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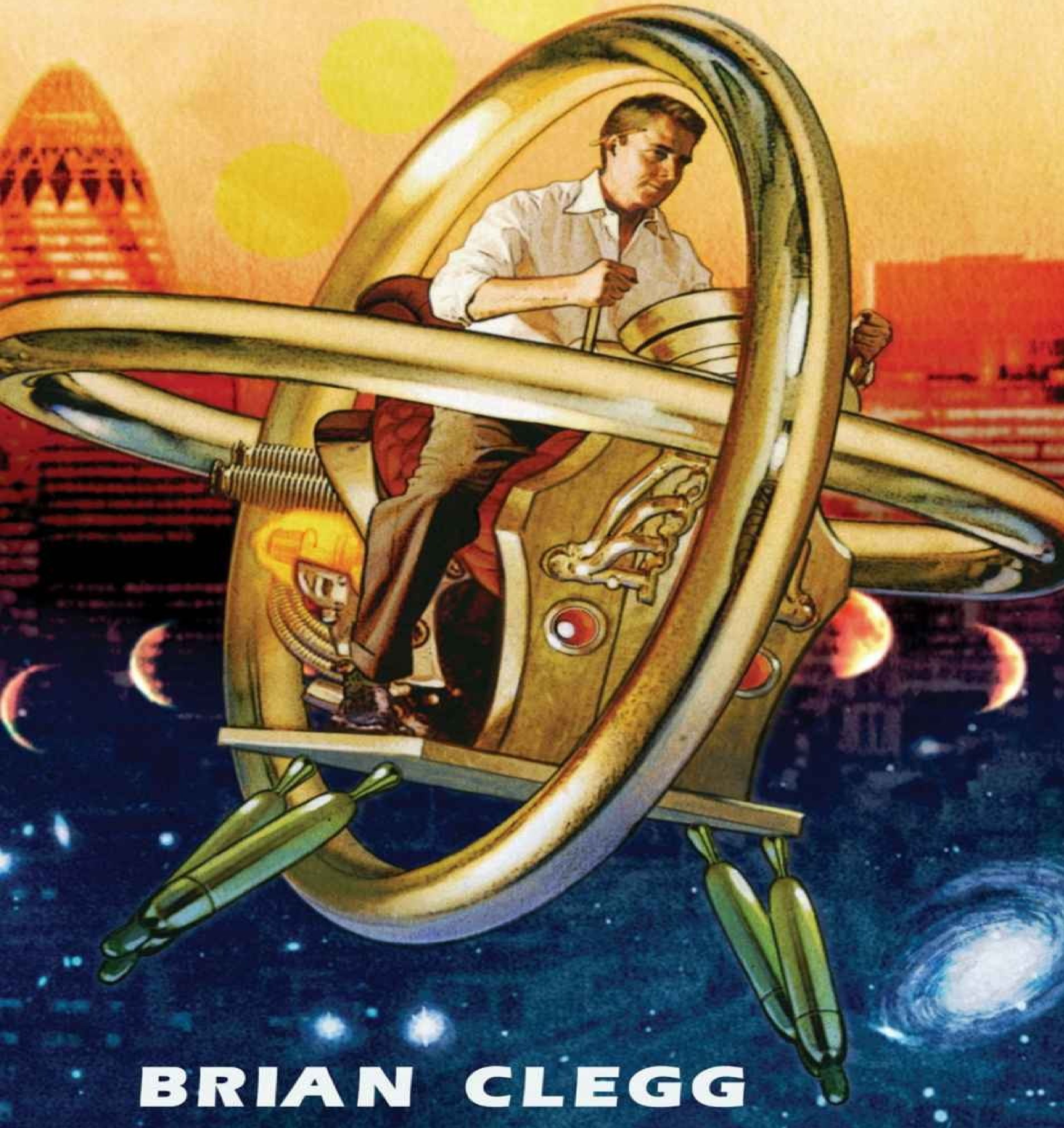
TIME MACHINE

The Real Science of Time Travel



BRIAN CLEGG

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Armageddon Science
Before the Big Bang
Upgrade Me
The God Effect
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Light Years
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BUILD YOUR OWN TIME MACHINE

THE REAL SCIENCE OF TIME TRAVEL

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DUCKWORTH OVERLOOK

First published in the UK in 2012 by
Duckworth Overlook
90-93 Cowcross Street, London EC1M 6BF
Tel: 020 7490 7300
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info@duckworth-publishers.co.uk
www.ducknet.co.uk

First published in the USA by St. Martin’s Press, New York

A catalogue record for this book is available from the British Library

eISBNs
Mobipocket: 978-0-7156-4350-1
ePub: 978-0-7156-4349-5
Library PDF: 978-0-7156-4348-8

FOR GILLIAN, CHELSEA, AND REBECCA

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ACKNOWLEDGMENTS

As always, this book would not have been possible without the expert help and support of my editor, Michael Homler.

Thanks to the many people who have helped me with information and ideas, including Dr. Marcus Chown, Professor Michio Kaku, Professor Ronald Mallett, Dr. Peet Morris, Professor Günter Nimtz, and Professor Ian Stewart.

CHAPTER ONE

A GLITTERING METAL FRAMEWORK

> *“Clearly,” the Time Traveler proceeded, “any real body must have extension in four directions: it must have Length, Breadth, Thickness and—Duration. . . . There are really four dimensions, three which we call the three planes of Space and, a fourth, Time. There is, however, a tendency to draw an unreal distinction between the former three dimensions and the latter.”*
>
> —Herbert George Wells (1866–1946),
> *The Time Machine* (1895)

Everyone can travel in time. Our adventures in this mysterious dimension are limited, but they exist. As far as forward travel goes, we are all on a conveyor belt through time, rolling into an uncertain future at a rate of one second per second. Inexorably we glide into the future, converting it into the present just as the moment that was once the present becomes the past.

We can also all travel backward in time, but this experience is quite different from our stately forward motion, uninterrupted except by death. Our travels backward are through the medium of memory, and lack that smooth steady progress of our forward motion. Instead, we jump around from time to time with startling rapidity. One moment we might be at a point in our childhood, which for some could be seventy, eighty, ninety years away. The next thing we know our memories are focused on events from ten minutes ago. There is no constraint to the speed at which memory can jump around in time.

You might argue, “That’s just memory; it’s not time travel.” After all, memories aren’t real. You aren’t actually there. But consider just how much your memories define who and what you are. Without them, you aren’t the same human being—this is what is so distressing about the onset of neural diseases where an individual loses his or her memories. The journey back in time produced by a memory may not involve being physically transported, but it is much more real to us than many objective “realities.” A strong memory will far outweigh a news report from the other side of the world. The news may reflect something that is happening at that moment in time, but for the observer it could something that is happening at that moment in time, but for the observer it could have relatively little significance.

There are even tourist destinations in the segments of time that have been relegated to history, points in our personal past that are hugely popular destinations for a whole host of mental time travelers. Most adults can remember where they were and what they were doing on September 11, 2001. These so-called flashbulb memories can be distorted like any other recollection. Yet this does not take away the fact that they are specific points in the time stream that many individuals can pinpoint and identify.

For those of us who are older, another date is a frequent destination, a date that is doubly significant for my personal interest in time travel. That date is November 22, 1963. Many people can remember what they were doing on that day when they heard the news that President John F. Kennedy had been assassinated. One of the effects of the terrible news was a disruption of TV schedules. And this was to have an impact on a show that was broadcast in the UK for the first time on the next day, Saturday, November 23, 1963.

The TV show was a new family drama called *Doctor Who*. Because so few people were watching TV in the aftermath of the Kennedy assassination, that first episode was repeated the following Saturday before the second episode was shown. It was *Doctor Who* that brought the concept of time travel to many British viewers, and later would be seen around the world. It proved an enduring concept, and after a break of a number of years, the show is again being made more than forty years later.

Although it wasn’t long after that I came across the H. G. Wells novel *The Time Machine,* it was *Doctor Who* that first got me thinking about what it would mean to travel in time. The show rarely explored the paradoxes and peculiarities of time, but early on it did indulge in visits to periods in Earth’s history, past and future. Before long, the writers would focus more on travel to distant planets and alien life, but it was always possible to use time as part of the story line. To be honest, I always felt a lot more affection for *Doctor Who* than for the sometimes labored political allegory of Wells.

However, we can’t dismiss that “glittering metal framework,” as the time machine is first described in the 1895 novel—it is hugely significant. Although traveling in time was not a new idea even then, fictional time travel before that book had relied on dreams or magic to transport the time traveler. In Mark Twain’s *A Connecticut Yankee in King Arthur’s Court,* for example, the central character, Hank Morgan, travels back to medieval England as a result of being hit on the head, and returns to the future after Merlin puts him into a magical sleep. (If your only experience of this story is the movie, read the novel—it’s a much darker and more thoughtful book than the on-screen version suggests.)

In books like Mark Twain's, time travel was fantasy, largely a mystical experience. But Wells transformed it into science fiction (even though that term was yet to be invented), a fictional concept of practical, solid achievement, opening up speculation about how time travel might be achieved and what the implications of traveling back to the Crucifixion, or visiting the far distant future of humanity, might be. Wells set us on the path of something more concrete, the product of the new, all-powerful science and technology that were transforming the real world—Wells brought us the time *machine*.

The idea behind his book was to become a standard of science fiction. Along with a number of other conventions—faster-than-light space travel, for instance—the concept of time travel would be used as the hook for a thousand stories. I absorbed a huge amount of science fiction as a teenager. It had, without doubt, a major role in my growing interest in real science. The possibilities for mind-bending storylines were endless.

Take Robert E. Heinlein's classic short story "—All You Zombies—" (often confused with "By His Bootstraps," which is also a time travel story). In this story, a time traveler returns to the past, where he unwittingly makes love to his own mother, fathering the child that will eventually be him. Later the mother, who turns out to have a genetic condition giving her both female and male sex organs, undergoes a sex-change operation. The now male mother is transformed into the time traveler himself. He has become a living paradox, a loop in time creating itself with no beginning and no end.

This sort of delightful paradox made time travel a gift to fiction writers, but the capability of freely moving around in time as if it were a true fourth dimension was assumed to be a fictional convention. It was the same kind of useful but unreal assumption as the ability to travel faster than light through some sort of "jump" or "warp" that has been common for many years in science fiction. But there was a surprise lurking behind that assumption.

There is no physical law that prevents time travel.

Reading those time travel stories involved a suspension of disbelief—but that was all that happened. No one really believed it was possible to build a time machine. It was fantasy rather than predictive science fiction. Time travel seemed so incredible that it would never be made real. Yet nothing in physics says we can't build such a machine.

Since 1895, when Wells published his book, science has moved on with frightening speed. And that progress has included the theories that makes time travel possible in principle. As we will see, turning these theories into practice has huge problems attached, which is why we haven't turned out time machines like automobiles off a production line. Yet look at the way technology sometimes moves forward. Consider how much of the technology that features in your everyday life was uncommon fifty years ago and unthinkable a hundred years ago. If we allow enough time, we may see time travel becoming real.

Unless we can use some sneaky possibilities of constructing small-scale time machines, the difficulties facing anyone wanting to make time travel possible mostly involve travel across huge distances or manipulating vast objects. These are difficulties that should, in theory, be possible to overcome as technology develops. It would seem that unless our current theories are incorrect, building a working time machine is only a matter of . . . time.

There are aspects of time travel that Wells got very wrong. His machine seemed somehow to work its way through time on mechanical principles involving an interaction between crystal structures and the time flow. Like many time machines in fiction, Wells's device proved remarkably easy to control. Little more was involved than setting the controls for a particular year and throwing a switch to head off to the past or future. Yet real time machines would almost all depend on an indirect means of time travel where such simple interaction with the timeline would not be possible.

Wells's machine also had an unusual symmetry when compared with a typical concept based on real science. In the time machine, it was as easy to travel into the future as it was into the past, and travel in either direction involved the same action, just like with travel in space. Most of *The Time Machine* is concerned with visits to the distant future, but the traveler returns in exactly the same way. However, some real time devices are likely to work in only one direction—and those that can be used either way will still need a different approach to select direction (usually traveling in one spatial direction to move forward and another to move backward).

In the Wells time machine, the traveler sits still and time shifts around him. This seems reasonable because that's how we experience movement in time on our day-to-day, second-by-second basis. However, most of the real mechanisms for time travel will involve moving spatially as well, reflecting the way that time and space are inextricably linked in the four-dimensional matrix of space-time. It is very unlikely that there will be a mechanism for time travel that doesn't involve motion.

We shouldn't be too dismissive of Wells, though. He does get one thing right with impressive accuracy. His protagonist explains that the time machine works by making use of time as a fourth dimension. This was a new concept back then, one that Wells addressed in fiction before it became a serious concept in science. Now, however, the notion of treating time as a dimension in an overall framework of space-time has become central to our understanding not just of time travel but of the universe as a whole.

Science would catch up with fiction when physical theory was transformed just a few years after *The Time Machine* came out, in the early years of the twentieth century. Our view of reality was about to be given a profound shock by a man who took this fictional concept of time as a fourth dimension very seriously indeed.

CHAPTER TWO

IT'S ALL RELATIVE

> *When a man sits with a pretty girl for an hour, it seems like a minute. But let him sit on a hot stove for a minute—and it's longer than any hour. That's relativity.*
>
> —Albert Einstein (1879–1955), allegedly in the *Journal of Exothermic Science and Technology (JEST)*

Two absolute essentials of real time travel are the linkage of space and time, and the influence of gravity on the space-time continuum. Both of these fundamental insights came to Albert Einstein in moments of dreamy contemplation. His two great concepts first emerged while he was resting on a grassy bank and while daydreaming in the office. Yet these idle moments would be crucial in our understanding of how time can be manipulated. To see where the ideas came from, we need to start a little earlier in the time stream.

The drab apartment block where Einstein was born on March 14, 1879, gave no indication of the greatness to come. It is no longer there: the building in the southern German city of Ulm was destroyed by a bomb in the Second World War. Young Albert's father, Hermann, from whom Einstein inherited his tendency to daydream, was a hardworking failure, a good counterexample to the old saw that if you try hard enough, you can achieve anything. Hermann put in a huge amount of effort, earnestly attempting to run businesses that had been funded by the family of Einstein's mother, Pauline, but he never had the focus, or the luck, that is necessary for success in business.

Although money was often tight, the Einstein family home seems to have been a happy one for Albert and his younger sister, Maria, or Maja as he always called her. But life outside the home was rarely to Einstein's liking. As soon as he started school, young Albert was to find irritation in a tense conflict between his urge to explore knowledge *his* way and the rigid educational system that existed in Germany at the end of the nineteenth century.

It seemed to Einstein that the system's role was to confine him, to stop him from discovering information and expanding his imagination. He had a stubborn streak in his personality, and the rigidity of the system made him inclined to rebel. From an early age he was unable to conceal his distaste for authority, and particularly for anyone who used his or her position to try to manipulate the way Einstein thought. Einstein was never one for following others, he liked to tread his own paths.

The dislike that Einstein felt for his educators was reciprocated. His first school was a Catholic establishment in the Bavarian capital of Munich (the Einsteins were ethnically Jewish but did not practice their faith). Einstein's father had moved the family to the city in a doomed pursuit of business achievements. The headmaster of the school once commented that it didn't matter what career young Albert tried, as he would never make a success of anything.

Things were different at home. There, playing with Maja in the overgrown wilderness that was their garden, or more often alone in his room, Einstein felt in charge of his destiny. At school he had no opportunity to do things his own way. The regimen was strict and rigid, a matter of following the rules, ticking the boxes, doing what was expected. Einstein found this stifling and infuriating in equal measures.

He might have hoped that things would get better when he moved on to the equivalent of junior high, but if anything they went downhill. The Luitpold Gymnasium took an old-fashioned approach, stressing a classical education above everything else. Einstein struggled with the Latin and Greek languages, which seemed entirely useless, and was bored by the humanities. His teachers in their turn thought him lazy and uncooperative (this was probably not too unfair an assessment).

Einstein was not the kind of person to give in when faced by this kind of opposition. He began to turn elsewhere for intellectual stimulation, relying more and more on books. A pivotal role in his development was played by a young friend of the family, Max Talmud. A medical student when Einstein first met him, Talmud was a regular at the family dinner table and entertained the young Einstein by passing on tantalizing and intriguing facts and bringing him the latest scientific books, often at a level that would stretch a university student.

The only thing that made Einstein's unhappy school life bearable was the stability and warmth of the family home. Yet this was to be taken away from him. In his latest business venture, Einstein's father moved his family to Pavia in the Lombardy region of Italy. This was not considered a suitable place for Albert to continue his education, so, reluctantly, he was left behind. With nothing to cushion the unpleasantness of school, and with compulsory military service looming—something the teenager knew he would find even more distasteful than school—Einstein cracked. He abandoned everything and headed off to Italy to join the family. His school then underlined the finality of his act by expelling him.

So at the age of sixteen, when most boys have little time for politics, Einstein set about persuading his parents to help him renounce his German citizenship. They weren't enthusiastic. Being stateless hardly promised a safe, easy future for their son. But Einstein was determined, and kept up the pressure until his parents had filled out the paperwork.

But it wasn't enough just to abandon Germany; he had to go somewhere. Einstein hardly spoke any Italian, making residence in Pavia unattractive. Instead, he settled on Switzerland. In part German-speaking, politically neutral, and almost obsessive about not interfering with the lives of its citizens, Switzerland seemed an ideal future home. And Zurich, a city in the German-speaking section of Switzerland, even had the perfect place where Einstein could build on his education by concentrating on science and technology. The Federal Technology Institute, known as the ETH after its German name, Eidgenössische Technische Hochschule, was the ideal establishment for someone obsessed with science. Einstein eagerly took the entrance examination. And failed.

Although the ETH was without doubt a center for excellence in science and technology, it expected its students to have a rounded education. Einstein was let down by his limited focus. He didn't care about any other subject; all he was interested in was science. To make matters worse, he was younger than the other candidates. The ETH was a university, not a high school. But the principal of the ETH was impressed by Einstein's obvious scientific ability and suggested that he spend a year in a Swiss high school before reapplying. The tactic worked. With support from the Wintlers, the family he was living with in Switzerland, Einstein broadened his knowledge, retook the examination, and passed with ease.

The environment of the ETH was totally different from that of his old-fashioned German schools. It had the academic depth and the concentration on science to keep Einstein's attention. But even there it wasn't plain sailing. The head of the physics department found Einstein's enthusiasm for taking his own approach overwhelming. He told his student: "You're a very clever boy, but you have one big fault: you will never allow yourself to be told anything." Despite occasional brushes with authority, though, Einstein was happy at the ETH.

Now, in stark contrast with the earlier years, it was the time that Einstein spent away from his family that was the best part of his life. His father had failed in another business venture and had been forced to take a regular job at low pay. Finances at home were dire and the mood was dismal, and Einstein tried to separate himself as much as he could from his family.

Although Einstein had found an intellectual home in the ETH, that didn't mean that he was the archetypal antisocial geek, more comfortable with formulas than with the opposite sex. He had a string of girlfriends, eventually meeting a girl who seemed very special. Her name was Mileva Maric, and Einstein became almost obsessed with her, perhaps in part because his usually successful charm was not winning Mileva's affection. Mileva would not return Einstein's attention until he had chased her for a good two years.

Even with the excellent science teaching available at the ETH, Einstein proved to be a poor student. He was very selective about which lectures he could be bothered to attend. If it had not been for his close friend Marcel Grossman, who made detailed notes of all the lectures Einstein should have attended, which he then used in frantic last-minute studies before the final examinations, there is little chance that Einstein would have received his degree. But with Grossman's help Einstein did graduate, only to go his own way once more, rather than follow a typical academic path.

The expectation was that someone like Einstein would apply for a post as a graduate student to cement his learning and work toward a doctorate. Instead, he looked for a job and hoped he could achieve a doctorate by dreaming up papers of his own devising in his spare time. This wasn't purely an extension of the rebelliousness that had typified his approach to academic life. Once Einstein had given up his German citizenship, he became stateless—not a good position to be in. He wanted to be accepted as a Swiss citizen, but this was possible only if he had a full-time job. He had no luck writing to well-known scientists, asking if they would take him on as an assistant, so he had to resort to teaching.

There is no record of the quality of the lessons Einstein gave, but it is entirely possible that like Isaac Newton before him, he was a better thinker than he was a teacher. Newton infamously lectured to empty rooms, so bad was his presentation style. Whether Einstein was good or terrible at inspiring others, he found the business of teaching took up too much of his thinking time. Once he gained Swiss citizenship in 1901 he began to search for a job that would be easier to coast through, giving him enough money to live on without distracting him from his real work. He saw himself as a solo adventurer, hacking his own way through the dense forests of unexplored science. It was his friend Marcel Grossman who would provide the answer to Einstein's employment needs.

Grossman's father was good friends with Friedrich Haller, the official who ran the Swiss patent office in Bern. Grossman introduced Einstein to Haller at just the right time, when a job vacancy had opened up. The post hadn't even been advertised yet. The position was patent officer (second-class), a role that involved working through the applications that came into the office and assessing whether they were worthy of a patent. After interviewing Einstein, Haller decided that his obvious intelligence and good grasp of theory made him an excellent choice for the post. The one irritation for Einstein was that Haller didn’t think he had enough life experience—so he was hired as a more lowly patent officer (third-class).

It might seem a job like this was tedious beyond belief for someone with a mind like Einstein’s, but in fact he found a satisfaction with his life that he hadn’t had since he was a child. He seemed to enjoy the stability of the work and reveled in the opportunity it gave him for free thought. Einstein wrote to his fiancée Mileva before she moved to join him: “It’s delightful here in Bern. An ancient, exquisitely cozy city.” By the time he was twenty-six, Einstein and Mileva were married and had a new baby son, Hans Albert.

Einstein was thrilled to have a child, but there was always a nagging memory whenever he saw the baby. This was not their first child. Mileva had given birth to a baby girl, Lieserl, before she came to Bern. At the time they were unmarried, and it was before Albert had a settled job. It had seemed impossible to bring up the child. Exactly what happened to Lieserl is unknown. Not surprisingly, given Einstein’s eventual fame, huge efforts were made to trace her in later life, but she was never discovered. It’s probable she was sent to Hungary to be brought up by Mileva’s family. Whether she survived the Second World War would never be discovered.

For the most part, though, Einstein was able to put aside thoughts of this sad start to his family life. Secretly, he had expected to find the job difficult—not because it was intellectually challenging, but because he considered himself poor at practical work. When he was at school he had written the usual essay about what he hoped to do when he grew up. He had said that he would end up teaching theory, as he had a “disposition for abstract and mathematical thought” but a “lack of imagination and practical ability.”

To Einstein’s surprise, the job at the patent office proved easy. When he read the applications, it was as if the inventions came into being in his mind. He might not be practical with his hands, but he was proving superb at assembling experiments in his brain. It was simple for him to visualize the inventions and to spot the flaws that made some of the ideas unworkable. The job was easy and low-pressure—ideal to give him time to concentrate on his own ideas. Giving the minimum attention to inventions, his mind took flight in the heights of theoretical physics. In one year, 1905, he would come up with three separate papers each of which was original and valuable enough to deserve a Nobel Prize.

One was on Brownian motion. This strange phenomenon, where small particles like pollen grains jump around in water, had been noticed years before.

At first the Scottish biologist Robert Brown, who recorded the effect, thought it was due to some sort of life force in the pollen. But he found that the same thing happened with ancient, long-dead pollen, and even with flecks of dust that had never been alive.

By 1905 a number of people had suggested that the jerky movement was due to water molecules smashing into the larger pollen grains and setting them in motion. But it was Einstein who produced a mathematical description of what was happening that matched observation. He provided the theory that showed that it was possible that atoms and molecules could cause such effects. It is hard to believe now, but the reality of atoms was still widely doubted at the start of the twentieth century. Many thought that atoms were just a useful model rather than real entities.

The second of Einstein's remarkable papers was on the photoelectric effect. This mathematical description of the way that light hitting certain materials would knock electrons out of them and generate an electrical current was the one that won the Nobel Prize for Einstein. It might seem that this was a relatively trivial item to study, but Einstein's new approach would have a radical effect on physics.

Einstein took literally the idea of the older German physicist Max Planck that light could be treated as if it came in little packets. Planck intended this idea only as a way of making calculations work, but Einstein worked on the assumption that light truly was made up of particles (which would later be called photons). This different way of looking at light not only explained the photoelectric effect, but also provided the foundations of quantum theory.

However, there was yet another paper written in that same momentous year, one that would make the first real time machine possible. This was a paper that would eclipse all the others in the minds of the public, if not of physicists. Few people might recognize the title, *On the Electrodynamics of Moving Bodies* (in the original German, *Zur Elektrodynamik bewegter Körper*), but the changes this paper would make to science would reverberate around the world. There are a number of conflicting accounts of how the idea first came to Einstein, but perhaps the best story (if not necessarily the most accurate account) is his daydream in the park.

According to this version of the discovery, Albert and Mileva had taken Hans Albert for a walk in Bern's elegant city park and Einstein decided to rest on a grassy bank while Mileva looked after the baby. Einstein lay back, picked a blade of grass, and shredded it between his fingers. As he did so, he let the bright sunlight filter through his half-closed eyelids, enjoying the warmth of the Sun on his face. His lashes split the light into a hundred flickering beams. Einstein pictured the light itself, imagining it flowing through space like an incandescent river. He allowed himself to float with the river of light, riding on the sunbeam. It was pure mental relaxation.

