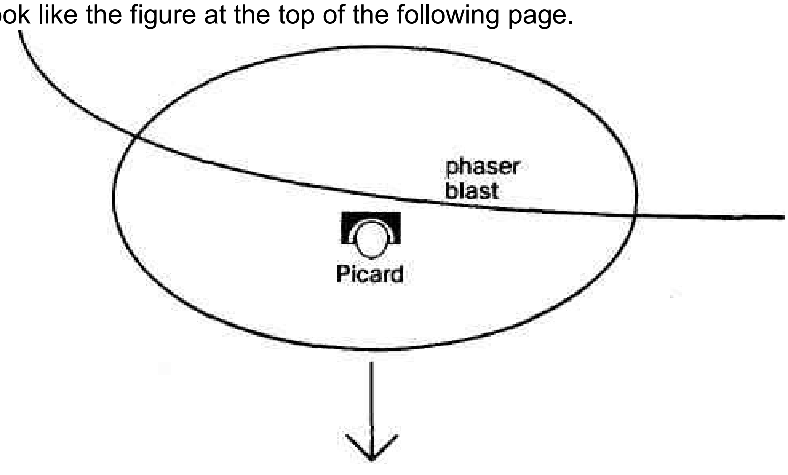
"How little do you mortals understand time. Must you be so linear, Jean-Luc?"
—Q *to Picard, in "All Good Things... .*

The planet Vulcan, home to Spock, actually has a venerable history in twentieth-century physics. A great puzzle in astrophysics in the early part of this century was the fact that the perihelion of Mercury—the point of its closest approach to the Sun—was precess-ing around the Sun each Mercurian year by a very small amount in a way that was not consistent with Newtonian gravity. It was suggested that a new planet existed inside Mercury's orbit which could perturb it in such a way as to fix the problem. (In fact, the same solution to an anomaly in the orbit of Uranus had earlier led to the discovery of the planet Neptune.) The name given to the hypothetical planet was Vulcan.

Alas, the mystery planet Vulcan is not there. Instead, Einstein proposed that the flat space of Newton and Minkowski had to be given up for the curved spacetime of general relativity. In this curved space, Mercury's orbit would deviate slightly from that predicted by Newton, explaining the observed discrepancy. While this removed the need for the planet Vulcan, it introduced possibilities that are much more exciting. Along with curved space come black holes, wormholes, and perhaps even warp speeds and time travel.

Indeed, long before the Star Trek writers conjured up warp fields, Einstein warped spacetime, and, like the Star Trek writers, he was armed with nothing other than his imagination. Instead of imagining twenty-second-century starship technology, however, Einstein imagined an elevator. He was undoubtedly a great physicist, but he probably never would have sold a screenplay.

Nonetheless, his arguments remain intact when translated aboard the *Enterprise.* Because light is the thread that weaves together space and time, the trajectories of light rays give us a map of spacetime just as surely as warp and weft threads elucidate the patterns of a tapestry. Light generally travels in straight lines. But what if a Romulan commander aboard a nearby Warbird shoots a phaser beam at Picard as he sits on the bridge of his captain's yacht *Calypso,* having just engaged the impulse drive (we will assume the inertial dampers are turned off for this example)? Picard would accelerate forward, narrowly missing the brunt of the phaser blast. When viewed in Picard's frame of reference, things would look like the figure at the top of the following page.



So, for Picard, the trajectory of the phaser ray would be curved. What else would Picard notice? Well, recalling the argument in the first chapter, as long as the inertial dampers are turned off, he would be thrust back in his seat. In fact, I also noted there that if
Picard was being accelerated forward at the same rate as gravity causes things to accelerate downward at the Earth's surface, he would feel exactly the same force pushing him back against his seat that he would feel pushing him down if he were standing on Earth. In fact, Einstein argued that Picard (or his equivalent in a rising elevator) would never be able to perform any experiment that could tell the difference between the reaction force due to his acceleration and the pull of gravity from some nearby heavy object outside the ship. Because of this, Einstein boldly went where no physicist had gone before, and reasoned that whatever phenomena an accelerating observer experienced would be identical to

the phenomena an observer in a gravitational field experienced.