Next day, working through the patent applications at the office, he let his mind wander back to that moment in the park. He imagined floating along with the sunbeams. What would he see? He was not limited to dreamy considerations of sunlight. Albert Einstein was aware of what lay behind the visual. He had read a translation of the work of the Scottish physicist James Clerk Maxwell, who had shown that light was an interplay between electricity and magnetism.

According to Maxwell, light progressed because moving electricity generated magnetism, and moving magnetism generated electricity. If you could get these waves moving at just the right speed, the electricity made magnetism, which made electricity, and so on, hauling itself up by its own bootstraps to flow unsupported across space. But there was only one speed at which this would continue, a speed that gave Maxwell a huge shock. It was the speed of light. He had discovered just what light was.

Back in the patent office in Bern, Einstein must have put the patent applications aside, perhaps standing to pace around the office. There was something wrong that cropped up when he combined Maxwell’s elegant theory with his daydream of floating along with the sunbeam. As far as he was concerned, in the dream, the sunbeam wasn’t moving. He and the light were traveling at the same speed, and that meant the beam was glittering unmoving beside him.

This was due to a concept called relativity, something that Galileo had first discussed hundreds of years earlier. If, for example, you are on an enclosed ship, moving steadily along on still waters without accelerating, there is no way of telling that you are moving. Relative to the ship, you are not in motion. Relative to the sea, you are moving—but so is the ship. From your viewpoint the ship doesn’t move; from the ship’s viewpoint you are stationary.

Similarly, when we think of ourselves as standing still on the ground, we need to remember that along with the Earth we are spinning around every twenty-four hours, shooting around as Earth orbits, and slamming across space at many miles per second with the Milky Way galaxy—at least if you measure your movement with respect to something outside the galaxy. All movement has to be relative to something, and when Einstein was floating along with the sunbeam, it was not moving with respect to him.

That made for a problem: if light wasn’t traveling at the one, specific speed that defined it, it couldn’t exist. Without moving at that speed the electricity would not generate enough magnetism, the magnetism would not produce enough electricity, and the whole thing would collapse. Einstein struggled with what he was seeing in his mind. Either Maxwell had got it wrong, or there was something very odd about light. And Einstein *knew* that Maxwell was right. So there had to be a problem with that daydream of floating along beside the sunbeam.

Common sense tells us that if we travel toward something that is moving, then it moves faster toward us than if we were still. If we travel away from it, it moves slower toward us. Relativity again. But light, Einstein realized, is different. Uniquely different. However we move with respect to it, the light continues to travel along at the same pace. In a vacuum this is very close to 300,000 kilometers per second, which is about 186,000 miles per second. Unlike everything else in the natural world, light *has* to travel at the same speed from any viewpoint.

Einstein wasn’t the first to realize that there were some strange consequences of the way light moved, but he was the first to pull the whole picture together. Over the next few weeks, in his spare moments at the patent office, Einstein worked through the consequences of his realization—and even he found the implications startling.

When this invariant speed of light was plugged into the equations of movement, other things had to give. Things that we generally assume are unchanging had to vary. Anything moving at near the speed of light, Einstein realized, would experience phenomena totally different from the everyday. When the speed of light was fixed, measurements that had previously been constant—an object’s mass, its size, and even the passage of time it experienced—became variable.

As an object approaches the speed of light it shrinks and gets hugely massive. Time for that object becomes detached from the progress of time in the slow-moving world. If we could compare a clock sitting beside us with one on a spaceship flashing past at nearly the speed of light, the one on the ship would have slowed down, getting slower and slower as the ship approached the speed of light and stopping entirely if it could ever achieve such a speed. This isn’t just an optical illusion—as far as the observer on the ground is concerned, time on the ship actually has slowed down.

We can see how this would happen by using a very special kind of clock, a clock where the pendulum is a beam of light. Imagine that a spaceship zooms past us at nearly the speed of light. On that ship is a clock consisting of a pair of mirrors, one above the other. Inside this unusual clock, the equivalent of a pendulum swing is the light traveling from the top mirror to the bottom and back again.

Now let's look at that clock from the point of view of the person watching the spaceship pass by (we have to assume the ship is transparent). We see the light pulse leave the top mirror. As it travels downward the whole mechanism moves sideways. So by the time the light reaches the bottom mirror, the light will not have traveled the shortest vertical distance between the two mirrors. Instead it will have traveled down a longer diagonal line. It will take the light longer to get to the bottom mirror than it would have if the ship had not been moving.

Similarly, when the light heads back to the top mirror, it will travel at an angle from the viewpoint of our outside observer. It will once more head off along a diagonal. So the distance it has to travel to get back to the top mirror will be greater from the outside observer's viewpoint. If the time taken for the light to make the journey, the equivalent of a pendulum swing or a clock's tick, is longer, then the clock is running slower from that outside viewpoint.

You might be thinking, "Yes, but this works only if the clock is positioned vertically with respect to the motion of the spaceship. What if we turn the clock on its side so the light moves back and forth in the same direction as the ship?" You will still measure exactly the same slowness in the light clock, but the calculation is rather more complex, as you have to take into account both the movement of the clock and the contraction in the direction of motion that Einstein's theory from 1905 predicts.

This effect of time dilation is most obvious when something is traveling at close to the speed of light. At the everyday speeds of items around us it isn't noticeable, which is why Newton's laws work pretty well without taking such changes into account. But modern instruments can detect variations at these levels—and show that Newton didn't quite get it right.

Atomic clocks, slicing time into fragments of less than one-billionth of a second, are small enough to fit into a suitcase. Take two of these hyperaccurate timepieces and synchronize them exactly. Fly one around the world while the other stays firmly on the ground. Place the clock from the plane back alongside its earthbound equivalent. Compare the times now—and the clock that made the journey will have fallen behind, perhaps by thirty-billionths of a second. While it was on the plane, time was running fractionally slower.

A frequent flier ages around one-thousandth of a second less than a counterpart on the ground after forty years of weekly Atlantic crossings. If the speed of light were a lot slower, the impact of special relativity on space and time would have been obvious all along. In a world where light traveled at only a quarter of a mile a second, that same frequent flier would have aged a year less than the colleague who never took to the air. It's the immense speed of light that stopped Newton's laws from being questioned sooner.

We can see this effect on time more clearly with particles called muons that can be found in nature traveling at near light speed. These particles are produced way up in the atmosphere when cosmic rays, high-energy particles from space, come crashing in toward the Earth. Muons decay very quickly, and they shouldn't survive long enough to make it to ground level. But because of Einstein's peculiar relativistic effects, their lifetimes are expanded by a factor of five as time slows for them. This gives them the opportunity to make it to the surface.

When Einstein published his paper, the strange view of the world it generated fascinated other scientists and the public alike. With his idea, dubbed "special relativity" (special in the sense that it's a special case because he considered only bodies moving steadily that weren't accelerating), Einstein found himself a worldwide media phenomenon. He could no longer remain hidden away in the patent office with his thoughts. This time around he was to take academia by storm.

Though the first academic approaches were to give him honorary degrees, in 1909 Einstein was offered the new chair of theoretical physics at Zurich University and left the patent office behind. It was also in 1909 that for the first time he undertook that rite of passage of the scientist, giving a paper at a conference. In this paper he revealed an equation that emerged from special relativity and that would always spring to mind when he was mentioned, now the most famous equation in existence: $E = mc^2$.

It might seem an obvious conclusion from the way that time slows to a standstill at light speed that if we were to travel faster than light, time would start to move backward—but that isn't a conclusion that it is possible to draw immediately. The light speed barrier is a kind of discontinuity in reality—we can't assume that things will continue in a steady fashion after passing through it (if that were possible). But the mathematics of special relativity does show indirectly that traveling faster than light opens up the possibility of moving backward in time. It all comes down to the relativity of simultaneity.

This is less complicated than the phrase suggests. From basic observations based on special relativity, we can see that the concept of two events being simultaneous is modified when the observer is moving. In a popularization of his work that he wrote, Einstein used the example of two lightning flashes hitting a railway line at the same time, but separated spatially. If you stood in the middle, and the light from both flashes arrived at your position at the same time, then you would know they were simultaneous.

However, if you were on a train, traveling down the track, you would see the flash you were traveling toward before the flash you were traveling away from.

Although the speed of light remained the same, the distance it had to travel altered. Now, relativity tells us that there is no special frame of reference. A frame of reference is really just a viewpoint of an individual. So one observer could be sitting on the track, the other traveling on a train. And because there is no special frame of reference, the view of the observer on the moving train is as valid as the view of the observer who isn't moving. Either two events can be simultaneous, or one can come after the other, depending on how you are moving.

Provided you don't move faster than light, if event A comes before event B in one frame of reference, you will never find the two reversed, so that B comes before A. However, once you do travel faster than light it's possible to show that there will always be a way to switch the order, to make B come before A. And once you can do that, with a little bit of fiddling about and traveling from place to place, you can move backward in time.

Special relativity provides a double opportunity for time travel. If you travel at a sizable fraction of the speed of light, time for you slows with respect to the outside world. In effect, you move forward in time. And if you can travel faster than light, you will have a means to move backward in time.

Special relativity was Einstein's first great contribution to the science of time travel. Although his second breakthrough came when he was established in academia, the idea behind it dated back once more to his time in the patent office. He later commented: "I was sitting in a chair in the Patent Office at Bern when all of a sudden a thought occurred to me. If a person falls freely he will not feel his own weight. I was startled. The simple thought made a deep impression on me."

The immediate impact of this thought may not be obvious, but let's first emphasize how true it is. The image that might first come to mind is someone skydiving, but he or she would be buffeted about by the air, so it's difficult to see that what Einstein said was true. But think of someone orbiting the Earth in a space station. We've all seen astronauts on TV floating freely. A simplistic idea of what's happening is that they have moved away from the Earth and they aren't affected by gravity, but this just isn't true.

If you took an object to the orbit of the International Space Station, which varies between around 300 and 400 kilometers above the Earth, left your object stationary above the Earth, and let go, it would fall. The gravitational attraction would be less than it is on the surface of the planet, but the object would still fall. The Earth's gravitational pull still has a significant impact as far away as the orbit of the Moon, or our satellite wouldn't stay in orbit. In reality, the astronauts and the space station, like our object, *are* themselves falling. But they fall in such a way that they manage to miss the Earth.

As well as moving downward, an orbiting space station (or astronaut) is also moving at a tangent, at 90 degrees to the surface of the Earth. Traveling like this alone would mean that the distance from the surface would constantly increase—if the space station wasn't falling, it would move out of orbit and head off into the solar system. It's the combination of falling and moving forward in a straight line that keeps it in orbit.

So people in free fall, like those on the space station, experience no gravity. Einstein deduced that acceleration—generally a change in velocity, and in the particular case of falling, the process of getting faster and faster as you fall—and being under the influence of gravity are essentially the same thing. They produce the same effects. They are equivalent.

There is one technical limitation to this "principle of equivalence." It is exact only when referring to a point but not when referring to a large object. If the principle of equivalence worked in every situation, it would be impossible if you were inside a spaceship without windows to know if you were being accelerated upward by the spaceship's motor, or if you were stationary on the Earth, feeling the force of gravity pull you downward. Both would pull you to the floor of the ship with the same amount of force. But the acceleration would be exactly the same at both the front and the back of the ship, while the pull of gravity would be very slightly different, as one end of the ship is nearer to the planet than the other. Looking at a particular point in space, though, equivalence holds.

From this simple idea would come Einstein's masterpiece, general relativity. This builds on the concept of special relativity to take in the real world where we aren't restricted to steady motion, and acceleration and gravity play their part. But general relativity is much more than an enhanced version of the laws of motion. It describes the behavior of the universe at the fundamental level—how space and time are influenced by the gravitational effects of matter.

Although mathematically general relativity would prove challenging even to Einstein, who needed help to deal with the complex multidimensional equations that lie at its heart, the concept behind it is quite simple. If the principle of equivalence holds, then effects that apply in an accelerating body should be interchangeable with the effects of gravity.

Einstein imagined being inside a falling elevator, and watching a beam of light that came in from outside and crossed the elevator as it fell. From outside the elevator, the light source was not moving, and the light clearly moved in a straight line; but from inside, it curved. In the fraction of time it took the light to cross the elevator, the elevator fell a little, so the light hit the far wall slightly farther up than expected. As he had decided that acceleration and gravity produced exactly the same effects, Einstein deduced that light's path should be bent as it passes close to a heavy object and comes under its gravitational influence.

But light travels in a straight line. How could he reconcile the two? Einstein envisaged the heavy object warping space itself, so that the straight line the light traveled along now passed through a curve in the fabric of space. This is often described as being a bit like putting a bowling ball on a tautly stretched sheet of rubber. The sheet distorts—warps—under the weight of the ball. A straight line drawn on the surface of the sheet now curves in toward the ball, so while a light beam will always be traveling in a straight line from its viewpoint, it will go in a curve from an outside observer's view.

The only difference between the rubber sheet and reality is that it is the whole of three-dimensional space that is curving when it encounters an object with mass, not a flat, two-dimensional sheet. This rubber-sheet model is useful to explain the way that light curves, but it isn't a perfect model. Usually you will see it used this way without thinking about another aspect of gravity. Imagine a heavy object like the Earth. Now we put another object—say a cannonball—in space near it. What will happen?

A simplistic application of the rubber-sheet model you will sometimes see is that the Earth produces a big depression in the rubber sheet. So when the cannonball is placed relatively near it, it will roll down into the depression—just as a cannonball placed in space will drop toward the Earth. Unfortunately, this use of the model employs a circular argument. What makes the ball roll down the depression in the sheet? Gravity. But we are using the sheet to explain the workings of gravity, so we can't use gravity as part of its mechanism.

It's a different picture when we consider light bending, or look at the path of a moving object, which takes a bent course as a result of gravity. In the model, the moving object is not rolling along the sheet but moving *through* the sheet, which represents space. As soon as we put a ball on the sheet, sitting outside of space, and allow it to roll down into the depression, we are distorting the model to the breaking point.

Once space is warped, our concept of straight lines is modified—and this will be important for the nature of the universe under the influence of general relativity. Just think of a conventional map of the world. You could draw a line from, say, New York to London and imagine naively that this was the shortest distance between the two places. But if you plot how planes actually fly the journey, you would draw a curve that headed quite a way north before coming back down to London. Why go out of your way like that? Because the map isn't reality.

A map is a projection. It takes the surface of the Earth, a two-dimensional object that is warped in a third dimension, and projects it onto a flat surface. When we really travel from New York to London, the plane is flying along a warped surface. And the shortest distance on such a surface is a curve called a great circle—a curve that looks ridiculously extended compared to a straight line when projected onto a map.

Similarly, in warped three-dimensional space the shortest distance between two points—the route taken by a beam of light—will become a curve, and the more that space is warped, the tighter that curve will be. In fact, it is more than just three-dimensional space that is warped. For along the way Einstein showed that, just as H. G. Wells had suggested, time acts as a fourth dimension. The “rubber sheet” that is being warped is not space, but space-time. Gravity has an impact on time as well as on space.

With the development of general relativity, Einstein had reached a peak of his success. Outside his working life, however, everything seemed to be deteriorating. The First World War had broken out. Einstein strongly opposed armed aggression and put a lot of effort and his new fame into supporting the pacifist cause, but with little effect. At the same time his marriage was falling apart. Einstein became ill after he had taken up a new position in Berlin, but Mileva stayed in Switzerland. It was a friend, Elsa Löwenthal, who nursed Einstein in his illness. The two became very close. Elsa was the opposite of Mileva. She was much more the hausfrau, not interested in science, but dedicated to Einstein. In 1919, after his divorce, Elsa became Einstein’s second wife.

As Germany moved into the 1920s, the official attitude of the country to Einstein became strangely ambivalent. Einstein the famous German scientist (his rejection of German citizenship carefully overlooked) was feted. A grateful state gave Einstein a house in Berlin by the Havel River as a fiftieth-birthday present. Yet at the same time, Einstein was portrayed as a Jewish scientist, which increasingly made him the subject of suspicion and slander. In 1932 he and Elsa left Germany, never to return. He was to find a new spiritual home in the Institute for Advanced Study (IAS) at Princeton University in New Jersey.

The IAS was set up by Louis Bamberger, a Newark businessman, and his sister Caroline. It brought together experts in the theoretical sciences (there were, and still are, no laboratories on the campus), alongside mathematicians and historians. It provided a relaxed environment where there was an opportunity to work without the distraction of students and lectures, something Einstein deeply appreciated. The institute provided all the good parts of a university (seen from an academic’s viewpoint) without the time-wasting chores. Here, with no teaching obligations, paid simply to think, he would remain happily for the rest of his life.

For more than twenty years at the IAS, Einstein put a huge amount of effort into trying to provide a theory that would bring together the working of all the forces of nature, so that electricity, magnetism, gravity, and the atomic forces could all be explained in the same way. Like all his successors to date, he failed, but that does not mean that he spent the time unproductively. He contributed his thoughts to a wide range of projects. For the first time, these included military applications. Although he remained a pacifist in principle, Einstein felt he had to support the Allies in the Second World War because of the sheer evil of the Nazi threat. He even encouraged U.S. president Roosevelt to begin researching the atomic bomb, as he was concerned that the Germans would get a working bomb before anyone else could.

Einstein didn't have any direct involvement in the bomb project, though. The atom bomb might have depended on his archetypal equation $E = mc^2$ in the way it converted matter into energy, but there was nothing about bomb-making in Einstein's theories. He was never interested in working at a practical level, and although he encouraged the president to ensure that the United States didn't fall behind, he might well have found it very difficult to work on a weapon of mass destruction.

In his last few years Einstein became more and more like the stereotypical absentminded genius, as the media had portrayed him. On one occasion he had to ring up his office to make sure exactly where he lived. He had some difficulty persuading the office, which had strict instructions not to give out his address, that it really was Albert Einstein they were speaking to. Early in the morning of April 18, 1955, in Princeton Hospital, Einstein died. The Einstein legend is remarkable, but like Newton's, it is well deserved. Some Einstein stories could well be exaggerated or even untrue, but even as myths they give an accurate picture of the man—and nothing can dim the contributions he made to science.

It's important to remember, though, that the Einstein of popular culture, the jovial, scruffy, elderly man with the shock of white hair, was not the Einstein who produced the theories of special and general relativity. Back in 1905, when he wrote his paper on special relativity, Einstein was twenty-six. A snappy dresser with short, neat dark hair, he looked nothing like those iconic images of his later life. This was a young, lively man, not an eccentric, absentminded old codger.

I have dedicated a chapter to Einstein because both special and general relativity enable us to manipulate time. This isn't just hypothetical theorizing—it's a fact that has a direct bearing on many of us who drive cars. The impacts of both special and general relativity on time have to be taken into account when operating the Global Positioning System (GPS) satellites. If these effects are ignored, the satellite navigation system would not work properly.

Special and general relativity have opposing effects on the clocks mounted in the GPS satellites. Special relativity comes into play because the satellites are moving with respect to the ground. This means the receiver on the ground sees the satellite’s clock as running slow. This has a direct impact on the use of GPS because the system depends on comparing clocks to get a fix on the location of your GPS receiver.

But special relativity isn’t the only factor. According to general relativity, clocks run slower under the influence of gravity. The stronger the gravitational pull, the slower the clock runs. This means that the clock on the satellite, under a weaker gravitational pull than the receiver on the ground, will run faster than it would if it were on the ground.

The two effects work in opposite directions, but they don’t cancel out, because the time shift produced by general relativity is stronger. Special relativity means that the satellites’ clocks lose around 7 microseconds a day (seven-millionths of a second), while general relativity means they gain around 46 microseconds a day, resulting in a net gain of around 39 microseconds a day. This might not sound like much, but GPS depends on split-second accuracy. Over time, the clocks would get further and further out of synchronization with the surface. If the GPS system didn’t allow for relativity, it would break down within minutes.

Just as both special and general relativity have an impact on GPS, each will contribute to mechanisms that allow for time travel. The important thing is that these are real, observed phenomena that result in the passage of time being modified. In everyday life, the effects are small because we don’t experience objects moving at close to the speed of light. But as travel rates get faster, or if truly massive bodies are involved, the effects are noticeable. If it becomes possible to go fast enough, the result can be a reversal of the flow of time. Or, at least, this is the hope of the scientists who are working on time travel.

Before we begin to understand the range of mechanisms that offer tantalizing possibilities of manipulating time, it’s worth taking a step back and examining time itself. After all, it’s difficult to work out how to travel through something if you don’t really know what you are dealing with. In doing so, we come up against a question that has terrified many a philosopher through the ages: What *is* time?

CHAPTER THREE

TIME PAST

> *We think we know what time is because we can measure it, but no sooner do we reflect upon it than that illusion goes.*
>
> —Robert M. MacIver (1882–1970),
> *The Elements of Social Science* (1921)

Most people find that time is a slippery subject to get their head around—and this is not a new problem. As long as there have been philosophers, human beings have pondered the nature of time. And struggled with it.

Greek philosophers battled the mind-bending aspects of time, and worried about whether or not it existed at all. A whole group of early philosophers, the Eleatic school—based in Elea in the south of Italy, near what is now Castellammare di Velia—dismissed most of the attributes of life we attribute to the passing of time—motion and change, for instance—as illusion. Their thinking comes through to us particularly strongly in the paradoxes that one of their number, Zeno, dreamed up to illustrate the oddness of our perception of change.

We don't know a lot about Zeno, except that he lived from around 490 to 425 BC and was a student of Parmenides. We also don't have any of Zeno's own writing, just the commentary of others on around forty of his entertaining paradoxes, of which two are particularly relevant to our consideration of the nature of time.

The first concerns Achilles and the tortoise, an unlikely unmatched pair who decide to set out on a race, with a surprising outcome. In the similar race in Aesop's fables, the tortoise beats the hare because of the hare's laziness and presumption. But here it is the nature of space and time (and a touch of generosity) that leads to Achilles' downfall and the tortoise's triumph.

At the beginning of the race, Achilles gives the tortoise a head start. It's only fair. Achilles is, after all, a hero. After the animal has traveled for a little while, Achilles sets off after it. It takes him very little time to reach the point the tortoise was at when he first started running. But by then the tortoise has moved farther. That’s no problem; it takes Achilles even less time to cover this new distance. But by the time he gets there, the tortoise has moved on again. And so it continues. Every time Achilles catches up with the point where the tortoise used to be, it has already moved on farther. He will, it seems, never catch it.

What is happening here is an illustration of the outcome of a particular kind of infinite series. Imagine the tortoise goes at half the speed Achilles does (it’s a particularly fit tortoise). Say Achilles gives it a one-second lead. Then it will take him half a second to catch up. In that time the tortoise will have moved the distance it takes Achilles a quarter second to cover. While Achilles is doing that, the tortoise will have moved the distance it takes Achilles an eighth of a second to run. And so on.

The resultant time that passes is the series 1 + ½ + ¼ + ⅛ + 1⁄16 + 1⁄32 . . . and so on. This is an example of a series where an infinite set of values adds up to a finite total—in this case, adding up those fractions all the way to infinity produces the value 2. So in practice, after two seconds, Achilles will power past the tortoise. Zeno’s paradox doesn’t hold Achilles up forever, because the infinite collection of movements takes only a small finite time to cover. But the paradox does fulfill its purpose of making the listener think about the nature of time and movement. Can you divide up time into an infinite set of infinitesimally small segments?

The other paradox of Zeno that is particularly fruitful when it comes to thinking about time is called “the arrow.” We have to imagine two arrows, one that has just left the bow and is flying through space, the other hanging motionless in space. Now let’s examine the situation at the moment in time that the first arrow is immediately above the second. We have to imagine examining a snapshot in time—quite an advanced concept for a period when photography wasn’t even conceived.

We see two arrows hanging in space, one above the other. At this moment in time, neither of them is moving. But here’s the thing. Let’s move on to the next moment in time. How does one arrow know to move, while the other stays the same? We can see no difference between the two arrows in the frozen moment, yet they behave totally differently. From a modern viewpoint there are clear differences. The arrows have different momentums, different levels of kinetic energy. Also, as Einstein’s special relativity shows, one arrow will perceive a clock on the ground differently than the other will. But still the paradox is another excellent stimulus to thought. If time really is divided into infinitesimal moments, in each of which a moving arrow isn’t moving at all, what is it about the passage of time that informs that arrow to change position in the next moment?

Zeno was concerned with the nature of motion and change, with just a glancing interest in time itself, but other Greek philosophers would take on time head on.

Perhaps the two best-known philosophers to ponder the realities of time in ancient Greece were Plato and Aristotle. Plato was born in Athens, around 428 BC. He may actually have been called Aristocles, Plato most likely being a nickname meaning “broad-shouldered.” He was the youngest son of an extremely wealthy family who dabbled in politics, but the upheavals following the final Peloponnesian War between Athens and Sparta made political activity a dangerous pursuit.

The execution of Plato’s philosophical master, Socrates, in 399 BC brought this message home with terrible force. Socrates was technically charged with heresy—neglecting the gods and introducing his own deities—but in reality, his crime was probably criticizing those in power. Socrates’ fate made Plato think that the study of mathematics, science, and philosophy was a safer option than the political life.

Plato’s approach to time was to tie it in with the concept of a creator god. In his *Timaeus* he describes the creation of the universe, which involves a “moving image of eternity” and “this image we call time.” He envisaged past and future as unreal extensions of the present, rather like the difference between movement and the body that is moving.

Aristotle, born in Stagirus in northern Greece in 384 BC, was a student at Plato’s Academy (not just an academy, but *the* Academy, set up in a grove of trees belonging to Academos). In time, Aristotle would become the most revered of the ancient Greek philosophers. He took Plato’s concept one step further, arguing that time, in effect, *was* motion. This seemed reasonable because time was always measured by motion—the movement of the Sun in the sky, or the movement of sand in an hourglass or water in a water clock.

Aristotle could not accept the nonexistence of past and future, because they are necessary for movement, his fundamental descriptor of time. If all you have is the present instant, there can be no movement, as Zeno had demonstrated with his arrow. In Aristotle’s world, if there were some strange circumstance where all motion ceased, where every atom (though Aristotle didn’t approve of the idea of atoms) came to a standstill, there would be no passage of time. According to Aristotle, time literally would not exist until motion began again.

Even better known, when it comes to his thoughts on time, was Saint Augustine, one of the most powerful minds in the early Christian Church.

Augustine was born into a farming family in AD 354 in Tagaste (now Souk-Ahras) in what is now Algeria, and became bishop of Hippo, a Roman city in North Africa, now called Annaba, also in Algeria. He was not without humor, famously remarking in his *Confessions* that he had prayed as a young man, “Grant me chastity and continence, but not yet.”

Confessions was written soon after Augustine was made bishop in 396. His ordination caused considerable controversy, both because he had been baptized abroad (in Milan, Italy) and also because he had experimented with various other religions and attacked the Christian Church before becoming a Christian himself. The criticism of Augustine was public and strident. His *Confessions* was his defense against his critics, but it also gave him an opportunity to explore the nature of creation as he saw it.

It’s hard not to feel sympathy for Augustine when he writes in *Confessions*,

> What is time? Who can explain this easily and briefly? Who can comprehend this even in thought so as to articulate the answer in words? Yet what do we speak of, in our familiar everyday conversation, more than of time? We surely know what we mean when we speak of it. We also know what is meant when we hear someone else talking about it. What, then, is time? Provided that no one asks me, I know. If I want to explain it to an inquirer, I do not know.

In trying to explain the nature of time, Augustine tells us that we can’t truly say that time exists, but rather it tends to nonexistence. By this he means that the past and future aren’t here and now, they aren’t part of the reality we directly experience—but equally, the present is constantly passing away. So in a sense time is more a direction than an entity.

Although Augustine wasn’t thinking of time machines, he does make one comment that is useful for us in wondering whether taking a journey through time is even possible. He says: “If future and past events exist, I want to know where they are. If I have not the strength to discover the answer, at least I know that wherever they are, they are not there as future or past, but as present. For if there [i.e., in the future] also they are future, they will not be there yet. If there also they are past, they are no longer there.” A simplistic view, yes, but an important one. If we are to travel to the future or the past, they have to become for us our subjective present.

It might seem frustrating, but although we have ways to describe time as part of the space-time continuum now, and even have the possibility of manipulating time, we don’t have much more of a view of what time *is* than early thinkers did. This is why you will find that practically every book written on time includes references to Aristotle and Saint Augustine. It’s a subject scientists don’t really discuss, leaving it to philosophers, and the philosophical approach doesn’t seem capable of giving us any useful scientific response.

It would be negligent to finish a discussion of the historical view of time without considering how we came to measure the passage of time the way we do. It is familiarly divided up into a mess of units—years, months, weeks, days, hours, minutes, and seconds—some of which are based on astronomical measurements, others on an arbitrary division that has little meaning for us anymore.

In principle the year, the month, and the day are all natural units of time. The year reflects the time it takes for the Earth to travel once around the Sun. The month ("moon-th") is loosely based on the time it takes the Moon to go through a full cycle of phases. And a day is the time it takes the Earth to go through a complete rotation.

The week is less straightforward, with strange origins that come in part from astrology. This is reflected in the names of the days, which were originally based on the five planets (other than Earth) known in ancient times—Mercury, Venus, Mars, Jupiter, and Saturn—along with the other two major heavenly bodies, the Sun and the Moon. In English only Saturday, Sunday, and Monday retain their astrological names, the rest being replaced by names based on Norse gods. So Wednesday, for instance, is named after Woden and Thursday after Thor. The other influence on the seven-day week was the Judeo-Christian tradition, which allowed for six days of work and a seventh, Sabbath day of rest.

We owe the division of the hour into minutes to the Babylonians, who operated a number system based on 60, which they had inherited from the Sumerians. (Seconds are a more recent concept, literally just a "second" such division.) Having twenty-four hours in a day came from an ancient Egyptian practice of dividing the day and the night into twelve hours each. (The number 12 is handy, being divisible by 2, 3, and 4.) Initially these hours were variable quantities—the darkness was divided into twelve hours and the daylight into twelve, which meant that the length of an hour would vary with the time of the year. Equal hours came into use only in medieval times as mechanical clocks became more popular.

Unfortunately, although the natural measurements that gave us the year, the month, and the day are good in principle, it's not possible for them to work accurately in practice. There aren't a nice round number of lunar months in a year as at 29.53 days there are around 12.37 in a year. And the solar year itself isn't an exact number at around 365.25 days. This led to trouble with calendars, which is reflected in the way our modern calendar has developed from the original Roman model on which it was based.

The first Roman calendar was a bizarre affair of ten months, covering 304 days. These ten months were named Martis (after the god of war), Aprilis (an obscure reference to the best time of year for raising pigs), Maius (probably after a local goddess), Junius (for Juno, the queen of the gods), and then, as if the Romans had run out of ideas, Quintilis (fifth), Sextilis (sixth), September (seventh), October (eighth), November (ninth), and December (tenth).

Soon after the calendar's inception, two more months, Januarius (after the two-faced god Janus) and Februarius (from the Latin word *februa*, festivals of purification) were tacked onto the year, bringing the total number of days to 355. It should have been 354 but even numbers were considered unlucky, so another day was arbitrarily added to make the length of the year an odd number.

This new version of the year was a great improvement on 304 days, but it still fell well short of matching reality. To cope with their year missing out on around 10 days, the Romans followed their Greek predecessors by adding an extra day or month now and again to try to even things up. The result was a calendar that lurched backward and forward across astronomical reality depending on the efficiency with which priests performed calculations and on political decisions about when it was appropriate to add these extra days and months.

Such an arbitrary mechanism did not fit well with the military precision that was Julius Caesar's trademark. According to the historian Plutarch, Caesar "called in the best philosophers and mathematicians of his time" to take the calendar in hand. The solution his working party settled on dated back to the Egyptian ruler Ptolemy III, but had been ignored up to then in the Roman world. It established a year of 365¼ days by the familiar approach of having three years in a row that were 365 years long, followed by a leap year that lasted 366 days.

Changing the length of the year wasn't enough, though, to bring things into line—the calendar had been allowed to drift away from reality for so long that the year 46 BC ended up an immense 445 days in length to restore the spring equinox (also called the vernal equinox) to its traditional date of March 25. The equinox, when the Sun comes into the same plane as the Earth's equator, roughly translates as "equal night," and this is sometimes interpreted as a time when day and night are the same length, though in practice the day is longer.

Caesar also changed the lengths of the months so that they alternated at 30 and 31 days, apart from the last month of the year, February, which had 29 days in a normal year and 30 in a leap year. Making the last month variable was sensible, but unfortunately Caesar then shifted February from its end-marker position by fixing the beginning of the year as January 1 instead of March 1. This brought the start of the year closer to the winter solstice (the shortest day), but made February a strange choice for the odd month out.

Beyond the minor changes of a day slipping back from February to January, and the renaming of Quintilis as Julius, after Caesar, and Sextilis as Augustus, after his successor, the basic calendar as we know it had been established. It’s a shame that Julius didn’t decide to change the other numbered month names, too, as his shift of the start of the year has left us with months nine to twelve labeled seven to ten. Yet even Caesar’s calendar was an approximation. That year of 365.25 days was still around eleven minutes away from the real year (as reckoned from one spring equinox to the next).

Did this really matter? What if the calendar did get several days out of synchronization with reality? Eventually, of course, the seasons would no longer correspond with the appropriate parts of the calendar, but it would take thousands of years for things to get really out of kilter. But such a drift did confuse farmers, who relied on the calendar for planting; and for the medieval Church, getting the calendar right was essential for the timing of religious festivals. Easter, for instance, should be the first Sunday after the full moon following the spring equinox.

As the thirteenth-century proto-scientist Roger Bacon pointed out, there was an increasingly bad match between the religious calendar and reality. What was the point of considering Sunday a holy day if every 125 years or so the special day shifted to a different point in the week? And what of the most important holy day of the year, Easter Day, the celebration of Christ’s resurrection? This too had begun to be celebrated on the wrong date thanks to the inaccuracies of the calendar.

By the thirteenth century, Bacon reckoned, the calendar had drifted ten days from reality, more than enough to mess up all the religious festivals. He argued in his great encyclopedia of science the *Opus Majus* (actually a huge six-hundred-thousand-word book proposal) that it was time for calendar reform. Bacon reckoned that by 1361 the calendar would have dropped yet another day out of synchronization with the real world. Something needed to be done. He suggested that a day be cut from the calendar every 125 years.

His plea went unheeded. It was not until 1582 that Pope Gregory XIII’s commission drew up a reformed calendar that instituted regular corrections to deal with the drift against astronomical reality. Although the new calendar vindicated Bacon’s ideas, being almost exactly as he had suggested it should be more than three hundred years earlier, he was given no recognition. What’s more, this new scheme was accepted at the time only in the Catholic countries. In Protestant parts of Europe there was suspicion of anything coming from a Catholic source. Great Britain and its then-colonies, America included, continued to drift in time until 1752 .

It’s often said that when the calendars were shifted to the modern Gregorian form, there were riots, demanding “our days back.” In fact there is little evidence of this, although there would have been considerable confusion over annual events. Just consider your birthday. Should you celebrate your birthday on the same date as the one you were born on, or on the anniversary of your birth, eleven days later? In Orthodox Christian countries, the new calendar was not adopted until the twentieth century, the latest to come into line being Greece in 1924.

The way we label time of day on our planet does give one trivial (if potentially entertaining) way to travel in time. Although the length of the day is based on the physical reality of the time it takes the Earth to make a full rotation, the way we divide time up across the surface of the planet is a matter of choice. As we have seen, the hour was an arbitrary division we got from the ancient Egyptians—but what hour is it at any particular moment in time?

The simplest approach would be to have the same time around the globe. Wherever you are it would be, say, 5:00 p.m. Or rather, it would be 17:00. Because that “p.m.” is a bit of a problem. We divide the day into “a.m.” and “p.m.,” short for *ante meridiem* and *post meridiem* (Latin for before the middle and after the middle)—specifically, before and after the middle of the day. If we had a fixed time for the whole planet, 17:00 would be in the morning in some places, in the afternoon in others, and elsewhere it would take place in the middle of the night. Times would be the same everywhere, but the time would no longer indicate what part of the day we experienced.

This doesn’t happen, because we have time zones. Before these were established, every place operated on its own local, sun-based time. There was no coordination of time, which could and did vary from city to city. Twelve noon in New York would be different from twelve noon in Boston. But the coming of the railways made it essential to be able to exchange times between different stations on the line. Time zones as we now know them were mostly introduced in the late nineteenth century. The current U.S. time zones, for example, were formalized in 1883.

The main time zones divide the world into segments that share the same time of day. If these were like the segments of an orange, each should be separated by 15 degrees of longitude, but in practice they are wiggly segments that veer here and there as they pass from pole to pole. The United States, for example, has four mainland time zones (excluding Alaska), from eastern standard time at five hours after Greenwich mean time (GMT) to Pacific standard time, eight hours after GMT. (A few locations around the world confuse matters by using half-hour and forty-five-minute variants.)

Some borders between time zones are at sea—and one particular border, the date line that separates one day from the next, is intentionally jagged so that it avoids landmasses. But with four time zones in the mainland United States, it’s inevitable that there are places where just taking one step means that you have moved an hour into the future or an hour into the past. Step across the border between Alabama and Georgia, for example, and you flip between eastern standard time and central standard time. This isn’t possible in China, which should cover as many as five time zones, but instead adopted a single universal time.

Another side effect of time zones is that it’s possible to arrive at the end of a journey before the time you set off. When the Concorde regularly crossed the Atlantic in three hours, travelers would arrive in New York two hours before they left London. Another trick that’s possible with time zones is to keep up with a new day. Fly at the right speed and you can spend a whole day flipping between New Year’s Eve and New Year’s Day. Or stand at one of the poles, and be in twenty-four different hours, all at the same time. (For practical reasons, both poles use GMT as their official time.)

From the point of view of serious time travel, this is little more than frivolous. We are exploiting the artificial time zones, which are just a convention to make our day-to-day measurement of time simple. Physics doesn’t recognize these distinctions. As all parts of the planet are essentially moving at the same speed, changing position on the Earth doesn’t change time. But the effect can be entertaining.

History, then, gave us some vague ideas of what time might be and a means of dividing it up. But surely modern science can give us a better description of the nature of time itself?

CHAPTER FOUR

TIME'S ARROW

> *Time flies like an arrow. But fruit flies like an apple.*
>
> —Anonymous—often used as an example of how difficult it is
> for computer software to understand the English language

Even when it seems that a modern scientist is going to explain the nature of time, we hit frustration. An obvious potential source for enlightenment is the book *A Brief History of Time* by the remarkable scientist Stephen Hawking. Of all living physicists, it is Hawking who is most often given the mantle of Newton, Einstein, or Feynman. Hawking is also instantly recognizable, remarkable for having reached his late sixties despite suffering from a form of amyotrophic lateral sclerosis, often known as Lou Gehrig's disease.

Some while ago I was in the quaint streets of Cambridge, England, and saw Hawking rattling along the cobblestones in his powered wheelchair. There could be no doubting who this was, he is such a familiar figure. This is all the more remarkable considering that he was expected to die in his twenties, before he could even complete his doctorate.

Hawking has been unable to speak for a good number of years, communicating using a computerized voice box that has become an audible trademark. A science fiction fan, he appeared in an episode of *Star Trek: The Next Generation* taking part in a poker game on the holodeck with other "historical" scientists. (He has also appeared on *The Simpsons*.) His book *A Brief History of Time* was the first of the new generation of popular science titles, going beyond a sense of wonder and description of the universe to explain the depth of modern physics in approachable terms. Or at least fairly approachable. It has been said the vast majority of copies of the book sold—more than 9 million worldwide—have never been read.

So have we here, in Hawking's book, a modern explanation of time that can take us beyond the medieval ponderings of philosophers? The title certainly seems to suggest so. And tantalizingly, in the first chapter, he hints that this will be the case. Among a list of deep scientific questions that he tells us have be the case. Among a list of deep scientific questions that he tells us have answers suggested by “recent breakthroughs in physics, made possible in part by fantastic new technologies” is “What is the nature of time?” But you can search the book from end to end for any suggestion of what time is or how it works. There is plenty on how we observe time, and how interaction with matter can change these observations, but nothing deeper. It seems this is a history of something that the author never gets around to defining.

Modern physics can be very pragmatic. Quantum theory, for example, relies on the idea “There’s no point worrying what quantum particles are; let’s just describe how they act.” Although some have attempted interpretations of quantum theory, most physicists long ago gave up worrying if light is a wave or a particle—it’s just light, and behaves in a certain, predictable way. Similarly, there seems to be limited benefit in discussing at length what time *is,* even though we can say how to manipulate it.

One distinction that can help with our understanding of time is the difference between a block universe and one of “unfolding becoming.” This is not a practical physical difference, but rather one of interpretation, like the different interpretations applicable to quantum theory.

The block universe was Einstein’s picture of how things are. It takes the idea of space-time to the logical extreme.

It’s easy enough to imagine the universe as a spatial entity. We may not be able to grasp the size—to begin with, we have no idea how big the universe is. If, as the big bang theory suggests, the universe is 13.7 billion years old, we know the limits we can see are 13.7 billion light-years in each direction. But because of the expansion of the universe, the light that took 13.7 billion years to reach us is coming from bodies that could be 40 billion light-years away now. And the universe itself could stretch much, much farther than this. It could even be infinite.

However, we can conceive of a vast “something” that represents the entire spatial content of the universe. The block-universe interpretation extends this model to include all of time—it envisages a four-dimensional block that is all of space and all time that will ever be, all of a piece. In the block universe, “now” is meaningless beyond a local, subjective observation. There is no difference between what we regard as past, as present, and as future. Incidentally, this view doesn’t make everything absolutely mechanical and deterministic. It can include the sort of probabilistic events that quantum theory demands—but these events take place within a monolithic block of reality. This can be achieved in a number of ways, for example by having a “many worlds” universe, where the universe splits into two blocks at each possible quantum decision.

The alternative view, unfolding becoming, depicts a universe that moves

The alternative view, unfolding becoming, depicts a universe that moves through time, traveling into an unknown and unknowable future. In this picture, unlike the block universe, there is a concept of “now” that applies to the whole universe, measured with respect to the cosmic background radiation that is thought to have emerged from the big bang. Rather than imagining a monolithic block, this conception depicts the universe as something constantly growing and transforming through time.

If the block universe is the correct picture, even if we managed to travel backward in time, we could never do anything that would change the future, at least within a particular quantum version of the universe. Because the future and the past already exist in the block, any action we take must already exist. (We have trouble with tenses emerging from time travel here. It might be more accurate to say that any action must will have existed.) By contrast, the universe of unfolding becoming has a different problem: the rate at which the passage of time occurs.

In the block universe it isn’t meaningful to talk of time passing at any particular rate, but in the unfolding picture the present “now” glides its way from past to future at a particular rate. But what is that rate? It’s popular to say a second per second (I did so in the opening chapter), but frankly, this is meaningless. If the “now” is moving, it moves with respect to time while also *being* time.

This confusion over units leads some philosophers to hold up the block universe as the more likely model for reality. Those who prefer unfolding becoming typically say that the “now” doesn’t move in the conventional sense. It’s a bit like the way we can regard light as a wave or a particle but it isn’t either really; it’s just light. The “now” progresses into the future but doesn’t move at a rate in the conventional sense.

In the end, both are interpretations, simple models, not necessary to make the math of time travel work, but useful for some in contemplating the nature of time.

One way modern physics has helped with our understanding of time is by providing a feel for the way that it, unlike the spatial dimensions, has an implied direction. As we’ve seen, the ancients associated time with movement, and Saint Augustine described it in a way that suggested that it has an inherent direction. We often hear the expression “the arrow of time” or “time’s arrow,” which reflects the apparent one-way nature of time’s flow.

This flow of time isn’t something we can take for granted. Most basic physics doesn’t distinguish between moving forward and moving backward in time. The physics view of the world is a bit like filming a pair of balls colliding on a pool table and bouncing off each other. You could run a movie of the collision in the opposite direction and it would look equally realistic.

Contrast this with our broader experience. The way we see the world is more like a movie of the sand running through an hourglass. Run that movie backward and it is very obvious that something unnatural is happening. It's this characteristic that makes time different from the other, spatial dimensions, where this is no preferential direction. Time has an arrow. What's more, it's this preferential direction that we are trying to break in order to move backward in time.

So where does time's arrow come from? Although this does not provide a total explanation, a lot of physicists would say that thermodynamics is very important to its existence. Developed to better understand the engines that powered the Industrial Revolution, thermodynamics is the nineteenth-century science of how heat moves from place to place; but the implications of thermodynamics are much more powerful than simply explaining how steam engines work.

It's important to have a basic grasp of thermodynamics in order to understand the concept of time's arrow, and it's easy to get hung up on the central feature of the second law of thermodynamics, a property called entropy. Just how important some scientists consider this second law to be can be realized when you hear what the great twentieth-century astrophysicist Arthur Eddington had to say on the subject:

> If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations [the equations that describe how electromagnetism works]—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in the deepest humiliation.

Thermodynamics came together at a time when the flow of heat was absolutely fundamental to the development of the Industrial Revolution. New types of engines, driven by steam, drew their motive power from the transfer of heat from place to place, and the laws of thermodynamics determine how that transfer happens.

The most basic law is the zeroth law (the novel numbering scheme arose because it was realized that this law was necessary only after the first law was established and named). This says that when two objects which can transfer heat between them have settled down into an equilibrium, no heat will flow. So if you have two objects at the same temperature in contact with each other, you won't find that one gets hotter and hotter while the other gets colder and colder—one won't influence the temperature of the other.

This doesn't mean that there won't be any energy moving. Temperature is a

This doesn't mean that there won't be any energy moving. Temperature is a measure of the overall movement of the atoms or molecules in something (anything). The faster they move, the higher the temperature. They are constantly moving—any atom above absolute zero (0 Kelvin, –273.15 degrees Celsius, or –459.67 degrees Fahrenheit) will be in motion to some degree. And this means that they will constantly be bumping against the adjacent body, giving and receiving energy. But the zeroth law tells us that the net flow of energy will be zero. It balances out.

The first law is equally straightforward, and is really just a restatement of the idea that energy is conserved. It says that the energy in a system (we'll come back to that "in a system") changes to match the work it does on the outside, or that's done on the system, plus the heat that is given out or absorbed. Work and heat are just different forms of energy, so all the first law says is that the energy in something will stay the same, apart from the amounts that flow into and out of it. Energy can't be magically created or destroyed.

Then we come to the second law, which is the big one as far as we are concerned. One way of looking at it, which reflects its origins in trying to understand steam engines, is that heat will move from a hotter part of a system to a cooler part. It can also be phrased "In a closed system, entropy stays the same or rises." That definition depends on understanding what entropy is—more about that in a moment.

For completeness, the third law of thermodynamics says that you can't get a body down to absolute zero, the coldest possible temperature, in a finite sequence of steps. You can never quite make it to 0 Kelvin. In one respect this emerges from quantum theory. According to the uncertainty principle, we can't know a particle's position and momentum exactly. But if we managed to get a particle to absolute zero it would stop moving. (That's effectively the definition of absolute zero; it's why there's nowhere lower in temperature to go.) Then we could know both where it is and its momentum (zero). Which isn't allowed.

Let's go back to the second law because this is the one of interest to us in trying to understand time's arrow. It says that in a closed system, entropy stays the same or increases. Entropy is a mathematical measure of the disorder in a system. Although "measure of disorder" sounds like a fuzzy concept, kind of like "how messy things are," it has a specific mathematical definition, based on the number of states that the system can be in.

In the real world, we take the view that entropy stays the same or increases as a matter of course. You can look at entropy as being the number of ways you can arrange things. Let's say you've a full coffee cup in your hand. Then you drop it on the floor and it shatters. Compare the two states. There's really only one way to arrange the coffee cup full of coffee. But all the shattered pieces of cup and splashes of coffee can be arranged in many different ways.

We find it natural that it’s much easier to take the original full coffee cup and change it into the broken pieces and scattered fluid (just open your hand and drop it) than it is to take all the pieces and drop of coffee, rearrange the pieces until they all fit together again, and reinsert all the coffee into the cup. It’s easier to go from order to disorder, to increase entropy, than it is to go the other way. It takes work (sometimes a lot of work) to create order. And work, in the sense that physicists use it, is just energy being transferred from place to place.

Back in the nineteenth century a number of physicists, notably Lord Kelvin, James Clerk Maxwell, and Ludwig Boltzmann, interpreted entropy in a particular way. They took a statistical view of a large collection of small particles, using what would become known as statistical mechanics to make predictions. This approach is essential when understanding how something like a gas behaves, as it’s impossible to keep track of every one of the billions upon billions of molecules in a container of gas—instead, we have to understand its behavior overall, and to do so we use statistics.

Imagine a very simple closed system, two boxes with a small door connecting them. The left-hand box is full of gas. This consists of many billions of molecules, all dashing around at high speed. Having all the molecules in one box is a more ordered state than having some of the molecules in one box and some in the other. Having all the molecules in one place has less entropy than having them scattered between locations.

Now we open the door. After a while, all things being equal, we expect the boxes to settle down into a state where there are roughly the same number of molecules in each container. The statistical approach gives us a way of understanding *why* time’s arrow runs the way it does, making entropy increase. There is just one way to organize the molecules with them all in the left-hand box. There are billions upon billions of ways of organizing them with equal numbers in both boxes. If each possible way of organizing the molecules has the same probability, then there is a vastly higher chance we will end up with roughly the same number of molecules in each box than with all the molecules in one box.

It’s like the difference between the chance that a single number will win a lottery (your ticket, for instance), and the chance that any number other than your ticket will win. There are just many more different ways you can lose, so statistically the chances are very high that one of the other tickets will be the winner.

If this picture of the statistical nature of entropy is correct, then the gradual increase of disorder is pretty well inevitable. Not 100 percent, absolutely certain. There is a finite, if very small, possibility of the molecules randomly assembling themselves in one box, just as there is a finite but very small chance of your ticket winning the lottery. But without intervention, without putting energy into the closed system, it is very, very unlikely.