Our example implies the following: Since Picard observes the phaser ray bending when he is accelerating away from it, the ray must also bend in a gravitational field. But if light rays map out spacetime, then *spacetime* must bend in a gravitational field. Finally, since matter produces a gravitational field, then *matter must bend spacetime!*

Now, you may argue that since light has energy, and mass and energy are related by Einstein's famous equation, then the fact that light bends in a gravitational field is no big surprise—and certainly doesn't seem to imply that we have to believe that spacetime itself need be curved. After all, the paths that matter follows bend too (try throwing a ball in the air). Galileo could have shown, had he known about such objects, that the trajectories of baseballs and Pathfinder missiles bend, but he never would have mentioned curved space.

Well, it turns out that you can calculate how much a light ray should bend if light behaved the same way a baseball does, and then you can go ahead and measure this bending, as Sir Arthur Stanley Eddington did in 1919 when he led an expedition to observe the apparent position of stars on the sky very near the Sun during a solar eclipse. Remarkably, you would find, as Eddington did, that light bends exactly *twice* as much as Galileo might have predicted if it behaved like a baseball in flat space. As you may have guessed, this factor of 2 is just what Einstein predicted if spacetime was curved in the vicinity of the Sun and light (or the planet Mercury, for that matter) was locally traveling in a straight line in this curved space! Suddenly, Einstein's was a household name.

Curved space opens up a whole universe of possibilities, if you will excuse the pun. Suddenly we, and the *Enterprise,* are freed from the shackles of the kind of linear thinking imposed on us in the context of special relativity, which Q, for one, seemed to so abhor. One can do many things on a curved manifold which are impossible on a flat one. For example, it is possible to keep traveling in the same direction and yet return to where you began—people who travel around the world do it all the time.

The central premise of Einstein's general relativity is simple to state in words: the curvature of spacetime is directly determined by the distribution of matter and energy contained within it. Einstein's equations, in fact, provide simply the strict mathematical relation between curvature on the one hand and matter and energy on the other:

$$\begin{array}{c} \text{Left-hand side} \\ \{\text{CURVATURE}\} \end{array} = \begin{array}{c} \text{Right-hand side} \\ \{\text{MATTER AND ENERGY}\} \end{array}$$

What makes the theory so devilishly difficult to work with is this simple feedback loop: The curvature of spacetime is determined by the distribution of matter and energy in the universe, but this distribution is in turn governed by the curvature of space. It is like the chicken and the egg. Which was there first? Matter acts as the source of curvature, which in turn determines how matter evolves, which in turn alters the curvature, and so on.

Indeed, this may be perhaps the most important single aspect of general relativity as far as Star Trek is concerned. The complexity of the theory means that we still have not yet fully understood all its consequences; therefore we cannot rule out various exotic possibilities. It is these exotic possibilities that are the grist of Star Trek's mill. In fact, we shall see that all these possibilities rely on one great unknown that permeates everything, from wormholes and black holes to time machines.

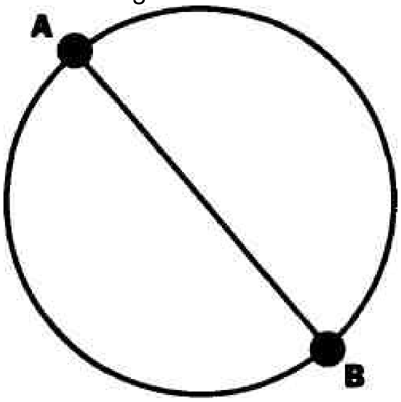
The first implication of the fact that spacetime need not be flat which will be important to the adventures of the *Enterprise* is that time itself becomes an even more dynamic quantity than it was in special relativity. Time can flow at different rates for different observers even if they are not moving relative to each other. Think of the ticks of a clock as the ticks on a ruler made of rubber. If I were to stretch or bend the ruler, the spacing between the ticks would differ from point to point. If this spacing represents the ticks of a clock, then clocks located in different places can tick at different rates. In general relativity, the only way to "bend" the ruler is for a gravitational field to be present, which in turn requires the presence of matter.

To translate this into more pragmatic terms: if I put a heavy iron ball near a clock, it should change the rate at which the clock ticks. Or more practical still, if I sleep with my alarm clock tucked next to my body's rest mass, I will be awakened a little later than I would otherwise, at least as far as the rest of the world is concerned.