One potential problem with this statistical approach is that because most physical laws don't distinguish between movement backward and movement forward in time, you could argue that entropy should increase as you head backward in time from any point as well as if you head forward. This can be countered by observing that the universe has yet to be in a state that is anything other than highly improbable. It's only when it is roughly in equilibrium that there is any significant chance of a backward trip on the entropy roller coaster. At the moment, such equilibrium is a long way off indeed, considering all the structures like galaxies, stars, and planets (and people) that currently inhabit the universe.

The idea of a "closed system" in the definition of the second law of thermodynamics is very important. If you ignore it, you can get into all sorts of trouble with entropy. For example, the Earth's entropy has decreased over time. Originally it was a random set of molecules, a disordered mess, and we have ended up with some very ordered constructs in the form of living beings, animals and plants. People have much less entropy than a scattering of all the different molecules that come together to make them up.

Some have argued that this decrease in entropy proves that we have a creator, as without intervention, disorder would not have been able to decrease in this fashion. The order is there, they suggest, because someone made it happen intentionally. But you can't apply the second law of thermodynamics to the Earth alone. The law says that entropy will not decrease *in a closed system*, one where energy can't get in from the outside or leak away (because in the end, the laws of thermodynamics are all about movement of energy). The Earth, very clearly, is not a closed system. The only reason it functions the way it does is that we are constantly provided with a huge amount of energy from the Sun.

The Sun pumps out 400 billion billion megawatts of power (power is just the amount of energy transferred per second), of which around 89 billion megawatts are available on the Earth in the form of the sunlight that hits our planet. To put this quantity of energy in proportion, that is five thousand times the amount of power that all of humanity's current consumption requires using all the different fuels we employ.

This flow of energy into the Earth more than compensates for the localized reduction in entropy caused by the development of living beings. It is entirely possible to have one part of a system where entropy is decreasing while at the same time another part's entropy is increasing to more than compensate. The Sun's entropy increases all the time as energy and matter flow out of it.

Entropy was not a concept that was readily accepted when it was first devised. Austrian scientist Ludwig Boltzmann, who came up with the second law of thermodynamics in 1877, was largely ignored by the scientific community. After years of struggling to get recognition, he committed suicide, so depressed was he by the reception given to his theories. Not long after his death, his ideas began to be taken seriously, and as we have seen, the second law of thermodynamics has become one of the most respected postulates of physics. It's a central tenet against which any new idea involving energy is tested. Yet Boltzmann didn't live to see his triumph.

So the second law of thermodynamics gives us a clear picture for any closed system. Entropy is a one-way street. It can stay the same, but usually it will increase. And this gives us a possible clue to the origin of the arrow of time. The universe is by definition a closed system. (However, we need to remember that the bit we occupy may be only a tiny fraction of the total universe.) This being the case, we can expect the entropy of the universe as a whole to gradually increase. Taking in the big picture, we expect that the universe will gradually decay into chaos.

This means that the nature of the universe with respect to time is not symmetrical. Astrophysicists assume that the universe is symmetrical spatially. To make general relativity work, it is necessary to assume that the universe is basically the same everywhere. Clearly it isn't in detail. If you look into the night sky, it doesn't look the same in every direction. In some directions there are more stars than others, particularly in the fuzzy belt of the Milky Way. But general relativity assumes that averaging things out, there is no difference between one place and another, no special direction. Yet we can't make that assumption about time, because of the second law of thermodynamics.

Time's arrow, then, seems to be based on an inherent physical property of the universe. And it has a powerful influence on the way we experience the world. Information is closely linked to entropy. Think of the difference between a random set of bits and the bits that define the information on this page in my computer. The bits that go to make up this page are ordered in a specific way. Only one arrangement of them will produce the words as you see them. Flip one bit and a *g* might transform into a b, changing *gun* into *bun.* But there are billions of possible alternative arrangements of those bits. The information that represents the page has lower entropy—it is more ordered—than a random arrangement of bits.

The memories stored in our brains depend on the input of energy to arrange the data that make them up. Memory is a local reduction in entropy, at the expense of more energy being used up. As a result, our memory of things parallels the increase in entropy of the universe. It is fixed to time's arrow. Saint Augustine was worried about why we couldn't remember the future, only the past. The second law of thermodynamics implies an arrow that makes this the only reasonable way for things to happen.

A lot of the difficulty we have with time is that our sensory response to it is so variable. Compare the way we see distance to our sensing of duration in time. Yes, we can be fooled by optical illusions, and perspective can make things look different from the way they actually are, but our perception of spatial dimensions doesn't vary depending on how we are feeling. We don't say, "I'm bored, so this room looks twice the size it normally does." It's quite different with our perception of the passage of time.

Einstein once claimed to have undertaken an experiment into the nature of time. He quoted this as the abstract of his paper on the subject: "When a man sits with a pretty girl for an hour, it seems like a minute. But let him sit on a hot stove for a minute—and it's longer than any hour. That's relativity." The journal he claimed it was published in was called the *Journal of Exothermic Science and Technology,* and the full paper is supposed to describe him attempting to undertake the experiment in question.

To get his experiment off the ground he needed the help of a pretty girl, who in this case was movie star Paulette Goddard, introduced to Einstein by mutual friend Charlie Chaplin. I have only ever seen this paper referred to as a genuine, if humorous, academic contribution, though the acronym formed by the initials of the journal suggests that Einstein made the whole thing up. (Even the suggestion that Einstein undertook an experiment is in itself an indication that this is a joke. He was no experimentalist.) Despite the humor, though, Einstein was making a serious point. Time appears to flow differently depending on how we are occupied.

The measurement of the flow of time is often divided into subjective and objective time to reflect this. Subjective time is the passage of time we consciously experience—Einstein's hour seeming like a minute while with the girl, and a minute seeming like an hour when sitting on a hot stove. Objective time is the steady tick of the clock, uninfluenced by how we feel and what we experience, though as Einstein showed, modified by movement in space and by gravity.

Science tends to go straight for objective time. This is the time that experiments respond to. Even the saying that a watched pot never boils is a reflection of the subjective rather than true experience—in practice it will boil in the same measured time whether or not you watch it. It may seem to take forever, but that's purely subjective.

The subjective approach won't help us build time machines, but it is useful in exploring some aspects of the nature of time. A philosophical approach known as phenomenology put forward by a number of philosophers, most famously Martin Heidegger, suggests that the flow of time, the apparent continuous stream of events, is itself a subjective phenomenon.

This is a view that is probably easier to support now than it was when first proposed around the start of the twentieth century. With a better understanding of the human brain's limitations and complexities, we are now much more aware of how good the brain is at glossing over discontinuity. We perceive, for example, a continuous, steady field of view from our eyes. Yet we have a blind spot where the optic nerve joins the eye, a spot that our brain fills in with a best guess of what's there. And our eyes spend much of their time jerking around in the tiny high-speed movements called saccades, requiring constant compensation from the brain. The image that we "see" is a construct, not a real smooth, moving reflection of reality.

It is entirely possible that time is similarly a series of disjointed moments, that it has a real granularity, but that we can't distinguish this because of the way we perceive events. It's arguable that we don't really experience the flow of time at all, but rather the constant "now." We don't find ourselves slipping from past into future, but rather occupying a present that is itself slipping through time.

The problem we have in addressing the nature of time is that it is easy to confuse the impression we gain of time subjectively with a measure of reality. For example, many cultures have traditionally regarded time as cyclical, rather than linear as science considers it. This is a reasonable enough assumption given all the cycles we see around us—the turning of the seasons, the life cycles of animals and plants. Then there's day and night, and the cycle of the Moon from new to full and back again.

It's easy enough to extend this cyclical view to a model of the nature of time. This leads to ideas of a wheel of fate, of events repeating themselves, even of the possibility of reincarnation. Yet when we look at the physical world, the world we have to manipulate to be able to travel in time, there is no evidence of this circularity. It is another subjective effect, highly valuable in understanding human beings and how they think and perceive the world around them, but not particularly useful in bringing time under our control in a more significant way than merely speeding up or slowing down its subjective passage.

The linear view (incorporating the distortions of relativity that mean a "straight line" can be warped by the presence of mass) is the starting point of practical time travel. We need to bear this linear view in mind if we are to get a better feel for the key aspects of time itself, an exploration that often involves asking the same questions that Aristotle considered over two thousand years ago.

Does time have a beginning? In our current best model of the universe, the big bang, it certainly does. According to this theory both time and space originated around 13.7 billion years ago, at least within our part of the wider universe. (It is possible that there have been other big bangs in other sections of the total universe.) In this model there was a clear beginning to time for us, with no meaningful concept of "before" possible here. However, this is not the only workable scientific theory of the origin of the universe, and some theories do not require time to have ever started, but rather consider it to have continued eternally without beginning.

While the beginning of time is shrouded in mystery, there is less doubt about the end of time. Even in a universe with a clear beginning, like the big bang, we have no physical process for time to end. Our expectation of a big bang universe is that it will continue to run down. The second law of thermodynamics, the one that gives us entropy, gives us only one direction to go—toward increasing disorder.

At the ultimate, such a picture would see everything getting colder and less active until, to all intents and purposes, time came to a stop because there was insufficient activity for the progress of time to be measured. More accurately, time would be heading toward an end but—as this is an infinite process—would never actually reach it. In mathspeak, time would tend toward ending but would never actually achieve it.

Aristotle used the nature of time as an illustration of infinity. He said that time was infinite because it had no beginning or end. But he also thought that time was infinitely divisible. Think of any period of time—then you can halve it. There was, Aristotle thought, no stopping the division of time into smaller and smaller segments. So it should be possible, according to his thinking, to take any unit of time and produce an infinite set of subdivisions.

There is now some doubt about this view. Echoing the granular idea of the phenomenologists, some physicists suggest that space and time are actually made up of tiny chunks, rather than being a smooth continuum. The physical limit usually applied is the Planck length, a tiny distance constructed just from fundamental constants. These are basic measures of fixed values in the universe, like the speed of light and the gravitational constant that links an object's mass and the size of gravitational force it will generate.

It has been suggested—though there is no clear evidence to substantiate this—

that the quantum nature of reality may result in space being divided up into units of Planck length, which is around 1.6 × 10^{-35} meters. That’s a ridiculously small distance. 10^{-35} means one divided by one followed by thirty-five zeros. There are 0.16 billion billion billion billion such units in a meter.

If this truly is a limiting minimum distance, then a sensible minimum time for the universe to tolerate is the time it takes light, the fastest thing in existence, to cross a single Planck length, leading to the Planck time of around 5.4 × 10^{-44} seconds. This could be seen as the digital tick of time, the limit below which it is impossible to follow Aristotle and divide time smaller, because such a smaller division has no physical meaning.

In the end, whether or not time is digital, divided up this way, doesn’t influence our ability to manipulate it, but it is an interesting thought that time might have such component parts. If true, the Planck time is the “natural” unit of time, the measure of time that isn’t based on something as parochial as what happens in our solar system, or what works for human beings. But as a practical unit it is so small as to be entirely useless.

We may not have pinned down time in the scientific way that Stephen Hawking promised to, but we at least have a clearer idea of the way time is treated. With this in place, we have a starting point to look at the possibilities for traveling through time. Yet there is a simple argument that seems to put the whole possibility of time travel into doubt without worrying about how to achieve it.

A parallel argument was used in the 1950s by nuclear physicist Enrico Fermi when considering the existence of alien life. He was in the canteen at Los Alamos, eating with a group of other physicists. They had been talking about UFOs, which had recently been splashed all over the news. Fermi was silent for a while, then suddenly said, “Where is everybody?”

If the universe were full of aliens, Fermi was thinking, why hadn’t they turned up in a more concrete way than the vague and dissatisfying reports of flying saucers? Similarly, when considering time travel, we need to ask, “Where are the time travelers?” We may not have the technology to move freely through time yet, but if time machines are going to be built at some point in the future, why haven’t the time explorers come back to visit us?

CHAPTER FIVE

THE TIME TRAVELERS’ CONVENTION

> *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 independence.*
>
> —Hermann Minkowski (1864–1909), quoted in Peter Louis Galison, *Minkowski’s Space-Time: From Visual Thinking to the Absolute World* (1979)

It’s just before 10:00 p.m. eastern standard time on Saturday, May 7, 2005. The extravagant classical columns and vast frescos of Morss Hall at the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, echo with the sound of shuffling feet as an audience of around four hundred people moves outside to the courtyard of the East Campus dormitory in preparation for a very special event. In a few minutes, the time travelers are scheduled to arrive.

For the past hour or so, performers and speakers including leading cosmologist Alan Guth have entertained the crowd with music and speculation about the nature of the universe and time travel, but now the time has come for the highlight of the evening. Time travelers from any and every point in the future have been invited to turn up and join the party.

Out in the courtyard a mist of stage fog has been pumped out to add a sense of drama to the landing stage where the time travelers are supposed to appear, located in the unlikely surroundings of a volleyball court. Everyone waits with bated breath. In the excitement, someone shouts a confused “Happy New Year!”

But no one comes—at least no certified time travelers (though some might argue that one or two attendees are *certifiable*).

The idea was a simple one that might at first seem trivial but was, in fact, rather clever. If time travel is possible, why not flag a certain place and time in history and invite time travelers to attend? As long as information on the event percolated into the future—and a combination of Internet, print media, and TV coverage would seem to guarantee this unless our civilization were destroyed—how could any time traveler resist?

Of course, the organizers mostly had a fun stunt in mind, the kind of practical joke that students have pulled on the world since time immemorial. But if time travel really was going to be possible in the future, could every single owner of a time machine resist the urge to turn up and cause a stir? Surely someone would arrive. It seems that 2005 was the year when humanity suddenly realized that it was time to grab the attention of the time-traveling public. Just over a month before the MIT event, Perth in Western Australia also tried to flag down any passing time machines with its own permanent marker in time and space.

Rather than rely solely on less tangible digital and printed records, an engraved plaque was set in place in Perth that reads:

> *In the event that the transportation of life from the future to the past is made possible, this site has been officially designated as a landmark for the return of inhabitants of the future to the present day.*

The plaque identifies 12:00 noon local time on March 31, 2005, as “destination day” and invites those travelers to turn up at the plaque, located in Forrest Place, Perth, helpfully giving the latitude and longitude in case the plaque should end up being moved to a museum, rather than left at its original site. In large letters at the bottom, between the crest of the City of Perth and a dove of peace, it proclaims, “We welcome and await you.”

I can’t find any official description of what happened that day in Perth, but I expect there was some form of welcoming committee, eagerly anticipating visitors from the future to pop into existence. Of course now March 31, 2005, is in the past, and we aren’t so much awaiting them as have been were awaiting them (English tenses definitely aren’t designed to cope with time travel). But either way, no one made “destination day” his time travel goal of choice.

So why were these 2005 events (and an earlier one in Baltimore as far back as 1982) failures? Why aren’t we inundated with visitors from the future? Leaving aside these formal invitations, you would expect that key events in history would be crowded with sightseers. Go back far enough and we haven’t got good enough records of what went on, but think of a few relatively recent events for which we have good video evidence: the assassination of President John F. Kennedy, for example. These are the moments in time that stick forever in the memories of those who were alive. Surely they would also be moments that visitors from the future would want to witness.

Stephen Hawking argued for a long time that this lack of visitors from the future demonstrates that time travel isn’t possible, but he has changed his mind, and it’s just as well. Because he was very wrong on this one. His argument was simply illogical. There are several reasons why time travel could exist and yet we might never have (consciously) seen a time traveler.

It’s just possible that there is something special about the past that makes time

It's just possible that there is something special about the past that makes time travel impractical, even though it is physically possible. It's possible to argue that the past is a fixed certainty, so there is no way that it can be changed. We know what happened—it already has, and it's widely documented. Perhaps this makes it impossible for us ever to travel into it—because we know we didn't. The future, of course, is different (unless you take the block-universe viewpoint)—there's nothing fixed about that, so nothing prevents a time machine from operating.

Some would argue this is sophistry, not unlike the time COP argument we'll meet in chapter 13. To argue that things can't be changed because they weren't changed is pretty close to a circular argument—and there's nothing to say that we would be aware of a changed past. If the past were changed, it would merely become the past as we all remember it. It's not really a scientific argument.

Alternatively, to move to a possible reason that's based less on hand waving and logic chopping, it is quite possible that any civilization that is capable of making a time machine is also capable of hiding itself from our eyes. With the exception of the technologies discussed in chapters 7 and 8, we don't have any kind of time-travel technology yet, but we do already have very basic forms of cloaking technology to make things invisible.

The most promising approach for an invisibility cloak involves metamaterials. These are complex structures that have special physical properties as a result of the way they are constructed. They are often layers of lattices or patterns of tiny holes in a metallic sheet, and it is this special composition that gives them their properties. All natural materials have a positive refractive index. When light hits a block of glass or a mass of water, the direction of the light beam bends in toward a line at right angles to the edge of the material. But a metamaterial has a negative refractive index. Light is bent farther away from the vertical. This might seem a trivial difference, but it means that metamaterials can manipulate light in unexpected ways.

One important application of metamaterials is making lenses that go beyond the absolute limit of all normal lenses. There is a scale below which no conventional optical microscope can focus, however powerful it may be. If you try to observe an object that is smaller than the wavelength of the light used to view it, the result is inevitably failure. But this limitation is shattered by superlenses made from metamaterials, which can take optical focus down to detail that was previously detectable only with electron microscopes. Not only can such metamaterial lenses be built for a fraction of the cost of an electron microscope, but they enable a different kind of observation, just as radio telescopes and visible-light telescopes can work together in astronomy to get a more complete picture.

more complete picture.

But the application we need, more reminiscent of Harry Potter or of a Klingon Warbird in *Star Trek* than of traditional physics, is invisibility. Because of their negative refractive index, metamaterials can bend light around an object, making it disappear. This has already been done on a small scale with microwaves, but it is harder with visible light, as the materials used absorb too much of the light to work effectively. However, there are alternative mechanisms that either optically amplify the restricted output of the metamaterial, or use different techniques to control the way the light is diffracted, so we may still have invisibility cloaking in the not too distant future. It’s not at all inconceivable that time travelers from the future could be moving among us without ever being noticed.

It’s also possible that we will develop a form of time travel that won’t work with a human being. Several of the possibilities we will see for time travel apply only to light, not to matter. If this is the case, we could still send a message into the past (and perhaps we could have expected at least a few cables sending apologies from the future to the time travelers’ convention); but we would never see an actual time machine arrive from the future or meet a time traveler.

Last, there are physical restrictions attached to many of the potential means of time travel that would make visits to 2005 unlikely. As we will see, the time-travel mechanisms based on relativity (and that’s most of them) can’t send their payload back further than the moment in time when the time machine was first switched on, or to a point in time before the beginning of the spatial journey that is often necessary as part of time travel. For such time machines there is an absolute barrier generated by the physics. However good your technology, this barrier means that the earliest a time traveler would arrive is still in our future (unless someone has already created a time machine that we don’t know about).

There is one get-out clause for this last consideration, however. It’s just possible that we could use a time machine constructed by another civilization. Human beings won’t create a time machine until some point in our future (if we ever do), so that earliest point is yet to arrive. But imagine that an alien visitor set up a time machine here in our past, rather like the monolith discovered on the Moon in the movie *2001: A Space Odyssey*. In principle an operating time machine could already be in our midst without our realizing it, which would enable time travelers from our future to appear in the here and now. But most scientists would consider this pretty unlikely.

It’s useful that Stephen Hawking comes into the story with his early doubts about time travelers, because some speculation that Hawking has published gives us the chance to examine one other aspect of meeting time travelers from the future that is rarely considered. Do we really want to meet people from the future? Could they prove dangerous?

future? Could they prove dangerous?

In April 2010, Hawking discussed the possibility of meeting alien life. The aliens are almost definitely out there, he suggested. But rather than “seeking new life” for friendly purposes in good *Star Trek* fashion, he argued, we ought to be trying to hide ourselves. He drew a parallel with what happened when European travelers encountered technologically less-developed civilizations. On the whole, the less-developed civilization did not come off too well. The Europeans were more interested in getting hold of any local wealth and resources than in making friends.

Of course, as we have developed technologically, we have also tended to try to preserve other cultures—but we don’t know for certain that the same development would occur in a high-tech alien civilization. The visitors might be quite happy to ignore us—or even to wipe us out—as they raided the Earth’s resources.

Just as aliens could consider us an inconvenience, people from the future might not regard us as human beings with equal rights. If they evolved from our current form or are some cyborg hybrid of technology and flesh, travelers from the future could easily consider twenty-first-century humans unworthy of preservation.

Unfortunately, we can’t follow Hawking’s suggestion and avoid signaling our existence in this case; there’s not a lot we can do to stop the people of the future from knowing that we are here. Information will pass from the present to the future whether we like it or not. And if time-travel technology is eventually made possible, it really won’t matter whether or not we organize conventions for time travelers to attend. The visitors will come.

It seems our attempts to lure time travelers to a particular point in space and time have so far failed. As the organizers of the MIT convention commented afterward, “Many time travelers could have attended incognito to avoid endless questions about the future.” Maybe, although that rather spoils the whole point of turning up. I doubt that everyone could resist at least dropping a hint.

Yet we have at least to contemplate the possibility that the whole idea is fantasy, that it simply isn’t possible to travel in time. To counter this, we need a scientific principle that makes time travel possible. Luckily, there are several of these, and there’s one that’s absolutely commonplace. I can guarantee that you—as well as everyone else in existence—have already traveled in time. To be precise, every one of us has experienced time travel into the future.

CHAPTER SIX

BACK TO THE FUTURE

> *I never think of the future. It comes soon enough.*
>
> —Albert Einstein (1879–1955), interview given on the liner *Belgenland* (1930)

There is a fundamental flaw in pretty well every time machine you see in fiction. It's true of the time traveler's device in *The Time Machine,* it's true of Dr. Who's Tardis—and, yes, it's true of Dr. Emmett Brown's time-traveling DeLorean in *Back to the Future*. The mechanisms these time machines use for traveling back and forth in time are the same. You just set the dial and go. Yet the reality of time travel is unlikely to be like this. The mechanisms of forward and backward travel are usually going to be entirely different.

Einstein might have unified time and space, but there is a fundamental difference between time and the spatial dimensions. In space there is no difference between traveling forward and traveling backward. This might not seem so if you try driving backward on a busy highway, but that's a special case. Typically there is no distinction between directions. If I show you a car traveling along a particular line, there's no way to tell whether it's going in the "positive" or the "negative" direction. But it's easy enough to tell whether a movie of a cup smashing to pieces is running forward or backward. As we've already seen, time has an arrow, a natural direction of flow.

This means that traveling forward in time is the easiest thing imaginable. It's a form of travel that involves no exertion of energy. No effort. No fancy time machine. No activity whatsoever. Just sit back and wait. Since starting to read this chapter, you have already traveled a good few seconds forward in time without the least effort. It just happens at a solid, unchanging pace.

That's fine if you've got all the time in the world and don't want to go too far into the future, but it's not really what we envisage when it comes to time travel. We want to get to our destination quicker. Perhaps surprisingly, this is also

We want to get to our destination quicker. Perhaps surprisingly, this is also something you have done. On a regular basis you have speeded up your experience of progressing into the future.

Assuming you didn’t have a sleepless night, the chances are you have passed through the last twenty-four hours at a rate of more than one objective second per subjective second. I don’t need to invoke the way subjective time drags out if you are bored or compresses when you are interested—this is a more solid block of high-speed time travel. Because for the portion of time when you were asleep, you did not experience the hours ticking past. If you had seven hours’ sleep, you got through the last day and night in just seventeen subjective hours (plus perhaps a little time for dreaming, if you can recall any from last night).

This feels like a cheat. Subjective time, as we have already seen, is fickle. Can you really say you got through the last day and night in seventeen hours if it included sitting through a lecture (say) that was supposedly forty-five minutes, but felt like three hours? There is a difference, though, between subjective time varying in speed a little and the time travel provided by unconsciousness, as some individuals can clearly attest. These are people who have experienced a significant leap into the future as a result of a coma.

Arkansas man Terry Wallis recovered consciousness after spending nineteen years in a coma. In July 1984, when he was twenty, Wallis was a passenger in a car that crashed. He awoke in 2003 to discover a whole new world. He had missed the *Challenger* accident and the Chernobyl nuclear reactor explosion, the Pan Am Lockerbie bombing and 9/11, Nelson Mandela coming to power in South Africa and the Clinton administration at home, Princess Diana’s death and the Columbine massacre. Although Wallis was not in a deep coma during most of the period, his experience had compressed those nineteen years into a much shorter time.

Comas can be medically induced, but only for a relatively short time. And even if a coma could safely be produced for, say, twenty years, it would not be an ideal way to travel into the future. Leaving aside the vulnerability of the traveler—would you really be happy to be in a state where you were totally at the mercy of others for years at a time?—being in a coma does not prevent the body from aging. Yes, you would wake up twenty years in the future, but with a body twenty years older. Ahead of you would be twenty years less of your life to live—and that is hardly ideal.

For some time now a number of companies have offered a mechanism that is supposed to get around this by stopping time for your body. This is cryogenic storage as a way of traveling into the future. The idea here is that your body will be stored, preserved at extremely low temperatures, until the technology exists to defrost you, revive you, and cure you of any illness you were suffering from. The assumption is that by the time you are revived any aging will be reversible, any biological problems will be able to be overcome—provided the essence of "you" was preserved in the frozen corpsicle.