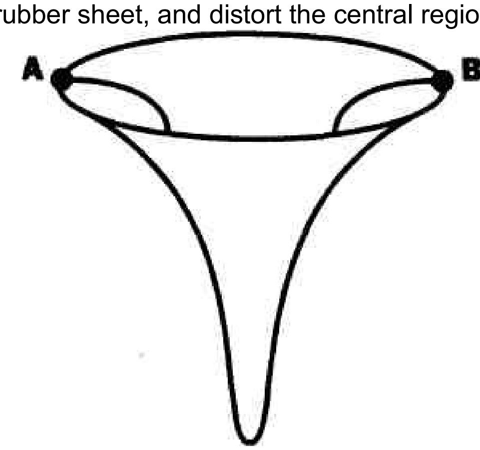
A famous experiment done in the physics laboratories at Harvard University in 1960 first demonstrated that time can depend on where you are. Robert Pound and George Rebka showed that the frequency of gamma radiation measured at its source, in the basement of the building, differed from the frequency of the radiation when it was received 74 feet higher, on the building's roof (with the detectors having been carefully calibrated so that any observed difference would not be detector-related). The shift was an incredibly small amount— about 1 part in a million billion. If each cycle of the gamma-ray wave is like the tick of an atomic clock, this experiment implies that a clock in the basement will appear to be running more slowly than an equivalent atomic clock on the roof. Time slows on the lower floor because this is closer to the Earth than the roof is, so the gravitational field, and hence the spacetime curvature, is larger there. As small as this effect was, it was precisely the value predicted by general relativity, assuming that spacetime is curved near the Earth.

The second implication of curved space is perhaps even more exciting as far as space travel is concerned. If space is curved, then a straight line need not be the shortest distance between two points. Here's an example. Consider a circle on a piece of paper. Normally, the shortest distance between two points A and B located on opposite sides

of the circle is given by the line connecting them through the center of the circle:



If, instead, one were to travel around the circle to get from A to B, the journey would be about *1 1/2* times as long. However, let me draw this circle on a rubber sheet, and distort the central region:



Now, when viewed in our three-dimensional perspective, it is clear that the journey from A to B taken through the center of the region will be much longer than that taken by going around the circle. Note that if we took a snapshot of this from above, so we would have only a two-dimensional perspective, the line from A to B through the center would look like a straight line. More relevant perhaps, if a tiny bug (or two-dimensional beings, of the type encountered by the *Enterprise)* were to follow the trajectory from A to B through the center by crawling along the surface of the sheet, this trajectory would appear to be straight. The bug would be amazed to find that the straight line through the center between A and B was no longer the shortest distance between these two points. If the bug were intelligent, it would be forced to the conclusion that the two-dimensional space it lived in was curved. Only by viewing the embedding of this sheet in the underlying three-dimensional space can we observe the curvature directly.

Now, remember that we live within a four-dimensional spacetime that can be curved, and we can no more perceive the curvature of this space directly than the bug crawling on the surface of the sheet can detect the curvature of the sheet. I think you know where I am heading: If, in curved space, the shortest distance between two points need not be a straight line, then it might be possible to traverse what appears *along the line of sight* to be a huge distance, by finding instead a shorter route through curved spacetime.

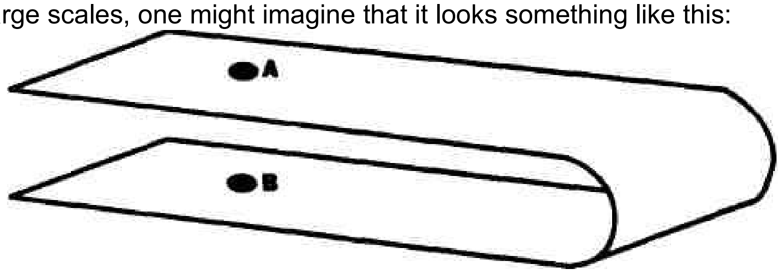
These properties I have described are the stuff that Star Trek dreams are made of. Of course, the question is: How many of these dreams may one day come true?