This approach has limited appeal for time travelers, as you have to be dead before you can start on your journey through time. (To be more precise, the procedure would be legal only if you were dead before you used it—you could in principle undergo freezing while still alive.) For most, this is too high a price to pay to travel into the future unless they are dying anyway.

Even if you qualify for the journey by being deceased, there are significant doubts about the practicality of cryogenic storage of human bodies given current technology. We know that embryos can be stored cryogenically—they routinely are as part of in vitro fertilization procedures. But these embryos are just simple bundles of cells with none of the complex structures of a human body. We have no certainty that a human body (and particularly a human brain) could be restored in the future. Nor do we know for certain that a frozen brain would retain the memories and personality of an individual indefinitely.

Furthermore, those relying on cryogenics are putting a lot of faith in a third party to ensure that their cryogenic state is properly maintained. And a final problem for the would-be time traveler is the motivation for the people of the future who would have to revive someone from cryogenic storage. Imagine you had been on ice for a hundred years. Yes, there might well be a novelty value in restoring you, if it were physically and medically possible. As a one-off. But what about whole warehouses full of people? What would such throwbacks from the past contribute to a future society? You would have to make sure there was a cast-iron trust fund to pay for your revival. Altogether, cryogenic storage is not a very satisfactory means of time travel.

There has to be a more controlled way to get into the future—and there is, provided for us by Einstein's special relativity (with a little help from the general variety). Special relativity, as we saw in chapter 2, means that the time on a clock that is moving with respect to Earth is slower than time on the planet as seen from Earth. Here is a first suspicion of a possibility of painless time travel into the future. All we need to do is to send someone off in a spaceship at high speed for a time, and her clock will get further and further behind the time on Earth. She is moving into the Earth's future.

That's the simplistic view. But special relativity is more tricky than this. An absolute essential of relativity is that there is no special frame of reference. In other words, from the Earth's viewpoint it's true that the astronaut is traveling away at high speed, and that the astronaut's clock is falling behind. But from the astronaut’s viewpoint, everything is the other way around. She is stationary. From her viewpoint it is the Earth that is moving away at high speed—and it is Earth’s clocks that are falling behind. If she had some way to transport herself instantly to the Earth, she would arrive not in Earth’s future, but in Earth’s past.

Even so, as we saw in chapter 2, relativity experiments have been undertaken using two incredibly accurate atomic clocks. The clock that was flown around the world was a tiny fraction of a second slower than the one on the ground. Forty years of weekly crossings of the Atlantic do leave a frequent flier one-thousandth of a second younger. And to establish the impact of relativity more dramatically, we have the evidence of the twins paradox.

This is a famous thought experiment that envisages a pair of twins—we’ll say twenty-five-year-old Karl and Karla. Karl stays on the Earth while Karla travels off at high speed in a spaceship. When she returns home, perhaps ten years have elapsed for Karla—but she discovers that Karl is now seventy-five. The twins are now very different ages. Say Karla left in 2050. By her clock it is 2060 when she gets back to Earth. But on the Earth it is the year 3000. Karla has traveled forty years into her future.

This example causes no end of confusion because the twins paradox is very often used to illustrate special relativity. Yet, as we have seen, special relativity is symmetrical. In the basic world of special relativity there is no way to say which twin is moving and which is stationary. There isn’t a mechanism for Karla to travel into the future using the simplest form of special relativity, which is why it’s so confusing that the twins paradox crops up so often as an example of relativity in action. The twins paradox does work—just as that atomic clock flown around the world really was a little slow—but not simply because of the stretching of time caused by the time dilation when flying away at high speed.

Let’s start with Karl and Karla and check exactly what happens. The trick that makes the paradox work (and it does work) is in the detail. Karla’s spaceship accelerates up to a high percentage of the speed of light and travels away from home for five years. At the end of five years, it decelerates to stationary with respect to the Earth, then accelerates back to its high speed, but this time in the Earthbound direction. After another five years traveling, thirty-five-year-old Karla returns to Earth, decelerates, and lands, to find her seventy-five-year-old twin waiting for her.

The reason the twins are no longer the same age is that something has happened to Karla that didn’t happen to Karl. A force was applied to her ship to accelerate her up to speed, then applied again at the far end of travel to reverse her direction, before finally being applied yet again at the end of the journey. This force was not applied to Karl and the Earth. The symmetry of their position was broken—the spaceship underwent acceleration, while the Earth did not.

As soon as acceleration takes place, the straightforward symmetry of special relativity falls apart. Remember, the “special” in special relativity means it’s a special case. It applies only to bodies in constant motion (or that aren’t moving at all). There can’t be any acceleration for basic special relativity in an unmodified form to apply. If there is acceleration, we have to take it into account in the calculations. And it’s the acceleration that effectively resets the Earth clock from Karla’s viewpoint. She really has aged less than her twin who stayed at home—or to put it another way, she really has traveled into the future.

In the case of the atomic clocks used in the real experiment, things are even further adrift from having no acceleration. First of all, the clock on the plane, like Karla, experienced acceleration from being stationary alongside the other clock up to the flight speed of the plane—maybe 800 kilometers per hour (500 miles per hour)—and deceleration back to stationary when it had finished its journey. But something else was happening.

In the classic twins paradox, the spaceship shoots off in a straight line for five years, stops, turns around, and shoots back in a straight line. (The lines are not necessarily exactly the same, as the Earth also moves, and the spaceship has to aim for where the Earth is going to be when it gets back; but the lines can be straight nonetheless.) On the plane, things were very different. It didn’t fly in a straight line, but in a curve.

This makes a difference when we examine the exact definition of acceleration. Acceleration is not about just a change in speed; it’s about a change in velocity. And velocity has two components—speed and direction. A body is accelerating if either or both of these change. So anything moving in a curve, constantly changing direction, is constantly accelerating, and once again simplistic special relativity doesn’t apply. We need to correct for the acceleration involved.

The twins paradox may be more complex than basic special relativity, but it works—as has been proved by experiment—and it provides us with our best potential mechanism for time travel into the future. It’s not going to be easy to produce a big jump into the future, as we’ll see in a moment, but it’s much more straightforward than any of the means for traveling backward in time that we will encounter later in the book. It is clearly possible today with existing technology.

Let’s imagine Karla has managed to get her spaceship up to half the speed of light. That’s 150,000 kilometers per second (93,000 miles per second). Quite some speed. And let’s imagine that from the Earth’s viewpoint she has been traveling for 10 years. Then Karla’s clock would say she has been en route for around 8.65 years. She turns around and travels back. The same thing happens.

So by Earth time, the journey has taken 20 years, but Karla has aged 17.3 years. She has traveled 2.7 years into the future—but it has taken her a very long time to achieve it. I don't think many people would be willing to use up over 17 years of their lives just to travel 2.7 years into the future.

The implication is that to use the twins paradox as a way of traveling into the future, we would need to travel at significantly more than half the speed of light. Exactly how fast depends on how far you want to go into the future, and how long you want the journey to take. Get very close to the speed of light and you can achieve practically any time jump into the future in a relatively small journey time. But there is a price to pay. Acceleration comes at a cost, a cost that increases hugely as you get closer to light speed.

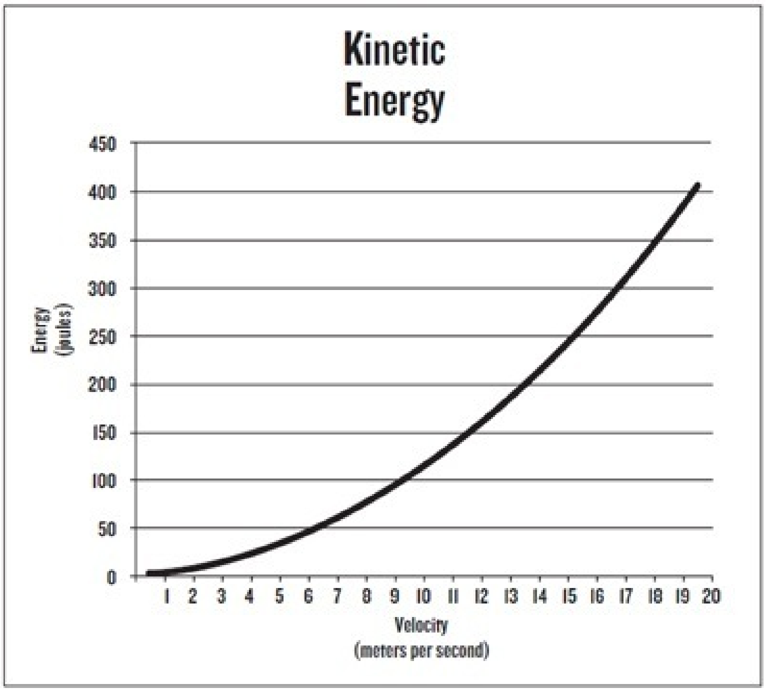
It's not that there is something inherently unachievable about velocities that are very close to the speed of light. Particle accelerators have pushed protons to better than 99.9999 percent of light speed. But to achieve this kind of speed with something a lot more massive than a single particle takes a whole lot of energy. Thanks to Newton's second law, we know that the more acceleration you want, the more force you have to apply. The force needed is just the mass you are trying to move times the acceleration you want. Multiply the force by the distance you apply it over and you get energy. So the more acceleration you want, the more energy you are going to need.

This is all classical physics stuff, the sort of thing you learn in high school. Another way to look at it is that the kinetic energy—the energy of movement—of the spaceship is given by the simple equation $\frac{1}{2}mv^2$, assuming we are sticking for the moment with Newton's view of the universe. The energy of motion of the ship is half the ship's mass multiplied by the square of its velocity. So you need to put in at least that much energy to get it up to any particular velocity. I say "at least" because if $\frac{1}{2}mv^2$ is all we need, we have to be able to convert perfectly into motion all of the energy we put into the spaceship. Admittedly there isn't much friction in space, but there will be some resistance from the gases and particles floating between the planets, and some of the energy will be lost as heat, so in practice the ship will need more than $\frac{1}{2}mv^2$.

Notice there's something worrying about that equation. The energy depends on the square of the velocity. A curve describing the amount of energy at a particular speed looks like this (I've kept it simple by making the mass 2 kilograms, so $\frac{1}{2}m$ is 1): As the velocity gets bigger, the energy starts to really shoot up. Let's do some simple sums. We'll assume we're dealing with a vehicle of similar weight to a space shuttle. That's around 100 tons, or 100,000 kilograms. And we'll go for a speed of 0.9c—90 percent of the speed of light. At this speed, Karla would age just 8.71 years on a journey that takes 20 years from the Earth’s viewpoint—she would travel 11.29 years into the future.

For practical reasons we’ll have to switch to scientific notation using 10^n, where n is the number of zeros after the 1, so 10^1 is 10, 10^2 is 100, 10^6 is 1,000,000, and so on.

The speed of our spaceship at 90 percent of the speed of light is 2.7×10^8 meters per second. So plugging our numbers into $\frac{1}{2}mv^2$ we get an energy requirement of $\frac{1}{2} \times 10^5 \times 2.7 \times 10^8 \times 2.7 \times 10^8$ which works out as 3.6×10^{21} joules. This isn’t a number that means a lot on its own. But let’s look at how much energy all the power stations in the United States put out. That’s around 450 gigawatts, or 4.5×10^{11} watts. One watt is a joule for a second. So all those power stations are pouring out 4.5×10^{11} joules every second. Impressive stuff. Only we need almost 10 billion times this amount of energy to get our ship to 90 percent of the speed of light.



So to get a space shuttle up to 90 percent of the speed of light, assuming we had no wastage of energy at all, requires the output of every power station in the United States running for 8×10^9 seconds. That’s around 250 years. A whole lot of energy. Especially when you consider that I’ve totally ignored one teeny factor in my calculations. Special relativity.

Relativity doesn’t just mean that time slows down as you get close to the speed of light. There are other effects as well. As a spaceship gets faster and faster, its mass increases. More mass means more kinetic energy—more energy than Newton thought is needed to get it in motion. When our space shuttle is traveling around 0.9 times the speed of light, its mass won't be 100 tons; it will be more. To make matters worse, the simple relationship of kinetic energy being $\frac{1}{2}mv^2$ no longer applies.

If you use the relativistic formula for kinetic energy (rather too messy to bother with here) and use it on our 100-ton (when stationary) shuttle at 0.9 times the speed of light, you end up with an energy of 1.2×10^{22} joules. Not hugely greater than Newton's version, but already tweaked upward. In practice we would have to run our power stations for around 830 years to produce this much energy. And the closer you get to the speed of light, the more important those relativistic effects are.

Even at this speed, though, Karla has to invest over 8 years of her life to get around 11 years into the future. Let's increase the pace a notch and take the ship to 99 percent of the speed of light. Now the 20-year journey would take only 2.82 years from Karla's viewpoint. She will have shifted 17.18 years into the future. This is a payoff that seems more worthwhile.

If we want to get the shuttle to 99 percent of the speed of light, Newton would tell us, we need 8.8×10^{21} joules, which means running our power stations for around 600 years. But Einstein gives us a very different picture. Relativity means that we would need 5.4×10^{22} joules. We're up to 3,700 years of power station output. As we get closer to the speed of light, the kinetic energy shoots up toward infinity.

Let's come back down to earth—or at least to space technology as we currently know it. The amount of power produced by the biggest rocket motors ever built, those on the Saturn V rocket used for the Apollo program, was around 1.5×10^{11} watts. Just how vast that is can be seen when we realize that it's about a third of the power of all the power stations in the United States. But that still means these engines, which in practice had only enough fuel to run for a few seconds, would have to be firing for around 2,500 years to reach just 90 percent of the speed of light.

To look at it another way, the Apollo astronauts, traveling faster with respect to the Earth than anyone else has ever moved, reached a little over 11 kilometers per second. Half the speed of light (which, remember, would shift you forward only 2.7 years after a 17.3-year journey) is 150,000 kilometers per second.

So although traveling forward in time is conceptually very simple, and entirely possible with today's technology, we confront the practical difficulty of needing a phenomenal amount of energy to make a big enough jump into the future for the effort to be worthwhile. In the unlikely event that we used gasoline future for the effort to be worthwhile. In the unlikely event that we used gasoline to power our time ship, it would need to carry around 60 billion tons of gas to produce the amount of energy we require. But our calculations have assumed we were moving only a shuttle weighing 100 tons. Just to move the gasoline would require nearly a billion times as much energy . . . which would require vastly more gasoline. And so on.

The only way to possibly make it practical would be to have a fuel that packed in much more energy than gasoline. Luckily there are several that do. Conventional nuclear fuel, the material used in nuclear power stations, is around 2 million times more powerful per unit of weight than gasoline. In practice, you would still need around 31,000 tons of nuclear fuel. Better, it's true, than the gas. But not workable. The only hope is to follow in the footsteps of *Star Trek*.

The fictional USS *Enterprise* is powered by the most phenomenal source of energy in existence, antimatter—and this is the only hope if fuel is to be carried on the ship. Antimatter engines sound like science fiction, and the exact mechanism used by the Enterprise *is* fictional, but antimatter itself is a real enough concept. Antimatter is the same as ordinary matter, but the particles that make it up have the opposite electrical charge to those in conventional matter.

Where, for example, an electron has a negative charge, the antimatter equivalent, the antielectron (usually called a positron) has a positive charge. There are similar antimatter equivalents of all the particles. When two oppositely charged matter and antimatter equivalents—an electron and a positron, for example—are brought together, they are attracted, smash into each other, and are destroyed.

The particles' mass is converted into energy, and though particles like electrons are very light, Einstein's famous equation $E=mc^2$ tells us that the energy produced will be equal to the mass of the particles multiplied by the square of the speed of light. That's a big number. A kilogram of antimatter, annihilating with an equivalent amount of matter, generates the equivalent of a typical power station running for around 12 years. (Depending on the antimatter used, there may be secondary particles called neutrinos produced in the reaction, which can reduce the energy output by half, but this is a relatively small consideration.) Antimatter is the ideal source of energy for our time ship, the most compact way to store energy that we have. It packs in one thousand times more energy than nuclear fuel.

However, the output of a single power station isn't quite as impressive as it sounds when we're faced with the voracious appetite of our special-relativity time ship. We need 450 times that output (the equivalent of all the power stations in the United States) running for 830 years to reach 0.9 times the speed of light. That's the equivalent of the amount of energy stored in 31 tons of of light. That's the equivalent of the amount of energy stored in 31 tons of antimatter. At last we've got to a weight that is manageable aboard our space shuttle. But we still have to bear in mind that at the moment the whole world's annual production of antimatter is about a millionth of a gram, so we aren't going to get to 31 tons, 31 billion times as much, in a hurry.

To make matters worse, we have no good way to convert the raw energy of the antimatter annihilation—in the form of an intense burst of gamma rays—into movement. And even if there were some way to harness that power, the mechanism would probably be extremely bulky and heavy. Even though nuclear fuel is 2 million times more compact than gasoline, you don't get nuclear-powered cars, because the reactor is simply too big, heavy, and dangerous to be contained under the hood. Harnessing the power of antimatter would probably require even bigger and heavier equipment.

If this weren't bad enough, all the assumptions I've made so far have been hopelessly optimistic. I have already mentioned the problem of the weight of the fuel and the mechanism used to convert it into motion. I also haven't allowed for the weight of the food and drink for our time traveler. She may have to be in her time ship for many years. And I've been merrily assuming that we can convert all the energy from the fuel into movement. In practice, most existing engines waste a lot of energy as heat (just think of how warm you would get sitting right next to a space shuttle launch).

And there are more problems still. To keep things simple, I assumed that all we need is the energy to get the time ship up to speed. So these figures depend on the ship's not being slowed down by the gravitational pulls of passing stars or interaction with any gas it passes through. That's a relatively small assumption. But another, much bigger factor that I ignored is lurking: what happens when the ship gets to the end of its voyage and turns round?

Ideally, the ship should be able to turn the kinetic energy of its flight back into antimatter; but there is no known way to do this. Producing antimatter is a painstaking business at the best of times. So the alternative would be to use that much energy again to stop the ship, another burst of energy the same size to get it up to speed on its return voyage, and a final blast to stop it when it returns to Earth. In all, that's four times as much energy as I was allowing for.

It seems that coming close to the speed of light for something as massive as a space shuttle verges on the impossible if you have to carry your fuel with you, however compact your energy source. The alternative is to find some way to power the ship without carrying the fuel. One approach is to use solar sails. These use the small but inexorable pressure produced by the Sun's vast electromagnetic output to provide motive power.

There is also a relatively small effect from the solar wind, the stream of particles that are pushed out by the Sun, but solar sails rely largely on the fact that the energy of light and other electromagnetic radiation can be converted into kinetic energy—motion—by impact on sails. We know that solar sails work, but relying on the Sun wouldn't be enough to get a time ship up to speed, as the power of the Sun drops off quickly as you move into the farther reaches of the solar system.

To use light-driven sails, there would need to be a huge, space-based bank of lasers that convert energy from a static generator into electromagnetic radiation and blast it out to the sails. This requirement means that photon sails (to call them solar sails becomes misleading when the Sun isn't the main motive power) would not work for a time-travel project. The trouble would come at the far end of the journey. Unless we had already traveled to the destination and set up another bank of lasers, plus their power source, there would be no way to slow down and turn around the ship. It would continue out into space forever.

If it is not practical to use a photon sail, the other possibility is that the ship could have a motor on board that somehow picked up its fuel from the environment as it traveled. There is matter in "empty space" that could be pulled in—but to use an antimatter reaction would still require the appropriate mass of antimatter to be carried, as this is unlikely to be found in any quantity floating freely in space, so this would only halve the fuel weight requirement for a matter/antimatter drive. Picking up ordinary matter wouldn't of itself provide all the necessary fuel.

One piece of technology that was dreamed up in the 1960s could provide a "power from nothing" motor—this is the Bussard ramjet. The idea is that a spaceship is pushed up to high speeds by conventional means. It then scoops up the natural hydrogen debris from space (somehow separating off all the other junk) and uses the pressure of the ship's high speed to compress the hydrogen until it can be made to undergo nuclear fusion, releasing energy to power the ship. It's a nice idea in principle, but all the known data on quantities of hydrogen available and potential for compression suggest that it's highly unlikely to work.

We need to bear in mind also just how difficult it is to get fusion to work. Nuclear fusion would be hugely useful on the Earth. It's how the Sun works, and it's a form of nuclear power that, unlike our current nuclear-fission power plants, uses cheap fuel and doesn't produce difficult-to-dispose-of high-level waste. Yet despite researching nuclear fusion for fifty years, we have yet to produce a fusion reaction that is self-sustaining. It's incredibly difficult, as you need to handle intense temperatures and pressures, and to keep the fusing material from touching anything else. This is proving difficult in huge research devices—it would be a much bigger step to get it working in a relatively small spaceship engine.

Even if we did manage to get our time ship up to a decent fraction of the speed of light, there would be other problems. Navigation at this speed would be a nightmare. And there would be plenty of hazards that simply couldn't be avoided. There would be the constant danger of collision with dust—at this speed, the tiniest particle of matter would be able to crash through pretty well anything. And as the time ship blasted into atoms of gas or, even worse, into high-energy cosmic rays, the collisions would be like those in a particle accelerator, producing floods of deadly radiation, which would require extremely dense shielding.

Using special relativity to travel a little way into the future is easy. It is entirely possible with today's technology. We do it every time we take a plane journey, but only by a tiny fraction of a second. The problem here is making the scale of the jump into the future sufficient to make undergoing the journey time worthwhile.

With all the technical problems involved in making meaningful special-relativity time travel into the future possible, I am inclined to say that the biological solution may deliver before the engineering solution. It is possible that we will be able to put a human body on ice (not literally), keeping it perfectly preserved without aging but unconscious, before we have the technology capable of pushing a spaceship to within a few percent of the speed of light.

It's a shame. It's messy. We want our time machine to be based on good, sound physics—but it looks as if there may well have to have a biological component for the journey into the future in the short to medium term. But before we give up entirely, there is another possible answer from relativity that would provide a vehicle to travel to the future yet would not need any high-speed movement at all. In fact, this is time travel you could undertake sitting in an armchair—though to make it practical, you would probably have to be out in space.

As we have seen, special relativity isn't the only way Einstein gave us to manipulate time. General relativity tells us that gravity makes clocks run slow. When the GPS satellite system is influenced by relativity, the most powerful effect on the satellite clocks is not that they are slowed down by special relativity due to their motion. The biggest influence is the way the clocks respond to experiencing a lower gravitational pull than we feel on the Earth's surface. Because the satellite clocks are in orbit, they experience a significantly lower influence from gravity than clocks on the ground do, which means they tick faster than their earthbound equivalents.

In principle, all we need to do to travel rapidly forward in time is to go and sit on a neutron star. A neutron star is the remains of a dying star that has undergone a collapse until each 100 million tons of matter in the star is condensed into a single cubic centimeter—about the size of a grape. The whole thing, with the vast mass of a star, is typically about the size of Manhattan.

Of course, sitting on any star comes with its own bag of problems. First, it's going to be uncomfortably hot. The surface of our Sun is around 5,500 degrees Celsius (9,900 Fahrenheit). The surface temperature of a neutron star can be as much as 1 million degrees Celsius. In practice we don't need to get as close as the surface to feel a huge gravitational pull, but any neutron-star time traveler would need some serious heat shielding.

Unfortunately, the temperature is the least of our worries. The very factor that makes a neutron star an excellent future-direction time machine also makes it impossible to get near. The gravitational pull of a neutron star is so strong that there would be huge tidal forces between the part of a traveler that was nearest the star and the part that was farthest away. A neutron-star visitor would likely experience a deadly tide.

Just think about the way that the tides work back here on Earth. If we imagine looking at the Earth from out in space at any particular time of day, one side of the planet is nearer the Moon, while the other is farther away by the diameter of the Earth, around 12,750 kilometers. The gravitational pull of the Moon is stronger on the side that is nearer to it, so the oceans are pulled more than usual in that direction—the water bulges out, forming a high tide. On the far side of the Earth, 12,750 kilometers farther from the Moon, the oceans are pulled less than usual in the Moon's direction. So the water also bulges outward on that side—another high tide.

The result of the neutron star's powerful gravitational pull would be an exaggerated version of the tidal differences exerted by the Moon. This would elongate any matter that came close, with the difference between the gravitational pull on the nearest bit and the farthest bit being enough to stretch the matter out like taffy. A time traveler's ship would be destroyed, stretched in a process that is given the name "spaghettification." The time traveler too would be shredded, pulled apart into a long, thin strip of matter.

Provided we have unlimited engineering capability, though, there is a way around this problem that removes the danger of being pulled apart and means that our time traveler doesn't have to start her time journey with a trip of many light-years into space. After all, the nearest neutron star detected so far is either the pulsar J0108-1431, which is around 326 light-years away, or a more recently discovered star in Ursa Minor, nicknamed Calvera, which could be as close as 250 light-years distant. Rather a tedious trip to have to make before you can take up time travel.

The engineering feat required would be to disassemble a neutron star into manageable chunks and transport them to a convenient location. Then we could use the pieces for time travel. Imagine the time traveler seated in a protective sphere in space. We start to surround her with neutron star material, always adding pairs of pieces on opposite sides. Or we could build up a sphere of neutron star material around her, spraying a thin layer that gradually builds up.