WORMHOLES: FACT AND FANCY: The Bajoran wormhole in *Deep Space Nine* is perhaps the most famous wormhole in Star Trek, although there have been plenty of others, including the dangerous wormhole that Scotty could create by imbalancing the matter-antimatter mix in the *Enterprise's* warp drive; the unstable Barzan wormhole, through which a Ferengi ship was lost in the *Next Generation* episode "The

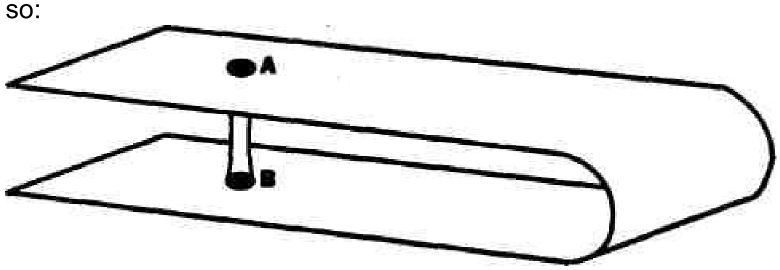
Price"; and the temporal wormhole that the *Voyager* encountered in its effort to get back home from the far edge of the galaxy.

The idea that gives rise to wormholes is exactly the one I just described. If spacetime is curved, then perhaps there are different ways of connecting two points so that the distance between them is much shorter than that which would be measured by traveling in a "straight line" through curved space. Because curved-space phenomena in four dimensions are impossible to visualize, we once again resort to a two-dimensional rubber sheet, whose curvature we can observe by embedding it in three-dimensional space.

If the sheet is curved on large scales, one might imagine that it looks something like this:



Clearly, if we were to poke a pencil down at A and stretch the sheet until we touched B, and then sewed together the two parts of the sheet, like so:



we would create a path from A to B that was far shorter than the path leading around the sheet from one point to another. Notice also that the sheet appears flat near A and also near B. The curvature that brings these two points close enough together to warrant joining them by a tunnel is due to the global bending of the sheet over large distances. A little bug (even an intelligent one) at A, confined to crawl on the sheet, would have no idea that B was as "close" as it was, even if it could do some local experiments around A to check for a curvature of the sheet.

As you have no doubt surmised, the tunnel connecting A and B in this figure is a two-dimensional analogue of a three-dimensional wormhole, which could, in principle, connect distant regions of space-time. As exciting as this possibility is, there are several deceptive aspects of the picture which I want to bring to your attention. In the first place, even though the rubber sheet is shown embedded in a three-dimensional space in order for us to "see" the curvature of the sheet, the curved sheet can exist without the three-dimensional space around it needing to exist. Thus, while a wormhole could exist joining A and B, there is no sense in which A and B are "close" *without* the wormhole being present. It is not as if one is free to leave the rubber sheet and move from A to B through the three-dimensional space in which the sheet is embedded. If the three-dimensional space is not there, the rubber sheet is all there is to the universe.

Thus, imagine that you were part of an infinitely advanced civilization (but not as advanced as the omnipotent Q beings, who seem to transcend the laws of physics) that had the power to build wormholes in space. Your wormhole building device would effectively be like the pencil in the example I just gave. If you had the power to produce huge local curvatures in space, you would have to poke around blindly in the hope that somehow you could connect two regions of space that, until the instant a wormhole was established, would remain very distant from each other. In no way whatsoever would these two regions be close together until the wormhole produced a bridge. The bridge-building process *itself* is what changes the global nature of spacetime.

Because of this, making a wormhole is not to be taken lightly. When Premier Bhavani of Barzan visited the *Enterprise* to auction off the rights to the Barzan wormhole, she exclaimed, "Before you is the first and only stable wormhole known to exist!" Alas, it wasn't stable; indeed, the only wormholes whose mathematical existence has been consistently established in the context of general relativity are transitory. Such wormholes are created as two microscopic "singularities"— regions of spacetime where, the curvature becomes infinitely sharp— find each other and momentarily join. However, in a time shorter than the time it would take a space traveler to pass through such a wormhole, it closes up, leaving once again two disconnected singularities. The unfortunate explorer would be crushed to bits in one singularity or the other before being able to complete the voyage through the wormhole.

The problem of how to keep the mouth of a wormhole open has been hideously difficult to resolve in mathematical detail, but is quite easily stated in physical terms: Gravity sucks! Any kind of normal matter or energy will tend to collapse under its own gravitational attraction unless something else stops it. Similarly, the mouth of a wormhole will pinch off in nothing flat under normal circumstances.

So, the trick is to get rid of the normal circumstances. In recent years, the Caltech physicist Kip Thorne, among others, has argued that the only way to keep wormholes open is to thread them with "exotic material." By this is meant material that will be measured, at least by certain observers, to have "negative" energy. As you might expect (although naive expectations are notoriously suspect in general relativity), such material would tend to "blow" not "suck," as far as gravity is concerned.

Not even a diehard trekker might be willing to suspend disbelief long enough to accept the idea of matter with "negative energy"; however, as noted, in curved space one's normal expectations are often suspect. When you compound this with the exotica forced upon us by the laws of quantum mechanics, which govern the behavior of matter on small scales, quite literally almost all bets are off.

BLACK HOLES AND DR. HAWKING: Enter Stephen Hawking. He first became well known among physicists working on general relativity for his part in proving general theorems related to singularities in spacetime, and then, in the 1970s, for his remarkable theoretical discoveries about the behavior of black holes. These objects are formed from material that has collapsed so utterly that the local gravitational field at their surface prevents even light from escaping.

Incidentally, the term "black hole," which has so captivated the popular imagination, was coined by the theoretical physicist John Archibald Wheeler of Princeton University, in the late fall of 1967. The date here is very interesting, because, as far as I can determine, the first Star Trek episode to refer to a black hole, which it called a "black star," was aired in 1967 before Wheeler ever used the term in public. When I watched this episode early in the preparation of this book, I found it amusing that the Star Trek writers had gotten the name wrong. Now I realize that they very nearly invented it!

Black holes are remarkable objects for a variety of reasons. First, all black holes eventually hide a spacetime singularity at their center, and anything that falls into the black hole must inevitably encounter it. At such a singularity— an infinitely curved "cusp" in spacetime—the laws of physics as we know them break down. The curvature near the singularity is so large over such a small region that the effects of gravity are governed by the laws of quantum mechanics. Yet no one has yet been able to write down a theory that consistently accommodates both general relativity (that is, gravity) and quantum mechanics. Star Trek writers correctly recognized this tension between quantum mechanics and gravity, as they usually refer to all spacetime singularities as "quantum singularities." One thing is certain, however: by the time the gravitational field at the center of a black hole reaches a strength large enough for our present picture of physics to break down, any ordinary physical object will be torn apart beyond recognition. Nothing could survive intact.

You may notice that I referred to a black hole as "hiding" a singularity at its center. The reason is that at the outskirts of a black hole is a mathematically defined surface we call the "event horizon," which shields our view of what happens to objects that fall into the hole. Inside the event horizon, everything must eventually hit the ominous singularity. Outside the event horizon, objects can escape. While an observer unlucky enough to fall into a black hole will notice nothing special at all as he or she (soon to be "it") crosses the event horizon, an observer watching the process from far away sees something very different. Time slows down for the observer freely falling in the vicinity of the event horizon, relative to an observer located far away. As a result, the falling observer appears from the outside to slow down as he or she nears the event horizon. The closer the falling observer gets to the event horizon, the slower is his or her clock relative to the outside observer's. While it may take the falling observer a few moments (local time) to cross the event horizon—where, I repeat, nothing special happens and nothing special sits—it will take an eternity as observed by someone on the outside. The infalling object appears to become frozen in time.

Moreover, the light emitted by any infalling object gets harder and harder to see from the outside. As an object approaches the event horizon, the object gets dimmer and dimmer (because the observable radiation from it gets shifted to frequencies below the visible). Finally, even if you could see, from the outside, the object's transit of the event horizon (which you cannot, in any finite amount of time), the object would disappear completely once it passed the horizon, because any light it emitted would be trapped inside, along with the object. Whatever falls inside the event horizon is lost forever to the outside world. It appears that this lack of communication is a one-way street: an observer on the outside can send signals *into* the black hole, but no signal can ever be returned.

For these reasons, the black holes encountered in Star Trek tend to produce impossible results. The fact that the event horizon is not a tangible object, but rather a mathematical marker that we impose on our description of a black hole to delineate the region inside from that outside, means that the horizon cannot have a "crack," as required by the crew of the *Voyager* when they miraculously escape from a black hole's interior. (Indeed, this notion is so absurd that it makes it onto my ten-best list of Star Trek mistakes described in the last chapter.) And the "quantum singularity life-forms" encountered by the crew of the *Enterprise* as they, and a nearby Romulan Warbird, travel backward and forward in time have a rather unfortunate nesting place for their young: apparently they place them inside natural black holes (which they incorrectly mistake the "artificial" quantum singularity inside the Romulan engine core for). This may be a safe nursery, but it must be difficult to retrieve your children afterward. I remind you that nothing inside a black hole can ever communicate with anything outside one.