What we have achieved here is getting our time traveler into the center of a neutron star without her ever coming near the outside. She is still being influenced by its gravitational field, but there is no tendency to turn her into spaghetti, because the field is balanced in all directions. Ever since Newton we have been aware that we would feel no gravity at the center of a sphere, and nothing in general relativity counters this.

Our time traveler will feel no pull of gravity as her time ticks forward at a highly retarded rate (or rather, from her point of view, as everyone else’s clocks race forward). At some point in the future, the sphere is disassembled and the time traveler can emerge. There is a limit to the capabilities of such a time machine. The more densely packed the material, the faster the traveler will journey into the future—but if the material is packed too densely, the time machine will collapse into a black hole and the traveler will be destroyed. It seems that a rate of about five years externally to one year internally is about the limit of such a time machine. You would have to stay inside the chamber for ten years to travel fifty years into the future—which arguably isn’t worth the amount of effort that would go into building the device.

For the moment such feats of engineering are impossible anyway, so we’re back to sleeping our way into the future. However, biology gives no route into the past apart from the tenuous filaments of memory. To get back in time, our only hope is physics. And the earliest practical example—something that has been possible in the laboratory for over a decade—was first demonstrated using a piece of classical music written over two hundred years earlier.

CHAPTER SEVEN

WARP FACTOR FOUR

> *In fact, it is often stated that of all the theories proposed in this century, the silliest is quantum theory. Some say that the only thing that quantum theory has going for it, in fact, is that it is unquestionably correct.*
>
> —Michio Kaku (1947–), *Hyperspace: A Scientific Odyssey Through Parallel Universes, Time Warps, and the Tenth Dimension* (1994)

In January 1995, at a conference in Snowbird, Utah, Professor Günter Nimtz of the University of Cologne amazed colleagues by playing them an excerpt of Mozart's Fortieth Symphony on a battered old Walkman. It wasn't the recording that was remarkable. It sounded scratchy and distorted. And it was a perfectly standard performance. What surprised the physicists was the way the music had reached the recorder in the first place.

"This Mozart," said Nimtz, "has traveled at over four times the speed of light. I think that you would accept that it forms a signal. A signal that moves backward in time."

Professor Nimtz's stunt was a shock to the conference attendees, but the science building up to his demonstration had been developing for around a century. This was the first of two potential examples of time travel that would come out of one of the most fundamental theories of modern physics, quantum theory.

Quantum theory is the science of the very small, the theory that explains the behavior of particles like atoms and photons of light that are building blocks of reality. Its reluctant founder was the German scientist Max Planck.

Born in Kiel in 1858, Planck found both science and music fascinating—he could easily have been a concert pianist. It was a career he perhaps gave significant thought to when he attended the University of Munich, beginning in 1875. Physics professor, Philipp von Jolly, was of the opinion that there really wasn't much left to do in the subject. The science was, Jolly believed, so near being a complete description of reality that it was only a matter of dotting a few i's and crossing a few t's before human knowledge was complete. To study physics would soon, he told the young Planck, become more a matter of history than of science.

Planck wasn't put off by this depressing thought. He continued in physics and went on to show that Jolly couldn't have been more wrong. In fact, most of what was assumed to be true in physics at the end of the nineteenth century would be shown to be at best an approximation and at worst profoundly wrong, all in the next few years. And Max Planck would, reluctantly, be at the heart of this revolution.

One of the t's that remained to be crossed in Jolly's limited worldview was the dramatically named "ultraviolet catastrophe." This was a result of observing hot things. Anyone who had ever worked metal, right back to the smiths of prehistory, was aware that as matter was heated up, it started to glow. The color it produced changed as the temperature grew. Relatively cool metal was red hot, then it became yellow, and finally white. This was no surprise. But the scientists at the end of the nineteenth century discovered something very strange about that glow.

They showed that a body radiating light should give off more and more energy, the higher the frequency of the light. As you got up past blue and into the invisible ultraviolet, the amount of energy being given off should have been phenomenally high. Nearly infinite amounts of energy should be pouring out of every piece of matter, up in these high frequencies.

This clearly wasn't happening. But what was stopping it? The way science typically approaches a problem like this is to develop a hypothesis—an idea, perhaps even a guess as to what is going on. The scientist then works out what should be observed if that hypothesis is true. The results are compared with reality, and either the hypothesis is adjusted, or more experiments are made and more measurements are taken to get a better and better idea of how the hypothesis holds up. Most hypotheses fall by the wayside, but some match reality with stunning accuracy, and are held up as likely theories to explain the physical world.

Planck had what he later described as a lucky guess. He accepted that the amount of energy given out would go up with frequency. That was inherent in the nature of light. But instead of allowing for a continuous spectrum of energy, permitting any and all levels of energy to be produced, he imagined that any particular atom in the glowing matter could only give off chunks of energy in particular sizes. A modern physicist might have given such a chunk a whimsical name, but Planck was classically trained and called it a quantum or plural name, but Planck was classically trained and called it a quantum or plural quanta, from the Latin term meaning “how much,” the same source that gives us the word “quantity.”

This apparently minor assumption had a startling effect on the math that had so troubled the Victorian physicists. It was no longer the case that the energy given off should shoot off toward infinity at the high end of the scale. Instead, by confining the energy produced to the packets or quanta, the energy given out at different frequencies would peak and then fall off sharply, just as was observed.

For Planck, the use of quanta was nothing more than a mathematical trick to make the numbers add up correctly. It was universally accepted that light was a wave, and waves didn’t come in packets. What he was describing was more like Newton’s old-fashioned idea from three hundred years previously that light was made up of particles, what Newton had called “corpuscles”—yet Planck knew that there were plenty of experiments that seemed to prove that light was a wave.

He was frank about his doubts in a letter he wrote to the American physicist Robert Williams Wood in 1931 (it’s often quoted as being written in 1901, but this seems to be an error): “In short, I can characterize the whole procedure as an act of despair, since, by nature I am peaceable and opposed to doubtful adventures. . . . A theoretical interpretation had to be found at any price, however high it might be.”

What Planck took to be nothing more than a mathematical method to fix a problem with calculation, Albert Einstein would take much further. As we have already seen, one of Einstein’s great 1905 papers, the one that won him the Nobel Prize, was on the theory behind the photoelectric effect. It seemed to Einstein that when light fell on a piece of metal and managed to blast electrons away from the atoms, the energy had to be coming in as actual quanta: not some theoretical mathematical construct, but actual physical entities.

In this, Einstein was building on experiments by the Hungarian physicist Philipp Lenard. Lenard had discovered in 1902 that the photoelectric effect didn’t care how bright or dim the light shining on a piece of metal was. The amount of energy an electron was kicked out with depended on only the color of the light. If light had been a wave, then the more light that was shone onto the metal, the more energy the electron should have. Einstein went one step further than Planck and accepted what his predecessor had found unacceptable. He believed that light was actually made of sealed-up little packets of energy.

It was the American chemist Gilbert Lewis who would give these packets a name, calling them photons, and another American, Robert Millikan, who proved that Einstein was right about what was happening with the electrons in the photoelectric effect. In one step, Einstein had gone from Planck’s mathematical trick to changing the fundamental description of how light and mathematical trick to changing the fundamental description of how light and matter were described, unwittingly leaving the way open for quantum theory to be developed.

As might be expected, Planck wasn’t too impressed by what this young upstart had done. In 1913, Einstein needed a reference from Planck to join the Prussian Academy of Sciences. On the whole, Planck was enthusiastic about the younger man, but he felt that he had to comment that Einstein sometimes “missed the target in his speculations, as for example, in his theory of light quanta.”

It wasn’t Einstein who went on to develop quantum theory after laying this initial foundation, though. The man who would bring it to its full glory was Danish physicist Niels Bohr, born in Copenhagen in 1885. As we will see, Einstein and Bohr would be mental sparring partners over quantum theory for many years.

Bohr’s first great advance was to employ Einstein and Planck’s quanta to explain the structure of the atom. It was known that atoms had both positive and negative charges inside them. Based on an idea of the British scientist J. J. Thomson, it had been assumed that the negative charges were spread through the body of the atom, which Thomson confusingly likened to a “plum pudding.” By this he meant a Christmas pudding, which has fruit like raisins scattered through the body of the pudding. The raisins were the negative charges (later identified as electrons), while the dough of the pudding was the positive charge.

This picture of the atom was shattered when New Zealand–born physicist Ernest Rutherford discovered the atomic nucleus (named later after the biological nucleus of a cell). At the Cavendish Laboratory in Cambridge, England, Rutherford’s assistants Hans Geiger and Ernest Marsden were using the decay of the natural radioactive element radium to produce alpha particles—heavy, positively charged particles—which were fired at a piece of gold foil to see how the atoms in the gold influenced the flight of the particles.

Unexpectedly, a few of the alpha particles bounced back. Rutherford compared the phenomenon to “firing a 15 inch shell at a piece of tissue paper and having it come back and hit you.” The Cambridge team’s discovery showed that the positive charge in an atom was concentrated in a small, dense core. A very small core indeed. If the atom were blown up to the size of a cathedral, the nucleus would be the size of a fly, buzzing around inside it.

This tiny, isolated nucleus left the negative charges, the electrons, without a home. Bohr thought of another situation where there is a central, relatively small but massive nucleus—the solar system. The distance to the outer planets is vast, yet they all orbit the Sun at the center of the system. Why couldn’t atoms be similar, with the negatively charged electrons orbiting the central nucleus? It’s a picture that’s still familiar today, and there is something very encouraging about being able to deduce the structure of something microscopic from something on a large scale. It’s as if the universe were a set of Russian dolls, one within another.

If you ask someone today to sketch an atom, the chances are that what he or she will produce will look a bit like a solar system. This model has not survived in physics—as we’ll later see, quantum theory tells us that the electrons exist in a fuzzy cloud of uncertainty around the nucleus, rather than as clearly orbiting miniplanets—but the image has stuck in the popular imagination. It works too well as a mental model to be easily discarded.

Almost as soon as he came up with the idea in 1913, Bohr realized that the model had a dangerous flaw. Although electrons whirling in orbits around a positively charged nucleus *seemed* similar to planets flying around the Sun, there was a fundamental difference. The force keeping them in place was not the same. With the planets, it is gravity that keeps them in their orbits, while in the atom it’s electromagnetism. And these two forces have little in common.

When a planet orbits the Sun (or a satellite flies around the Earth), two things are happening. The planet is falling toward the Sun under the pull of gravity, and it is flying in a straight line at a tangent to the Sun. The two movements come together to make a circular orbit. As long as the planet doesn’t slow down, the two will continue to balance out and the planet will orbit around the Sun indefinitely.

As we’ve seen, even though the speed of the planet is constant, this orbital motion is a kind of acceleration. That’s because acceleration is a change in velocity—and velocity combines speed and direction. Although the planet’s speed remains the same, its direction is constantly changing under the force of gravity.

That’s fine, but if we transfer the picture to an electron flying around the atomic nucleus, there’s a problem. When an electron is accelerated it gives off energy in the form of light. So if the electron were accelerating around an orbit, it would spiral into the nucleus, blasting out light, and the atom would collapse. Every single atom in existence would self-destruct in a fraction of a second. This (thankfully) doesn’t happen. So Bohr had to find some way to keep the electron on track. Literally.

He imagined that electrons could travel only in fixed orbits, as if they were running on tracks laid around the outside of the nucleus. An electron could lose or gain energy in the form of a quantum of light by giving off or absorbing a photon—but these came only in fixed units. The electron wouldn’t gradually move from one level to another, allowing it to spiral in to the nucleus. Instead, it could only make jumps—quantum leaps—from one track to another.

After Bohr's first step into quantum strangeness, other players entered the field. Prince Louis de Broglie, Werner Heisenberg, Erwin Schrödinger, Paul Dirac, and Max Born all made contributions to understanding how the tiny particles that underlie reality behave. One essential result was Heisenberg's uncertainty principle. This states that there are pairs of pieces of information about a quantum particle that are linked. The more we know about one of the pair, the less we can know about the other.

One such pair is momentum (mass times velocity) and position. The more accurately we know a particle's momentum, the less we can know about exactly where it is. If we find out the momentum in some detail, then the position could be spread over a huge area. And it's not just that we can't measure the position more accurately—at that point in time, the particle doesn't have a more accurate position.

The other development in quantum theory that would lead to Professor Nimtz's demonstration of faster-than-light communication in Snowbird, Utah, is Schrödinger's wave equation. This is the fundamental equation of quantum physics, which describes the way a particle behaves. When Schrödinger originally formulated it, the equation seemed to say that quantum particles would spread out over time, occupying a great expanse of space. After a certain amount of time elapsed, an electron could be as big as the Earth. This didn't make sense. But Max Born would show that the equation did not describe the particle's location, but rather the probability of finding a particle in any particular location.

Now imagine we've got a particle like an electron or a photon that comes up against some kind of barrier that the particle can't get through. Schrödinger's equation tells us that it has a certain probability of already being on the other side of the barrier. This is less likely than its being on the side of the barrier that it started on—but the probability is still real. The equation tells us that there's a real chance that the particle will get to the other side of the barrier without ever traveling through the space in between. This process is known as quantum mechanical tunneling.

The name "tunneling" is a bit of a misnomer because of that "without traveling through the space in between" part. The particle doesn't actually tunnel its way through the barrier like a mole burrowing through the ground. It disappears from one side and reappears on the other side without any passage of time, a phenomenon that physicists label "zero tunneling time." This process sounds like an obscure theory, something highly unlikely ever to happen in practice, but in reality it is responsible for all of us being alive.

The driving source of energy behind all life on Earth is the Sun. (A few organisms thrive on the heat from “black smoker” vents at the bottom of the sea, but without the Sun it is unlikely even these bacteria would exist.) Without the Sun’s light generating heat, powering photosynthesis, and creating our weather systems, we wouldn’t be here. This light is produced by the nuclear fusion process in the Sun. In the intense heat and pressure of a star, hydrogen nuclei fuse together to make the next element up the chain, helium. In the process energy is given of—energy that powers the Sun and warms us all.

Unfortunately, this reaction should never happen. Hydrogen nuclei are positively charged. They repel each other. Even though these particles are very energetic at the high temperature and under the huge pressure that exist at the heart of the Sun, there’s not enough force to overcome that powerful repulsion. The particles can’t get close enough together to fuse. In effect, the repulsion is a barrier: something that the hydrogen nuclei have to get over in order to get close enough together. And this is a barrier that can be tunneled through.

Most hydrogen nuclei will never make it through. Schrödinger’s equation tells us it is much more probable that they will stay on their own side of the repulsive barrier. But a few particles will undergo quantum mechanical tunneling, will appear on the other side of the barrier, and will fuse. Because there are so many particles in the Sun, millions of tons of hydrogen are converted to helium every second, producing that essential flow of energy that keeps us alive.

In the late 1990s, Professor Raymond Chiao of the University of California at Berkeley was experimenting with quantum mechanical tunneling using photons of light. Einstein had always said that nothing could travel faster than light, but Chiao found a way for light itself to break the light-speed barrier. This is hugely significant because, as we have seen, if a message can be sent faster than light, it can, in effect, slip backward in time.

Imagine a simple experiment where light traveled a unit of distance through a vacuum, then tunneled the same distance through a barrier, then traveled the same distance again through empty space. It covered 3 units of distance. The first and the last section were traveled at the usual speed of light, 300,000 kilometers per second, often simplified to c. The center, tunneled, section was traversed instantly. So the light took two-thirds of the time it would normally take to cover the 3 units of distance. Its speed was 3/2c, that is, 1.5c—one and a half times the speed of light.

Chiao and his team demonstrated this tunneling phenomenon, measuring light traveling at 1.7 times its normal speed. If the light beam could be made to carry a signal, that message would, according to relativity, have the potential to communicate backward in time. But Professor Chiao had no plans to win a lottery by sending back the results, or worries about destroying the fabric of reality by opening up time paradoxes.

The University of California experiment relied on generating individual photons, and the mechanism that made this possible provided no way of controlling when a photon would emerge. Without such control, these randomly generated photons could not carry a message. Imagine trying to send someone a signal using round balloons as dots and long balloons as dashes in Morse code—only you had no control over which balloon came out next. Moreover, there was no way of deciding which photons would get through the barrier—most don't—and so it seemed impossible to keep a signal flowing. There was technically a time slip, but it couldn't be used.

At the time, Professor Chiao was unaware of developments in another laboratory in Cologne, Germany, developments that had been inspired when a scientist was casually scanning through a scientific paper while riding on a train.

Professor Günter Nimtz of Cologne University in Germany was on his way home after attending a meeting in Stuttgart. With nothing entertaining to pass the time, he flipped through a paper on undersized waveguides, written by a team at the National Institute for Research into Electromagnetic Waves in Florence, Italy. (Even scientists rarely read academic papers for fun.) A waveguide is little more than a rectangular metal tube that has the same effect on microwaves as a fiber optic cable does on light.

The "undersized" part meant that the waveguide was smaller than the wavelength of the microwaves, in itself not unusual. But Dr. Anedio Ranfagni and his colleagues were reporting something strange: when the microwaves were pushed through the waveguide, they seemed to slow down. As far as microwaves are concerned, an undersized waveguide is a barrier, just like the ones we have already met. Nimtz expected that the only way the microwave photons would get through this barrier was by tunneling, and it seemed wrong that this should result in the waves slowing down.

Nimtz showed the paper to his postdoctoral student, Achim Enders, who was on the train with him. Enders, now a professor in his own right working at the Institute for Electromagnetic Compatibility at the University of Braunschweig, Germany, couldn't make sense of the report either. They decided to try to repeat the experiment when they got back to the lab.

As the results started to mount up from the Cologne experiment, it seemed that either the Italians were wrong, or Nimtz and his colleagues had made a big mistake. Instead of slowing down the microwaves, tunneling through the undersized waveguide seemed to speed up the passage of the photons. Time and time again, Nimtz's group repeated the experiment and found the same result.

When the Cologne team got in touch with the scientists in Florence and pointed out their result, it soon became obvious that the Italians had made an error. Tunneling did push the photons beyond light speed.

Now both Nimtz and Chiao had succeeded in breaking what had been assumed to be an unbreachable barrier. Chiao dismissed this result as interesting but insignificant. It wasn’t, after all, possible to send a signal this way, it was just a matter of random photons jumping through the barrier. But Nimtz held a different view. As he was to demonstrate at that meeting in Snowbird in January 1995.

The ski resort of Snowbird, Utah, is a dramatic location for a conference, located as it is above Little Cottonwood Canyon, a good eight thousand feet feet above sea level. It’s not high enough to bring shortness of breath, but the air is noticeably thin. The thin air made some people feel a little drowsy—but any drowsiness at the conference was washed away when Nimtz spoke.

Initially he worked with slides of graphs on an overhead projector, walking back and forth in front of the delegates, occasionally peering at his notes through half-moon spectacles. But then he pulled out a battered Walkman, a portable cassette tape player that was the iPod of its day. It belonged to his son. Nimtz repeated the view given by Chiao, that there was no possibility of sending a message through the faster-than-light link. Then he said, “I want you to listen to something.”

Nimtz pushed the play button on the Walkman. Through the built-in speaker came a noisy hiss, and then, faintly but perfectly recognizably, the elegant opening notes of Mozart’s Fortieth Symphony. Nimtz allowed the music to play for a few moments as the delegates raised their eyebrows and exchanged glances.

“This Mozart,” said Nimtz, “has traveled at over four times the speed of light. I think that you would accept that it forms a signal.” He was playing a piece of music that had the potential to move backward in time. I have a recording of this superluminal classical music, and it’s playing as I type this. The sound is thin, but I have no problem recognizing the music or distinguishing the instruments. It’s quite clear.

Initially Nimtz undertook this experiment using an undersized waveguide like the Italians. Then he switched to Chiao’s style of barrier, called a photonic lattice. This is a multilayered sandwich of Plexiglas and air that provides a similar barrier for tunneling. Later still he would employ his most dramatic equipment, ideal for demonstrations. This was a pair of huge prisms, using a phenomenon that had been noticed by Isaac Newton, though Newton found it impossible to explain.

When a narrow beam of light is shone through a transparent material, like a sheet of glass, it bends on the way in, then bends back again on the way out. A prism, a block of material with a triangular cross section, will bend the light in the same direction both times it passes through the edge of the block. As different colors bend by different angles, this results in the familiar spread of the colors of the rainbow when visible white light is used. But if the light beam hits the inner wall of the prism at a suitable angle, instead of passing out into the air, it will be reflected back into the material, a process known as total internal reflection.

What Newton discovered by accident was that if a second prism is placed against the face of the prism where the light went through total internal reflection, and then the two prisms are moved a little way apart, some of the light will start to come out of the second prism instead of reflecting internally. To Newton, this was a mystery, but we now know that the escaping photons are tunneling across the barrier formed by the gap and emerging in the second prism.

With visible light, the prisms and the gap required are quite small, but Nimtz does the experiment with microwaves. These have a significantly longer wavelength, and mean that he can use huge plastic prisms, 40 centimeters along each side, providing a piece of apparatus that is big enough to be clearly visible from a demonstration bench in a classroom.

Whichever apparatus is used, the effect is the same. The beam exceeds the usual speed that light travels at. As demonstrated, this is purely an effect of insubstantial light. Other quantum particles do tunnel. But solid objects comprise many billions of particles, so you would have to wait longer than the lifetime of the universe for that much tunneling to take place. It could happen, but it’s very, very unlikely. We could never use a tunneling barrier to send a material object back in time. And even with photons, the time shift involved is very small. But is there a way to use this equipment to send a message back in time and make use of that shift? Nimtz says there isn’t. To see why, we have to delve into the nature of the signal that is being transmitted.

One issue that causes a lot of controversy in the superluminal community is over just what was being measured when a signal is described as traveling faster than light. There’s more than one way to look at the speed of light when you think of it as a wave. Imagine a pulse of light—not a single photon, but a short burst. You can think of this as a chunk of wave, moving forward through space. You could say that the speed of the light was the speed that the whole chunk moved—or the speed that a particular point in the wave moved. Usually those would be the same thing, but not always. The chunk of wave could distort in shape, making it appear to travel faster than it really did.

You can picture this by imagining two runners pounding along side by side in a race. The winner is the one who breaks the tape first. They both run at exactly the same speed, but at the end of the race, one runner sticks his arms out while the other keeps hers by her side. The runner who stuck his arms out would break the tape first—he would have completed the course faster even though pace by pace both runners traveled at the same speed. A similar effect can occur if the pulse of light is reshaped as it passes through the barrier, making it seem as if it arrived faster than it really did.

Nimtz got around this problem by using light that had a very narrow range of frequencies present. This limited the possibilities for reshaping the pulse and reduced the possibility of confusion over timing. Since then, signals have also been transmitted using single photons, where there is no "chunk" to reshape, still giving the same results.

Nimtz points out, however, that we need to remember just what a signal *is* to understand why his experiments won't allow us to send a message back in time. At its heart, a signal is a series of zeroes and ones, like the bits in a computer. This is the most basic form of information. Such a signal is usually sent along a light beam (whether via the form of light called radio to your car radio or TV, or to the microwave receiver in Nimtz's experiments) by a process known as frequency modulation. The signal starts as a "carrier," a smooth, steady wave. The information is then added to the wave, making small changes to the frequency. It might be, for instance, that we make the next up-and-down motion come a little sooner to indicate a 1.

However, we can't tell whether a 0 or a 1 is being sent until the wave has completed its up-and-down motion once—we need a whole wavelength. To actually gain a march on time, the wave needs to get ahead of time by one complete wavelength—and that has not been achieved. All the experiments have managed is a small percentage shift against the wave itself. Mozart's Fortieth shifted in time—but only by a fraction of a wavelength. To make matters worse for would-be time machine builders, to make a bigger shift requires a thicker barrier. But the bigger the barrier, the more the signal gets attenuated as it passes through. Before there's a possibility of getting a meaningful piece of data through, not a single photon manages to penetrate the barrier.

When asked if these superluminal experiments will ever get a meaningful shift in time, Professor Nimtz has enigmatically said, "I never say 'never.' " But as yet no experiment has pushed the quantum particles far enough through a barrier to trigger any of the strangeness of true time travel.

Not all quantum effects are so limited in their range, though. Our next possibility to use quantum theory to break the time barrier is an effect that can produce an instantaneous connection over any distance. It can work from one side of the universe to the other without any time elapsing. A challenge to Einstein’s limits, indeed.

CHAPTER EIGHT

ENTANGLED WEB

> *God runs electromagnetics on Monday, Wednesday, and Friday by the wave theory, and the devil runs it by quantum theory on Tuesday, Thursday, and Saturday.*
>
> —William Lawrence Bragg (1890–1971), quoted
> in Daniel J. Kevles, *The Physicists* (1978)

If there is one name you can't escape when it comes to time travel, it's Albert Einstein. Should we ever decide we need a patron saint of time travel, it surely has to be Saint Albert. Relativity provides the basic foundations of time travel theory, and in both the previous chapter and this we see a way that relativity and quantum theory, both the children of Einstein's genius, can be used to produce an actual mechanism.

Like the superluminal experiments in the previous chapter, the application of quantum theory discussed in this chapter, quantum entanglement, requires no massive superfast spaceships, no engineering feats far beyond our current capabilities. It is technology that can be worked on the desktop in the laboratory today. But Einstein's views of quantum theory were quite different from his attitude to relativity. Quantum theory he hated. He was sure it was wrong.