Nevertheless, black holes, for all their interesting properties, need not be that exotic. The only black holes we have any evidence for in the universe today result from the collapse of stars much more massive than the Sun. These collapsed objects are so dense that a teaspoon of material inside would weigh many tons. However, it is another remarkable property of black holes that the more massive they are, the less dense they need be when they form. For example, the density of the black hole formed by the collapse of an object 100 million times as massive as our Sun need only be equal to the density of water. An object of larger mass will collapse to form a black hole at a point when it is even less dense. If you keep on extrapolating, you will find that the density required to form a black hole with a mass equal to the mass of the observable universe would be roughly the same as the average density of matter in the universe! We may be living inside a black hole.

In 1974, Stephen Hawking made a remarkable discovery about the nature of black holes. They aren't completely black! Instead, they will emit radiation at a characteristic temperature, which depends on their mass. While the nature of this radiation will give no information whatsoever on what fell into the black hole, the idea that radiation could be emitted from a black hole was nevertheless astounding, and appeared to violate a number of theorems—some of which Hawking had earlier proved—holding that matter could only fall into black holes, not out of them. This remains true, except for the source of the black-hole radiation, which is not normal matter. Instead, it is empty space, which can behave quite exotically—especially in the vicinity of a black hole.

Ever since the laws of quantum mechanics were made consistent with the special theory of relativity, shortly after the Second World War, we have known that empty space is not so empty. It is a boiling, bubbling sea of quantum fluctuations. These fluctuations periodically spit out elementary particle pairs, which exist for time intervals so short that we cannot measure them directly, and then disappear back into the vacuum from which they came. The uncertainty principle of quantum mechanics tells us that there is no way to directly probe empty space over such short time intervals and thus no way to preclude the brief existence of these so-called virtual particles. But although they cannot be measured directly, their presence does affect certain physical processes that we *can* measure, such as the rate and energy of transitions between certain energy levels in atoms. The predicted effect of virtual particles agrees with observations as well as any prediction known in physics.

This brings us back to Hawking's remarkable result about black holes. Under normal circumstances, when a quantum fluctuation creates a virtual particle pair, the pair will annihilate and disappear back into the vacuum in a time short enough so that the violation of conservation of energy (incurred by the pair's creation from nothing) is not observable. However, when a virtual particle pair pops out in the curved space near a black hole, one of the particles may fall into the hole, and then the other can escape and be observed. This is because the particle that falls into the black hole can in principle lose more energy in the process than the amount required to create it from nothing. It thus contributes "negative energy" to the black hole, and the black hole's own energy is therefore decreased. This satisfies the energy-conservation law's balance-sheet, making up for the energy that the escaping particle is observed to have. This is how the black hole emits radiation. Moreover, as the black hole's own energy decreases bit by bit in this process, there is a concomitant decrease in its mass. Eventually, it may completely evaporate, leaving behind only the radiation it produced in its lifetime.

Hawking and many others have gone beyond a consideration of quantum fluctuations of matter in a background curved space to something even more exotic and less well defined. If quantum mechanics applies not merely to matter and radiation but to gravity as well, then on sufficiently small scales quantum fluctuations in spacetime itself must occur. Unfortunately, we have no workable theory for dealing with such processes, but this has not stopped a host of tentative theoretical investigations of phenomena that might result. One of the most interesting speculations is that quantum mechanical processes might allow the spontaneous creation not just of particles but of whole new baby universes. The quantum mechanical formalism describing how this might occur is, at least mathematically, very similar to the wormhole solutions discovered in ordinary general relativity. Via such "Euclidean" wormholes, a temporary "bridge" is created, from which a new universe springs. The possibilities of Euclidean wormhole processes and baby universes are sufficiently exciting that quantum fluctuations were mentioned during Hawking's poker game with Einstein and Newton in the *Next Generation* episode "Descent."[1] If the Star Trek writers were confused, they had a right to be. These issues are unfortunately currently very murky. Until we discover the proper mathematical framework to treat such quantum gravitational processes, all such discussions are shots in the dark.