As we have seen, German physicist Max Planck had observed that light energy could be conceived of as coming in little packets, or quanta, though he himself never believed they existed. Einstein went a step further in the 1905 paper on the photoelectric effect that won him his Nobel Prize. He assumed these quanta were real, not just a useful mathematical trick. But the field of study he had helped to found soon ran off in a direction that he didn't like.

As scientists like Bohr, Heisenberg, and Schrödinger began to develop the field, it became clear that quantum theory would bring a worrying degree of uncertainty into science. According to quantum theory, it wasn't possible to think of the universe, in good Newtonian fashion, in terms of predictable, mechanical processes. At the level of quantum particles, probability ruled the roost. While you could accurately say what the *probability* of a quantum event occurring was—the decay of a radioactive atom, for example—you could never predict exactly when it would happen.

It was a good friend of Einstein's, Max Born, who embedded probability firmly in the heart of quantum theory, going far beyond the simple matter of when an atom decayed. As we have seen, Erwin Schrödinger had come up with an equation to describe the wavelike behavior of quantum particles, but as first proposed, this equation was hugely problematic. It seemed to imply that a particle like an electron would spread out in all directions, thinning out into a ridiculously huge entity, instead of remaining a point particle.

Born suggested that the equation did not describe the direct physical nature of the particle, but rather the probability that the particle was in a particular location. Instead of a quantum particle having a specific, predictable position, like everything we are familiar with in the observable world, it was a fuzzy mess of probability, with Schrödinger's equation describing the chances of coming across the particle in any particular place. And the theory worked—supremely well.

We still have a series of letters that Einstein exchanged with Born, and in them, Einstein expressed his frustration at his friend's ideas. Specifically, he objected to the randomness with which quantum theory predicted electrons should be sent flying from an atom exposed to radiation:

> I find the idea quite intolerable that an electron exposed to radiation should choose of its own free will, not only its moment to jump off, but also its direction. In that case, I would rather be a cobbler, or even an employee in a gaming house, than a physicist.

That was on April 29, 1924. His "employee in a gaming house" remark is especially telling. Einstein was objecting to the way that quantum theory has probability at its heart. It might seem that a croupier in a casino is also working somewhere that probability rules, but Einstein knew that things were entirely different. The behavior of a roulette wheel is predictable with enough information. Although the ball's trajectory is apparently random, it is in fact responding to laws of nature that determine its path. If we were to set the ball and wheel in motion in exactly the same way twice in a row we would get the same results.

The same theoretical predictability applies to other casino games involving dice or cards. But when an electron escapes from an atom it involves a genuinely random process. There is no information that will enable you to calculate when it will be emitted and in which direction it will fly off. You can calculate the probabilities of what might happen, but you can't predict what will happen to a specific electron.

This whole business clearly nagged at Einstein, worrying him immensely. A few months later, on December 4, 1926, he wrote to Born some of the most famous lines he ever penned:

> Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the "old one." I, at any rate, am convinced that He is not playing at dice.

This is often condensed to "God doesn't play dice." In a roundabout way, Einstein was emphasizing that, for him, the behavior of nature could not be based on randomness—on the outcome of imaginary dice throws—but had to be founded on some sort of hidden, fixed information that was yet to be discovered.

Take a particle that had a fifty-fifty chance of being in a particular state. From Einstein's view, this had to be like a coin that has been flipped, but is still under its owner's hand, so we don't know what the outcome is. There's a fifty-fifty chance of the coin's coming up heads, say. But when we lift that hand to discover which is the actual value, the coin is already in position. It already has one face upward.

Quantum theory said that particles are entirely different from the hidden coin. Before being measured, quantum theory said, a particle is in both states at once. It is the act of observing it that forces it to click into one state or the other. Einstein believed that somewhere underneath the apparent randomness was hidden information that said which state the particle would be in when it was observed.

Yet if this hidden information was there, no one could discover it.

In the 1920s and 1930s, the master proponent of quantum theory remained the Danish physicist Niels Bohr, who had dreamed up the structure of the atom. For a number of years, Einstein delighted in throwing up challenges for Bohr, thought experiments that he hoped would show that quantum theory was wrong. It all started at the Fifth Solvay Congress in Brussels, which took place in 1927.

The congress (or conference) was one of a series of meetings started and funded by Belgian industrialist Ernest Solvay, primarily as a vehicle for Solvay to get a wider audience for some rather odd personal ideas about science. The scientists Solvay invited politely listened, totally ignored him, then went on to discuss the matters that were really exciting them. This invitation-only event featured the most starry groups of physicists ever to be gathered in one place.

At least twice at the 1927 conference, Einstein came up with a challenge for Bohr at breakfast—a technical problem that he was sure exposed a flaw in quantum theory. On both occasions, by dinner the same day, Bohr had come up with an explanation that did away with Einstein’s problem. Briefly Bohr would be worried by Einstein’s challenge, but soon he would be able to explain it away.

Three years later, the pair were back in Brussels again for another Solvay Congress, and this time Einstein seemed to be onto a winner. He devised an experiment which seemed to provide a way to measure both the energy of a particle and the time the measurement was taken with as much accuracy as you liked, something that was prohibited by the Heisenberg uncertainty principle, which said that there were some pairs of measurements of particles, like position and momentum, or time and energy, where the more you knew about one measurement, the less you knew about the other.

This thought experiment really threw Bohr, who is described as trotting along excitedly beside Einstein while Einstein walked quietly away from their meeting with a “somewhat ironical” smile on his face. Einstein felt that he had the upper hand.

It wasn’t until the next morning, after a sleepless night, that Bohr was able to respond to Einstein. It seemed that Einstein had made a fatal—and definitely “ironical”—error in setting up his imaginary experiment. He had forgotten to include the impact of general relativity. As we have seen, one of the effects of general relativity is that time is slowed down by the influence of gravity. The addition of general relativity effects made Einstein’s thought experiment produce exactly the results predicted by the uncertainty principle. Bohr and quantum theory had triumphed again.

Einstein was a great teaser, and Bohr was clearly slightly unnerved by these attacks on his theory, even though they seem to have grown out of Einstein’s genuine disquiet about the basis of quantum theory in probability. Even eighteen years later, Bohr was clearly wary of Einstein’s challenges. The physicist Abraham Pais recounts how in 1948 he was attempting to help Bohr put together an account of his disputes with Einstein. At the time Bohr was visiting the Institute for Advanced Study at Princeton, and was using the office adjacent to Einstein’s. (Technically the office he was in was Einstein’s, but Einstein preferred the more cramped confines of the room that should have belonged to his assistant.)

Bohr was supposed to be dictating his text to Pais, but the Dane was famous for making rambling statements. As often happened, he was having trouble stringing together a sentence in an acceptable form. He could juggle the concepts in his head, but Bohr found it difficult to translate them into comprehensible wording. The eminent scientist was pacing rapidly around the table in the middle of the room, almost running, repeating, “Einstein . . . Einstein . . .” to himself.

After a little while he walked to the window and gazed out, repeating now and then, “Einstein . . . Einstein . . .” as an apparent punctuation for his thoughts. At that moment the door opened very softly and in tiptoed Einstein himself. He signaled to Pais to keep quiet, with what Pais later described as “his urchin smile” on his face.

It appears that Einstein had been ordered by his doctor not to buy any tobacco. This was an injunction Einstein decided to take literally. He couldn’t go to the tobacconist, but it would be okay to raid Bohr’s tobacco, which was in a pot on Bohr’s table. After all, by stealing the tobacco, he was sticking to the medical guidance not to buy any. As Einstein crept into the room, Bohr was still facing the window, still occasionally muttering, “Einstein . . . Einstein . . .”

On tiptoe, Einstein made his way toward the desk. At that point Bohr uttered a final, loud “Einstein!” and spun around to find himself face-to-face with his longtime opponent, as if his incantation had magically summoned his rival. Pais commented: “It is an understatement to say that for a moment Bohr was speechless. I myself, who had seen it coming, had distinctly felt uncanny for a moment, so I could well understand Bohr’s own reaction.”

This was years later, though. After the 1930 Solvay Congress it would be five years before Einstein came back with a rejoinder to Bohr, and this time, instead of a casual challenge over breakfast, he produced a detailed scientific paper that threw down the gauntlet to Bohr and quantum theory, suggesting that if you followed quantum reasoning to its logical conclusion you ended up with nonsense.

Einstein’s move away from casual teasing reflected the increasingly dark situation in Europe. Hitler’s Germany drove Einstein reluctantly to the United States, where, as we have seen, he set up residence in what would be his academic home for the rest of his life, the IAS. Here, with two collaborators, Boris Podolsky and Nathan Rosen, Einstein produced the paper that highlighted a remarkable quantum phenomenon with a particular significance for time travel. Published in *Physical Review* on May 15, 1935, and called “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?” the paper became universally known by the initials of its authors, EPR. In good *Julius Caesar* fashion, this paper set out to bury quantum theory, not to praise it. Einstein intended to smash quantum theory by showing just how incredible its implications were. He had had enough of picking at details—now he would destroy the theory itself.

Unlike the attempts to throw Bohr off track at the Solvay Congress, the EPR paper was logically flawless. There was no room to discover errors in the science. It set out a real paradox, forcing anyone who accepted quantum theory to have to defend what Einstein deemed indefensible. There were two possible interpretations of EPR. Either quantum particles did carry hidden information, as Einstein suspected, and hence quantum theory was wrong; or locality was a meaningless concept when quantum particles were in a special state called entanglement.

Locality is something we take for granted. It's the idea that in order to influence something from a distance we have to send something across the gap that separates us. For example, I can't get words into your head across a room without using some means of communication to transfer those words from place to place. The mechanism might be sound—a transfer of energy from place to place in the form of compression of the air. Or it could be photons of light in the flashes of a semaphore lamp or the laser signals in a fiber-optic cable. I could hold up a sign for you to read or send a radio message. More simply, I could throw something across the gap between us. But whatever mechanism I choose, something has to pass from me to you.

Even when it isn't obvious that something is passing from place to place—for example, when a magnet attracts a piece of steel, or when the gravity of the Earth pulls something toward it without any obvious connection between the two—we now believe that there is a communicating stream of particles (photons and gravitons) traveling from source to subject to bridge the gap. These communicating particles are limited by the speed of light. But EPR seemed to suggest that there was something that could smash that barrier.

EPR showed that when two particles are in a special state, when they are entangled, they must either carry hidden information or be able to influence each other instantly, however far apart they are. With entanglement there is no wait for something to travel from A to B, carrying the information required. We make a measurement on one particle, and it instantly has an effect on the other particle at any distance. Locality does not apply.

As far as Einstein and the other authors of EPR were concerned, this discovery sounded the death knell for quantum theory. It seemed so obvious that locality had to apply (especially as instant communication casually ignored the central implication of Einstein's special relativity, that nothing can travel faster than light) that the authors assumed EPR showed that quantum theory was flawed. "No reasonable definition of reality could be expected to permit this," says the EPR paper.

Briefly, Bohr was thrown by the implications of EPR. The paper is phrased in a confusing way that seems to have misled Bohr initially into thinking that the thought experiment described in the paper was trying to measure both position and momentum accurately and simultaneously, something that is prohibited by

Heisenberg’s uncertainty principle. Bohr was misled by this unnecessary complication—the use of both position and momentum was not needed for the paper’s point to be true; either would do.

Einstein seems not to have been responsible for this part of the paper. His English was not great when EPR was written, and it’s thought he left these details mostly to coauthor Nathan Rosen. Einstein later commented in a letter to Erwin Schrödinger that the aspect of dealing with both position and momentum “ist mir wurst,” literally meaning “is sausage to me”—idiomatic German for “I couldn’t care less about it.”

Once Bohr saw through this confusion he had little interest in EPR. Although he had none of Einstein’s problems with basing quantum theory on probability, and was firmly convinced that quantum theory was correct, he was not happy with the idea of nonlocality: He largely dismissed EPR as nothing more than an interesting technicality that had little real relevance for the future of physics. Apart from anything, EPR was just a thought experiment that could not be carried out in practice. The concept of entanglement was fine, but the implications that Einstein raised weren’t anything to get worried about.

It seemed for a while as if quantum entanglement would be swept under the carpet and ignored, a small oddity in the history of physics, but two very different men would bring it back into the limelight and reveal the remarkable consequences of entanglement in practice.

First was a physicist called John Bell. Born in Northern Ireland, the redheaded Bell worked in the 1960s at the Conseil Européen pour la Recherche Nucléaire (CERN), the vast international research establishment that concentrates on high-energy particles, nominally located in Geneva but in fact straggling over (or, rather, under) the border between Switzerland and France. Best known now for the spin-off success of its electronic communication vehicle, the World Wide Web, and its huge accelerator, the Large Hadron Collider (LHC), CERN was then a much smaller and less publicized establishment.

Bell was working in particle physics, but as a spare-time activity he was doing some theoretical work on quantum theory. In part this was because he sympathized with Einstein. Bell too was unhappy with the basis of quantum theory in probability, and he wanted to find out where the theory went wrong. He later commented, “I hesitated to think it might be wrong, but I *knew* that it was rotten.” By this he seems to have meant that whatever lay at the heart of quantum theory wasn’t described very well—the explanations of quantum phenomena simply didn’t make sense.

It was not the existence of quantum theory per se that offended Bell, but the fuzziness of what was said about it. The purpose of his intervention in 1964 was to devise a new thought experiment that made it clearer that only if quantum theory was wrong could you have local reality—“reality” here meaning that there were true, if hidden, values of what was being measured rather than a fuzzy probability distribution. Bell once commented, “I felt that Einstein’s intellectual superiority over Bohr, in this instance, was enormous; a vast gulf between the man who saw clearly what was needed, and the obscurantist.” According to physicist Andrew Whitaker, Bell considered Bohr’s response to the EPR paradox incoherent.

Bell’s apparent contempt for Bohr has to be taken in context. I don’t believe any scientist would deny that Niels Bohr was a great physicist. It’s highly unlikely that John Bell would have suggested otherwise. Bohr made a huge contribution to our understanding of the physical world. It’s just that most onlookers would rather he had not resorted to his obscuring tactics and had stuck to more practical things. No one ever accused Bohr of being a great communicator.

In Bell’s thought experiment, published in an obscure and short-lived journal called *Physics,* Bell showed how an indirect measurement would prove that either two particles could indeed influence each other instantly at a distance, or quantum theory had gaping holes in it. Bell described an experimental setup where the outcome would be different depending on whether locality held up, or quantum theory’s predictions were true and entanglement, the phenomenon that Einstein called “spooky action at a distance,” really was a mechanism for instant communication.

John Bell had provided a way to put EPR to the test, an experimental basis for choosing between quantum theory and local reality, but writing this paper was still more of a hobby than real work to him. Anyway, Bell was a theorist rather than an experimental scientist, with neither the opportunity nor the inclination to follow up his paper in the laboratory. Rather surprisingly, perhaps because it appeared in such an obscure publication, there was limited interest in picking up on Bell’s idea.

It’s true that there were several attempts by a U.S. team of Abner Shimony, Mike Horne, John Clauser, and Richard Holt, beginning in 1969, to use entangled pairs of photons to check out Bell’s theorem, but the results were inconclusive. Most came out on the side of quantum theory, but at least one case suggested that it was wrong. These early experiments were pushing the technology of the day to its limits. The potential errors in the experiments were too large to be sure which way the outcome fell, so the results were uncertain.

Turning Bell’s ideas into a real-life experiment that had widely accepted results that would make or break quantum theory and prove whether or not entanglement truly provided a spooky connection at a distance would instead be entanglement truly provided a spooky connection at a distance would instead be the work of a maverick young French scientist, Alain Aspect.

Aspect, born in 1947 in the southwest of France, grew up in a rural backwater near the famous Bordeaux wine region but moved to Paris to study physics. Looking more like a football player than the stereotypical nerdy scientist, Aspect was a big man with an impressive flowing mustache. Rather than head straight to research from his doctorate, he took three years off to help with aid work in the Republic of Cameroon in western Africa. It was here that he began to take an interest in quantum entanglement and the challenge thrown down by John Bell.

In his spare time, Aspect read up on the latest developments in physics, particularly quantum physics. At the time this was a subject that had fallen out of fashion. It might seem odd to mention fashion in association with physics. It’s easy to assume that science is purely objective and stands nobly above trends and fads. But this isn’t the case. Science is just as much subject to fashion as hemlines—but fashion in science is decided by the fields that are winning a lot of academic support and by the areas where politicians feel that they can see a return for their money.

In the early seventies, the trends in the hard sciences were toward smashing particles together with greater and greater energy to explore the fundamental makeup of matter, or developing new theories of cosmology, providing dramatic speculation on how the universe was formed. Both areas remain in vogue today. Particle physics was particularly attractive because of the sheer novelty and speed of developments. I was an undergraduate at the time, and it seemed that almost every week one of our lecturers would excitedly announce that a new particle had been discovered. Even better, particle physics involved building enormous, shiny machines that looked good on TV. The politicians could see a tangible outcome for their investment.

Quantum theory, on the other hand, had the feeling of a field where there was little left to do, where theory matched experiment with boring predictability. The quantum world might still seem strange and new to us, but to physicists of the time, it was an old man’s game. Hoewever, Aspect was intrigued by the Einstein, Podolsky, and Rosen paper, by then well over thirty years old. Somehow he had come across not only the original paper, which at least was a well-known relic of physics history, but also John Bell’s obscure extension of the EPR concept in the direction of practical testing. With time on his hands, Aspect could think through in detail just how he would put John Bell’s test of entanglement into practice.

Sometimes having time to think is a luxury that is missing in academic life. It may well be that the inability to do anything practical while he was in Africa would prove Aspect’s greatest weapon in meeting the challenge of would prove Aspect’s greatest weapon in meeting the challenge of entanglement. By the time he returned to Paris he was determined to settle the outcome of Bell’s thought experiment once and for all, and he believed he knew how to do it.

When Alain Aspect returned to the Center for Optical Research at the University of Paris, he and his team built an apparatus to take measurements on a pair of entangled photons as they flew away from each other. There were two possibilities. Either the values that would be measured were already established before the particles were separated—they were hidden away, ready to be measured. Or, as quantum theory required, the values were established at the moment the measurement was taken. If, by then, the particles were far apart, they would have to communicate instantly to make sure that the value of the second particle corresponded to that of the first.

The readings from Aspect’s experiment would show whether or not the state of one photon had a direct effect on the other. But there was always a concern that the two detectors used to make measurements on the photons could somehow “conspire”—that information could somehow pass from one detector to the other, making it unnecessary for the spooky connection of entanglement to be responsible for the transmission.

The measurements Aspect was taking depended on the orientation of his photon detectors—which direction they were pointing in. What he thought of doing was to change the position of the detectors so frequently that there wasn’t time for information on the orientation of one detector to somehow reach the other. If Aspect could manage that, and the experiment showed that there was no hidden information, then the outcome could be produced only if there really was an instantaneous link thanks to entanglement.

Outpacing the speed of light was a tricky task. Aspect would have to get his detectors to change direction millions of times a second. At the time it was physically impossible to do this using motors or other standard mechanical means. Instead, he used a little-known property of water—that its refractive index changes if you squeeze it.

As you may remember from high school, the refractive index measures how a substance bends light when the light travels into it or out of it. And at one particular angle, the “critical angle,” light stops traveling into the substance and instead bounces off it. Aspect arranged for his entangled photons to arrive at just the right angle so that when the water wasn’t being squeezed they would pass into it, but while the water was being squeezed the photons bounced off.

A force was applied to the water by a transducer. Like a loudspeaker without the cone, this squeezed the water 25 million times a second, switching the direction of an incoming photon like a railroad switch routing trains. Depending direction of an incoming photon like a railroad switch routing trains. Depending on the position in the transducer's cycle, and hence how much the water was squeezed, an incoming photon would travel to one of two differently oriented detectors. There was no time for any communication to occur between the particles other than via entanglement.

The outcome showed beyond reasonable doubt that Bell's theorem gave quantum theory the thumbs-up. There really was an instant communication, rather than hidden information that preset the properties of the photons. Aspect was asked what he thought Einstein would have made of the results of his experiment, had he been alive. His careful response was: "Oh, of course I cannot answer this question, but what I am sure of is that Einstein would certainly have had something very clever to say about it."

Since that first experiment, numerous others have examined the phenomenon of entanglement in different ways, and provided more direct confirmation of entanglement's instantaneous communication. All such experiments have come down on the side of quantum theory and confirmed the way that entanglement ignores locality.

Of itself, entanglement is fascinating, but the real impact since its discovery has come from the way that it can be used. Quantum entanglement provides a mechanism to produce unbreakable encryption; is an essential component of quantum computers, which can undertake calculations that would take a conventional computer the lifetime of the universe to work out; and even makes it possible to emulate a small-scale *Star Trek* transporter and teleport a quantum particle from one place to another.

However, the aspect of entanglement that is of interest to the would-be time traveler is the instantaneous nature of the communication between two entangled particles. Remember, this connection defies locality. It doesn't need anything to pass from one particle to the other for it to occur. The instant a property of one particle is measured, the other one clicks into place. Just imagine being able to use this mechanism to send a message anywhere, without any delay.

Light speed is the absolute limit to communication at the moment. This has obvious limitations even when satellite communications are used on the Earth—we've all seen the delay when a TV news reporter is speaking from a distant city—but it would be much worse if we ventured farther into space. If we established a base on Mars, for example, signals would take around four minutes to reach home. And if we ever made it to the nearest star, we would be waiting around eight years for an answer to a question as the message crossed four light-years in each direction.

Instant communication would overcome this problem, doing away with irritating gaps in long-range phone calls and making it possible to directly control unmanned space probes from the Earth. But the implications for a would-be time traveler would be far greater.

To be precise, we’re really talking about the implications for a time *communicator* here. Instant messages don’t allow us to send a human being through time, but they do provide the mechanism for a message—for information—to penetrate back into the past. Oddly enough, the technique involves some of the same technology that we saw used in chapter 6 for travel into the future.

In the scenario described there, when our astronaut twin Karla is traveling at 0.9 times the speed of light (270,000 kilometers per second) she ages 8.71 years on a journey that from Earth’s viewpoint takes 20 years. Let’s imagine she is still on the outbound leg, just nearing turnround. Say she left the Earth in January 2050. Now, halfway through her journey, from the Earth’s viewpoint it’s January 2060. But on the ship, just 4.35 years have elapsed. It’s still May 2054. So if we can use entanglement to send a message from the Earth to the ship, it will leave in 2060 and arrive in 2054, having passed 5.65 years backward in time.

At this stage, Karla has not experienced the acceleration that will bring asymmetry between her and Karl on Earth. So from her viewpoint it is the Earth that is zooming away at 0.9 times the speed of light, and it is Earth clocks that are slow. At the point in time that Karla receives the message 4.35 years have elapsed. But to her, the Earth has been moving away at 0.9c for those 4.35 years. So from her viewpoint Earth clocks will be running slow. (Remember, this is before the acceleration that “resets” Earth clocks from Karla’s viewpoint.)

The 4.35 years that have elapsed on the ship will be the equivalent of 1.89 years on the Earth from the ship’s viewpoint. Earth time will be 2.46 years behind. If Karla sends an instant message back to Earth, it will arrive in November 2051, just over 8 years earlier than the original message was sent out. The message will have traveled 8 years back in time.

There’s an inherent limit to this kind of time travel. The earliest it can get a message back in time is the point at which the spacecraft took off. The closer the spaceship gets to light speed, the closer the instant message will get to that original departure date. But it can never get beyond that barrier. This isn’t a mechanism for getting a message to the distance past. You couldn’t use it to get a warning back to April 14, 1865, for instance, to drop Abraham Lincoln a hint that he really would benefit from avoiding John Wilkes Booth. The moment when the ship that is used as a relay is launched is the ultimate limit of backward travel. But this wouldn’t stop such a device from being used to pass back lottery results, nor would it prevent the sort of paradoxical twists and turns we will meet in chapter 13.

How close have we got to making this happen? The three essentials to make a time communicator are to be able to create entangled particles (and keep them entangled), to send one off in a spaceship at a reasonable percentage of the speed of light, and to use the entangled link to communicate. We need to look at each of these requirements separately.

Over the years since Alain Aspect's work, scientists have got highly skilled at creating entangled particles. Initially the favored method was to generate a pair of photons by blasting calcium atoms with twin lasers. An electron in the calcium is pushed up in a high-energy state, then drops back, producing not one but two photons, which appear in an entangled state. This was the approach taken by Alain Aspect for his experiments.

More recent experiments have tended to use beam splitters to entangle particles. Beam splitters are mechanisms to get two existing photons entangled; moreover, scientists can use them to make particles other than photons entangled. For instance, get two clouds of rubidium atoms, each entangled with a photon they have emitted, send the photons through a beam splitter the right way, and the atom clouds become entangled.

Beam splitters sound a touch sci-fi—but we've all seen them in action. At its simplest, a beam splitter is a mirror that lets some photons through and reflects others back. Stand in front of a window in a well-lit room at night and look at the glass. What do you see? Yourself. The window transforms into a mirror. If it were an ordinary mirror, nothing would come out the other side. But if you were to go outside your house and take a look at that same reflecting window, you would clearly see into the well-lit room. A fair amount of light—most of it, in fact—is passing through. The window of your home is acting as a beam splitter.