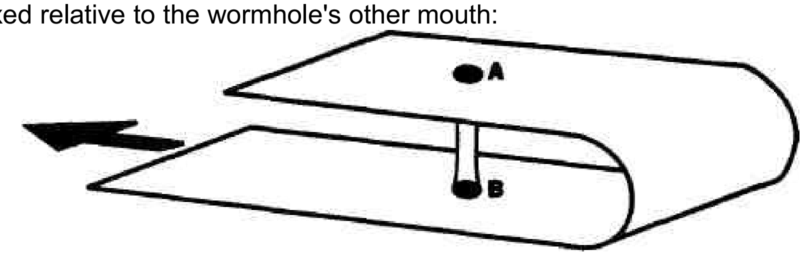
What is most relevant to us here is not the phenomenon of black-hole evaporation, or even baby universes, as interesting as they may be, but rather the discovery that quantum fluctuations of empty space can, at least in the presence of strong gravitational fields, become endowed with properties reminiscent of those required to hold open a worm-hole. The central question, which also has no definitive answer yet, is whether quantum fluctuations near a wormhole can behave sufficiently exotically to allow one to keep a wormhole open.

(By the way, once again, I find the Star Trek writers remarkably prescient in their choice of nomenclature. The Bajoran and Barzan wormholes are said to involve "verteron" fields. I have no idea whether this name was plucked out of a hat or not. However, since virtual particles—the quantum fluctuations in otherwise empty space—are currently the best candidate for Kip Thorne's "exotic matter," I think the Star Trek writers deserve credit for their intuition, if that's what it was.)

More generally, if quantum fluctuations in the vacuum can be exotic, is it possible that some other nonclassical configuration of matter and radiation—like, say, a warp core breach, or perhaps Scotty's "intermix" imbalance in the warp drive—might also fill the bill? Questions such as this remain unanswered. While by no means circumventing the incredible implausibility of stable wormholes in the real universe, they do leave open the larger question of whether wormhole travel is impossible or merely almost impossible. The wormhole issue is not just one of science fact versus science fiction: it is a key that can open doors which many would prefer to leave closed.

TIME MACHINES REVISITED: Wormholes, as glorious as they would be for tunneling through vast distances in space, have an even more remarkable potential, glimpsed most recently in the *Voyager* episode "Eye of the Needle." In this episode, the *Voyager* crew discovered a small wormhole leading back to their own "alpha quadrant" of the galaxy. After communicating through it, they found to their horror that it led not to the alpha quadrant they knew and loved but to the alpha quadrant of a generation earlier. The two ends of the wormhole connected space at two different times!

Well, this is another one of those instances in which the *Voyager* writers got it right. If wormholes exist, they can and will be time machines! This startling realization has grown over the last decade, as various theorists, for lack of anything more interesting to do, began to investigate the physics of wormholes a little more seriously. Worm-hole time machines are easy to design: perhaps the simplest example (due again to Kip Thorne) is to imagine a wormhole with one end fixed and the other end moving at a fast but sublight speed through a remote region of the galaxy. In principle, this is possible *even if* the length of the wormhole remains unchanged. In my earlier two-dimensional wormhole drawing, just drag the bottom half of the sheet to the left, letting space "slide" past the bottom mouth of the wormhole while this mouth stays fixed relative to the wormhole's other mouth:



Because the bottom mouth of the wormhole will be moving with respect to the space in which it is situated, while the top mouth will not, special relativity tells us that clocks will tick at different rates at each mouth. On the other hand, if the length of the wormhole remains fixed, then as long as one is inside the wormhole the two ends appear to be at rest relative to each other. In this frame, clocks at either end should be ticking at the same rate. Now slide the bottom sheet back to where it used to be, so that the bottom mouth of the wormhole ends up back where it started relative to the background space. Let's say that this process takes a day, as observed by someone near the bottom mouth. But for an observer near the top mouth, this same process could appear to have taken ten days. If this second observer were to peer through the top mouth to look at the observer located near the bottom mouth, he would see on the wall calendar next to the observer a date nine days earlier! If he now decides to go through the worm-hole for a visit, he will travel backward in time.

If stable wormholes exist, we must therefore concede that time machines are possible. We now return finally to Einstein's remarks early in the last chapter. Can time travel, and thus stable wormholes, and thus exotic matter with negative energy, be "excluded on physical grounds"?

Wormholes are after all merely one example of time machines that have been proposed in the context of general relativity. Given our previous discussion about the nature of the theory, it is perhaps not so surprising that time travel becomes a possibility. Let's recall the heuristic description of Einstein's equations which I gave earlier:

$$\begin{array}{c} \text{Left-hand side} \\ \{\text{CURVATURE}\} \end{array} = \begin{array}{c} \text{Right-hand side} \\ \{\text{MATTER AND ENERGY}\} \end{array}$$

The left-hand side of this equation fixes the geometry of spacetime. The right-hand side fixes the matter and energy distribution. Generally we would ask: For a given distribution of matter and energy, what will be the resulting curvature of space? But we can also work backward: For any given geometry of space, including one with "closed timelike curves"—that is, the "causality loops," which allow you to return to where you began in space and time, like the loop the *Enterprise* was caught in before, during, and after crashing into the *Boze-man*—Einstein's equations tell you exactly what distribution of matter and energy must be present. So in principle you can design any kind of time-travel universe you want; Einstein's equations will tell you what matter and energy distribution is necessary. The key question then simply becomes: Is such a matter and energy distribution physically possible?

We have already seen how this question arises in the context of wormholes. Stable wormholes require exotic matter with negative energy. Kurt Gödel's time-machine solution in genera! relativity involves a universe with constant uniform energy density and zero pressure which spins but does not expand. More recently, a proposed time machine involving "cosmic strings" was shown to require a negative-energy configuration. In fact, it was recently proved that any configuration of matter in general relativity which might allow time travel must involve exotic types of matter with negative energy as viewed by at least one observer.

It is interesting that almost all the episodes in Star Trek involving time travel or temporal distortions also involve some catastrophic form of energy release, usually associated with a warp core breach. For example, the temporal causality loop in which the *Enterprise* was trapped resulted only after (although the concepts of "before" and "after" lose their meaning in a causality loop) a collision with the *Bozeman,* which caused the warp core to breach and thereby caused the destruction of the *Enterprise,* a series of events that kept repeating over and over, until finally in one cycle the crew managed to avoid the collision. The momentary freezing of time aboard the *Enterprise,* discovered by Picard, Data, Troi, and LaForge in the episode "Timescape," also appears to have been produced by a nascent warp core breach combined with a failure of the engine core aboard a nearby Romulan vessel. In "Time Squared," a vast "energy vortex" propelled Picard back in time. In the original example of Star Trek time travel, "The Naked Time," the *Enterprise* was thrown back three days following a warp core implosion. And the mammoth spacetime distortion in the final episode of *The Next Generation,* which travels backward in time and threatens to engulf the entire universe, was caused by the simultaneous explosion of three different temporal versions of the *Enterprise,* which converged at the same point in space.

So, time travel in the real universe, as in the Star Trek universe, seems to hinge on the possibility of exotic configurations of matter. Could some sufficiently advanced alien civilization construct a stable wormhole? Or can we characterize *all* mass distributions that might lead to time travel and then exclude them, as a set, "on physical grounds," as Einstein might have wished? To date, we do not know the answer. Some specific time machines—such as Gödel's, and the cosmic-string-based system—have been shown to be unphysical. While wormhole time travel has yet to be definitively ruled out, preliminary investigations suggest that the quantum gravitational fluctuations themselves may cause wormholes to self-destruct before they could lead to time travel.

Until we have a theory of quantum gravity, the final resolution of the issue of time travel is likely to remain unresolved. Nevertheless, several brave individuals, including Stephen Hawking, have already tipped their hand. Hawking is convinced that time machines are impossible, because of the obvious paradoxes that might result, and he has proposed a "chronology-protection conjecture," to wit: "The laws of physics do not allow the appearance of closed timelike curves."

I am personally inclined to agree with Hawking in this case. Nevertheless, physics is not done by fiat. As I have stated earlier, general relativity often outwits our naive expectations. As a warning, I provide two historical precedents. Twice before (that I know of), eminent theorists have argued that a proposed phenomenon in general relativity should be