We accept this partial reflection as common sense and natural, but once you start to think about the detail of what is happening, it's highly strange indeed. So strange, it had Isaac Newton very worried. Just imagine what's happening. A stream of photons hits the surface of the glass. Some of those photons are reflected back. Many aren't reflected and instead pass through the glass. So how does a particular photon know what to do? It's the usual quantum challenge—we know the probability that something will happen, and on average the right quantity of photons will be reflected, but what makes one photon travel through and another bounce back is a mystery.

It was this uncertainty that puzzled Isaac Newton. His mental picture of light was of a stream of "corpuscles," tiny particles flowing toward the glass. He couldn't understand why some of those particles hitting a window bounced back and some didn’t. The most obvious suggestion was that there were irregularities in the surface of the glass. If this were the cause, it would be as if tiny bits of the surface were mirrors, while other, larger areas were clear. In this picture, corpuscles hitting the mirrored segments would bounce back while the rest traveled through. It makes a lot of sense. But as Newton realized, it’s wrong.

Newton had done a fair amount of lens making for his optical experiments, and he knew that as you polish the glass of a lens with finer and finer material, resulting in smaller and smaller scratches in the surface of the glass, it becomes transparent. Very fine scratches don’t seem to affect transparency. Yet if the cause of partial reflection were irregularities in the surface of the glass, these bumps and cavities would have to be so small that they couldn’t be seen—so fine that they should never produce reflections.

With a modern quantum viewpoint there is no obvious cause for the partial reflection, and as with so many other aspects of quantum theory, we simply have to accept the probabilistic nature of the process (even though, like Einstein’s, our minds may rebel against it). But this is only the start of the strangeness of the beam-splitting window. Light passing through a piece of glass hits not one but two interfaces. First it passes from air to glass as it leaves the room; then, after traveling through the depth of the glass, it moves from glass to air as it escapes to the outside world.

It’s not surprising that the second transition could also produce a reflection, back into the glass from the interface between glass and air—but things aren’t that simple. The total amount of light reflected from a piece of glass depends on how thick the glass is. Does this matter? It should hardly be surprising that the amount of light that reflects from the outside of the window depends on how thick the glass is. But in practice the amount of reflection from *both* surfaces of the glass depends on the thickness. Get the thickness right and you can reduce the reflection from the inside of the window to practically nothing.

Think about that for a moment. You shine a beam of light on the inside of your window. Normally, some photons will reflect back. But if the glass is the right thickness, the photons will somehow know how thick the glass is *at the point they hit the inside surface of the window,* and instead of reflecting back, they will carry on through. Strange indeed.

Once you realize just how bizarre the process of partial reflection is, it’s somehow not entirely surprising that a beam splitter can produce entanglement. The practicalities are messy, but this is a powerful way to set up entangled pairs of particles.

It’s also necessary to keep those particles entangled as one shoots off in a rocket. The problem is not the fact that the particles are separated, but the way photons (or other quantum particles) have a tendency to interact with their surroundings. Anton Zeilinger and his team at the University of Vienna have sent entangled beams for several kilometers through air, keeping them entangled. But to keep our entangled particles secure we've less of a problem than Zeilinger had.

Say we entangled a pair of ions, charged particles of matter, via the indirect beam-splitter method. We could keep those ions in airless shielded chambers, suspended in electromagnetic fields to prevent them from coming into contact with other matter or light. In principle we can keep entangled particles indefinitely. If there were a danger of losing the entangled link over time, we could use a kind of hot-potato technique, repeatedly passing on the entanglement to a new particle to keep the link going.

When it comes to the ship, as we saw in chapter 6, it is difficult to achieve the sort of speeds required to make a worthwhile journey into the future. But here we are less fussy. The ship does not need to be manned, so we aren't worried about wasting an astronaut's time. And the shift would need to be only a fraction of a second to start producing time paradoxes—or a few minutes to win the lottery. For that matter, we wouldn't have to accelerate a 100-ton space shuttle—the payload would be only a few tiny particles, so the probe could be much smaller. Given time for the difference to build up, this is achievable with present-day technology. We have plenty of probes out there traveling around 50,000 kilometers per hour with respect to the Earth.

That sounds fast—it is—but the speed of light is 300,000 kilometers per second. That's 1.08 billion kilometers per hour. So those probes are traveling at around 0.005 percent of the speed of light. Even so, after ten years of travel, the probe should enable a time shift of the order of a second. Not massive, but usable—and that assumes we can't go any faster with next-generation probes. Realistically, we should be able to get a practical time shift with today's technology.

All then rests on the third requirement: being able to use that entangled link to send a message. Intuitively, it seems obvious. Make a change to one particle, and the change is reflected in the other one. Let's keep our message really simple, the most basic message we can send. That means resorting to binary, the language, or rather the alphabet, of computers. Binary is made up solely of the numbers 0 and 1. So counting 1, 2, 3, 4, 5 becomes instead 1, 10, 11, 100, 101. (This is where the geeky T-shirt reading "There are 10 types of people, those who understand binary, and those who don't" gets its joke from.)

The most basic piece of information we can send is one bit, which has two possible values, zero or one. That would be enough, for example, to predict the outcome of a coin toss if we could send the bit of information into the past. Or, as we'll see in chapter 13, it could be used to set a time travel paradox in motion. To represent our 0 or 1 bit, we'll use a fundamental property of a quantum particle, its spin.

The concept of spin is based on an imaginary idea that the particle is spinning around on its axis, like the Earth. But it should be stressed that this doesn't represent what's actually happening. Physicists don't think that spin is really a measure of the direction a particle is spinning in. It's just a handy (if confusing) name for one of the particle's properties. Unlike the spin of a ball, quantum spin is digital. If you measure it in a particular direction it will always be either "up" or "down." It can't be anything in between. Depending on the value of the spin property, the probability of its coming out "up" could be anything between 0 and 100 percent—but the spin can have only one of those two results when measured.

This sounds usefully like something that can be used to send a bit of information. It is a binary digital property. So we measure the spin of the particle on Earth at an agreed time. Let's say it turns out to be spin up. Instantly, "simultaneously" the particle on the probe clicks into the spin down state. But thanks to relativity, that simultaneous event takes place slightly in the past as seen from Earth. We're on our way to sending a message back in time. If we make spin up represent 0 and a spin down 1, we've sent a message of "1" to the ship.

Unfortunately, there's a big problem. Measuring a particle's spin is not the same as throwing a switch. Before measurement the spin didn't have a value. The particle's spin was both up and down simultaneously. Once we take the measurement, the spin had a known probability (let's say fifty-fifty) of becoming, say, spin down. In this instance it did turn out to be spin down. And that information was transferred instantly to the other particle. But there was no way we could control the outcome.

The state the Earthside particle ended up in was one of those probability-driven events that so frustrated Albert Einstein. It was random. So all we succeeded in sending was a random bit of information. (Note, by the way, that if there were truly hidden information, as Einstein thought, and we could discover that information in advance, in principle we *could* use this to send a message through time.)

It's frustrating. It is so obvious that it should be possible to send a message using the instantaneous link of entanglement, but the randomness of the quantum effect gets in the way. All is not lost, though. How about using the entangled nature of the particles itself as the bit of information, so it doesn't matter what the outcome is?

the outcome is?

When we make the measurement on the particle on Earth, its entanglement is broken. This is how quantum entanglement can be used as a secure method for exchanging an encryption key to make an unbreakable cipher. If anyone intercepts the key as it travels from sender to recipient, the entangled link is broken and the key is never used. (Here the randomness of the outcome is a positive asset. We can use the random value as part of the key for a cipher.) So why not have a particle with the entanglement still in place represent 0, and one where we've made a measurement, breaking the entanglement, as a 1?

For this to work, we have to be able to determine whether the particle on the probe is still in an entangled state. The good news is that this is possible. Otherwise we couldn't use entanglement to keep that cipher key secure. But there's a price to pay. To determine whether or not the particle on the probe is still entangled, we need to send some information out to the probe from the Earth by a conventional link. This message can't travel faster than light. By the time the information gets to the probe, it's too late. The time shift into the past has been lost. We can determine whether or not the particle on the probe is still entangled, but not instantly. And without that capability for instantaneous transmission there is no way to send a message into the past.

Entanglement does reach instantly across any distance. To be more precise, it seems that as far as entangled particles are concerned, distance doesn't exist. They act as if they are part of the same thing. Imagine you had a very long rod that was totally rigid. You push one end. Immediately, simultaneously, the other end moves. Your "signal," the push, gets from one place to another instantly. But nothing has moved at more than the speed of light.

The rod example doesn't work in practice because any real object isn't totally rigid. When you push one end, there's a small compression which will pass down to the end of the rod at less than the speed of light. But it still makes a good picture for the way entangled particles seem to act—as nonlocal, extended versions of themselves, not as two distinct objects with a message passing from one to the other at superluminal speeds.

It appears that using entanglement on its own isn't the answer. But we shouldn't give up hope immediately. As we have seen, entanglement is already being used to build a matter transmitter, using a phenomenon known as quantum teleportation.

It seems unlikely, but physicists have managed to duplicate the action of a *Star Trek* transporter on the scale of single particles. So is this a way to beat the light-speed barrier and send a message (or a person) through time? Just listen to these encouraging words from a book on time travel technology: "If you transfer from Earth to Mars, for instance, you will instantly arrive at your destination, but the light conveying the image of your departure will take several minutes to cross the void and catch up. . . . In this case you go back into the past by whatever gap is introduced by the speed with which light makes the same journey."

Even if we don't take this particular example at face value, if we could perform quantum teleportation to send a person instantly to a distant space probe, he would travel back in time, just as much as the message we looked at earlier in the chapter.

In practice, there are some real problems with teleporting a person. First there is the ethical issue. Quantum teleportation involves modifying a distant particle so that it becomes identical at a quantum level to the original particle. In the process, the original particle loses its identity. If we could use the same process on a person, we would be producing an exact copy, down to the individual quantum particles, and destroying the original as we did so.

This doesn't sound like an ideal way to travel. Admittedly our bodies are always replacing bits and pieces. Pretty well every atom in your body has been replaced in the last ten years—even those that make up the bones. But this doesn't take away the fact that the "you" that you currently experience would be ripped to pieces by a matter transmitter while a duplicate was constructed at a distance. I certainly wouldn't fancy it.

Then there's the problem of scale. Quantum teleportation has so far involved single particles, or a single property applied to a group of particles. It hasn't been achieved on anything close to a tangible physical object. Let's see what's involved to perform teleportation on a whole human body. That has typically around 10^{28} atoms in it. That's 1 with twenty-eight zeros after it. Ten trillion trillion trillion atoms. To teleport a human being you would have to scan every single one of those atoms.

If you scanned the atoms at the rate of a million a second, it would take 100,000 trillion years to scan a whole human being. This isn't promising for a technology that depends on being able to transport someone instantly. It's just possible that we could develop some sort of holistic scanning device that could make measurements on every atom in a body at once, but that seems very unlikely at the moment.

So let's take a step back from teleporting a human (with something of a feeling of relief) and just send through a handful of particles. That should be enough because, whereas we can't control a property of an entangled particle to send a message, we can use the properties of a group of particles we teleport, setting them up in a way that spells out a message before we teleport them.

In principle, we could teleport that handful of particles, with all their properties, onto a high-speed probe that has already built up a good distance, and so provides us with a time slip. It seems as if we have achieved our goal. But (as you probably expected by now) there's a catch.

Our quantum teleportation time machine depends on the key statement I quoted, "you will instantly arrive at your destination"—and that simply isn't true. As we have seen already, the entangled connection between quantum particles that is used in teleportation does act instantly across any distance. But quantum teleportation involves more than just a spot of entanglement. Imagine we are teleporting just a single particle. The process would go something like this.

We set up an entangled pair of particles, send one off in our probe, and keep the other on Earth. After a while we decide we're ready to perform the teleportation. We take our particle on Earth that is to be teleported. This is a third, separate particle, not one of the original entangled pair. We interact the subject particle with our local member of the entangled pair. As we do so, we take some readings on the interaction.

In undertaking that interaction, we have instantly influenced the distant member of the entangled pair on the probe. But we haven't performed teleportation yet. There is a final piece to the puzzle. Now we have to send the information that came out of the readings we took on Earth out to the probe. When that information arrives, we take an action on the distant member of the entangled pair. The action we take depends on the information that has been sent. Finally, our distant particle has become, at an absolute quantum level, the particle we started off with.

Notice what happened here. Information from readings taken locally had to be transmitted to the distant particle in order to complete its transformation into the duplicate of the original. It was only after that information had been received, and the distant particle was modified, that we achieved teleportation. And the fastest we could send that information to the probe was at the speed of light.

Quantum teleportation isn't instantaneous, even though one of the channels it uses *is*. The suggestion that it happens in an instant seems to be based more on *Star Trek* than on physics (and even in the TV show there is a noticeable delay between dematerialization and reappearing). The fact is that entanglement on its own can't send a message at all, while through teleportation we can send a message, but it will travel no faster than the speed of light.

However you attempt to twist its application, entanglement isn't the answer to time travel. But entanglement isn't the only strange concept that has emerged from the new physics of the twentieth century—there are other tantalizing possibilities. As yet these are only theoretical, less certain than entanglement, but they could enable us to step beyond the bounds of time.

CHAPTER NINE

PHANTOMS OF TIME

> *Nothing puzzles me more than time and space; and yet nothing puzzles me less, for I never think about them.*
>
> —Charles Lamb (1775–1834), *The Letters of Charles and Mary Anne Lamb,* vol. 2 (1976)

From human experience, echoing the thermodynamic arrow of time, time always seems to flow in a single direction. But the flow of time we experience is not an absolute requirement as far as much of physics is concerned. This was something that occurred to the man who inspired Einstein to produce his theory of relativity. When Einstein dreamed up special relativity he was relying on a set of equations that described how electricity and magnetism would interact, putting more reliance on those equations than on the apparently intuitive idea that light’s speed should vary as you move with respect to it. Those equations were produced by the Scottish scientist James Clerk Maxwell.

Maxwell was not a contemporary of Einstein’s—in fact, with a satisfying coincidence, he died in the same year as Einstein was born, 1879. This wasn’t the first great pairing of scientists sharing a birth and death year. Newton was born in 1642, the year Galileo died. However, to make that link work, you have to look at Newton’s dates a certain way. Newton was born on Christmas Day 1642 according to the calendar of his time, but by modern reckoning, after the shift to the Gregorian calendar, he was born on January 4, 1643. Maxwell and Einstein give us no such problems, but it shows how tricky time can be.

James Clerk Maxwell was born in 1831, in Edinburgh, Scotland. He was brought up with plenty of exposure to nature on his parents’ estate at the manor house of Glenlair, but initially his experience of education was not encouraging. After his mother’s death when he was only eight, young James was sent to school in Edinburgh. He was small for his age, stuttered, and had a broad country accent. But despite bullying and the nickname “Dafty” that followed him for years, he proved an academic success and moved on to Edinburgh University at sixteen, and three years later to Cambridge University in England.

Maxwell’s recommendation to the master of his college at Cambridge from his old professor in Edinburgh read, “He is not a little uncouth in his manners, but withal one of the most original young men I have ever met with.” Maxwell’s work would prove the professor right, as far as the originality goes. Maxwell and Michael Faraday between them would make a bigger impact on modern physics than any other nineteenth-century scientists.

One of Maxwell’s interests, spurred on by some observations that had been made by his hero, Faraday, was light. Most physicists limited themselves to optics, to observing how light behaved. But Faraday, known for his expertise in magnetism and electricity, had speculated on what light actually *was*.

Although it was merely speculation, Faraday suggested that light was a vibration, a wave, like sound, but instead of moving forward and backward like a sound wave, it moved side to side as it traveled. He also felt that it was in some way connected to magnetism and electricity.

When Maxwell came to think about the same subject, he imagined that light passed through the “ether”—the invisible medium it was then assumed to be a wave in, rather like a mechanical model of a fluid—and that it was influenced by various forces. Perhaps inspired by Faraday, he tried fitting electrical and magnetic waves to his picture and discovered there was a particular way that an electrical wave and a magnetic wave could support each other, one generating the other in a perfect dance of constant regeneration. But this could work at only one particular speed. When Maxwell calculated that speed, he found it to be the speed of light. He commented:

> This velocity is so nearly that of light, that it seems we have strong reason to believe that light itself (including radiant heat and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.

In the end, Maxwell formed his mathematical analysis of light into eight equations, which would later be whittled down by Oliver Heaviside and Heinrich Hertz into four stark and simple lines of mathematics. These describe how light can haul itself up by its own bootstraps and keep itself going. At the speed of light, the magnetism generates just the right amount of electricity, which generates just the right amount of magnetism, and so on. It can’t stop; it can’t slow down (in any particular medium); it has to keep going at the same, constant speed if it is going to exist.

Although Maxwell never recognized it, seeming to have a blind spot on the matter, his theory did away with the need for the ether. This electrical-magnetic combination could cross empty space because it wasn’t a wave in a material combination could cross empty space because it wasn't a wave in a material where the atoms of the material bounce around in a particular way. It was much more refined—a wave in magnetic and electrical fields with no need for matter as a medium.

I generally go out of my way not to include equations in a book, but this is one set I like to make an exception for because Maxwell's equations (in the form derived by Heaviside and Hertz) are so beautifully spare and simple looking. This is all you need to describe the behavior of electricity and magnetism that allowed Maxwell to deduce the nature of light:

$$\nabla \times \mathrm{E} = -\frac{\delta}{\delta t}\mathrm{B}$$

$$\nabla \times \mathrm{H} = -\frac{\delta}{\delta t}\mathrm{D} + \mathrm{J}$$

$$\nabla \cdot \mathrm{D} = \rho$$

$$\nabla \cdot \mathrm{B} = 0$$

This way of representing the equations does cheat a little. They are equations in more than one dimension, working on matrices of numbers rather than a single value. So the upside-down triangle, called a "del," involves change in all three spatial dimensions simultaneously. However, you don't need to understand the math for the equations to give you a broad feel for the elegant simplicity of Maxwell's discovery.

The first shows how a changing magnetic field produces electricity. The second shows how electricity generates magnetism. The third gives us a way to link the electrical field that is produced to the electrical charge present. And the final one tells us that there can't be isolated magnetic poles (so called monopoles): they always come in matched pairs.

The mathematical description of light based on Maxwell's work had one oddity that was largely ignored at the time. There is more than one way to solve the equations. You may remember solving quadratic equations at school. Each equation had not one, but two possible solutions. Similarly, Maxwell's equations predicted that light should have two modes of operation, what were called "retarded waves" and "advanced waves." The retarded waves are light as we observe it, but the advanced waves should travel backward in time—still at the speed of light, but in the reverse direction on the timeline.

If it was somehow possible to use an advanced wave to send a communication to a distant beacon, then send another advanced wave back to the original source, the message should arrive back before it was sent.

Advanced waves have never been observed, and for a long time it was assumed that they were just a peculiarity of the math, and there was no physical phenomenon to correspond to the advanced solution, leaving only the retarded solution, the familiar light that travels forward in time. But there was always a school of thought that assumed the advanced waves were present, just not observed. Apart from anything else, there was no scientific reason to abandon the mathematics that predicted advanced waves. They were just arbitrarily being ignored because they didn't seem to make sense.

There is something of a parallel between advanced waves and the idea of virtual particles. The electromagnetic interaction between, say, an electron and the nucleus of an atom involves a flow of photons between the electron and the positively charged nucleus. We never see these photons—they never escape into the real world, so they are referred to as virtual. But virtual particles can be shown to exist by disrupting the environment that contains them, "exposing them" to the real world. Some argued that advanced waves were a bit like this—present, perhaps even significant in the workings of the universe, but not observable, because of our thermodynamically biased arrow of time.

Two of the greats of twentieth-century American physicists, John Wheeler and Richard Feynman, suggested that there was a circumstance where advanced waves did have a visible effect. When an atom gives off a photon of light, the atom recoils, like a gun recoiling when it is fired. This is conventionally explained as working in a similar Newtonian fashion to the gun recoil—the atom is influenced by the departing photon. But there's a problem with this explanation: it involves self-interaction.

In order to cause a recoil, the electromagnetic field of the atom would have to act upon itself. And whenever this kind of result is generated, the tendency is for the predicted outcome to head off for infinity. There's a kind of feedback loop that should send the whole thing out of control. And yet atoms are emitting photons all the time, and no such problem arises. Although there have since been mechanisms proposed to get around this self-interaction, or to make it acceptable, Wheeler and Feynman suggested a solution that was simultaneously more elegant (as there was no fudging involved) and more radical.

In quantum electrodynamics, the theory that describes the interaction of light and matter, there are usually three participants in any action: a matter particle that generates a photon, the photon, and a second matter particle that absorbs the photon. The two events of creation and absorption might be separated by billions of years—for example, when a photon from the early years of the universe is finally detected in the cosmic microwave background radiation, which is often called the "echo" of the big bang—but both of these events are part of the photon's life history.

In what would come to be known as the absorber theory of radiation, Wheeler and Feynman suggested that there were not one but two photons involved in such a process. One was the normal light traveling from the first atom to the second in normal time—the photon that corresponded to the retarded wave. The other traveled from the target atom (the "absorber") backward in time to arrive at the initial atom at the same moment the retarded photon was dispatched. The incoming photon, the equivalent of the advanced wave, would hit the source atom and cause what was interpreted as recoil. That way no self-interaction was required, because it was a separate photon that caused the movement of the atom.

Each of these two photons envisaged by Wheeler and Feynman would have half the energy (or in wave terminology, they would have half the amplitude), and since they both traveled at exactly the same speed in opposite directions, one forward in time, one backward, they would always be at exactly the same place at any given time. Although this idea is rarely considered anymore, it isn't totally ridiculous. Not only does it do away with the need for self-interaction, but it brings the full solutions of Maxwell's equations into play, rather than just selecting the results which match what we observe and ignoring the others, with no justification.

This might seem like so much fantasy on Wheeler and Feynman's part. It requires a photon departing an atom to have a sort of predestined interaction in a ghostly form with the atom it will eventually collide with. But this isn't much stranger than the workings of a beam splitter described on pages 137–39. Remember that the chances of a photon bouncing off the inside of a glass window are affected by the thickness of the glass. The other side of the glass has an effect on what happens at the inner surface. Similarly, here we have to envisage the "other side" of the light beam—the atom that will eventually absorb it—having an effect on the photon at the time it is emitted.

The interesting thing about the absorber theory is that it requires an emitted photon to have a target. For a photon to be produced, it has to be going somewhere. In traditional physics, the photon could in principle head off into the void forever, never to interact with another bit of matter for all eternity. That difference between the two approaches is enough to enable a form of communication through time—if only absorber theory is true.

Imagine there exists a particular area of the sky where there are lower-than-average amounts of absorbers—the matter that can receive a photon. Travel out in that direction for some distance, taking a good photon absorber with you. Now start to transmit from Earth in that direction. To begin with, the transmitter won't be able to send out much power in that direction, as it can send out photons only if they are going to be absorbed, and the area is deficient in absorbers. But when the distant station puts the good absorber into the beam, the power output of the transmitter will peak.

On Earth, by monitoring the output power of the transmitter you can register a form of signaling from the distant station, as it puts its absorber in and out of the beam. It's a bit like semaphore with a lamp and a shutter, the only difference being that the light is traveling backward in time, arriving at the *transmitter* before the absorber is moved.

Now we need one more layer of complexity. At the moment a signal is being received on the Earth earlier than when it was sent from the distant station. But to usefully send a message back in time it has to go from the Earth and get back to the Earth. So there would have to be a second transmitter/absorber pair heading back toward Earth. This way a message from Earth will be received at the distant station in the Earth's past, then get back to the Earth in the past of that point in time, a double journey into the past.

Even though this has a double dip into the past, it still doesn't enable us to send a message back before the time machine was built, as we need the transmitter working on Earth before we can observe its variation in power.

There is one catch, however. The Earth is a good absorber of light—it would never give enough contrast with the signaling absorber for the message to be received backward in time from the distant station. To make it work, there would need to be a receiving station in a direction with low absorption relatively near the Earth, which then passed on to the Earth the message that had traveled back through time as a conventional (retarded-wave) signal. Some of the backward shift would be lost this way, but not enough to make the whole exercise worthless.

The whole idea of using advanced waves has one big problem, of course. It is just a theory. There is no experimental evidence that these time-reversed waves exist. The best attempt to find them has produced nothing. This doesn't mean they don't exist. Any one experiment can be flawed, and it's entirely possible that the beam that was sent heading off into space was being fully absorbed, and so produced no variation in power output. We don't have the practical means to switch a distant absorber in and out of the beam yet. So at the moment there is no confirming evidence that will turn an engaging theory into practice. But that doesn't mean it won't ever be found, or that it's not a fascinating concept.

At first hearing, advanced waves sound like another contribution the great Richard Feynman made to our ways of understanding the quantum world. Along with the Swiss scientist Ernst Carl Gerlach Stückelberg (but working separately), Feynman came up with a solution to the Dirac sea problem that implied the existence of particles that moved backward in time.

It’s often pointed out that British physicist Paul Dirac predicted the existence of antimatter (see page 89), and specifically deduced from theory that there had to be an antielectron or positron some time before it had been discovered. And this is true. But what is less often mentioned is that his prediction was based on a picture of the universe that many regarded as so far out in left field that it was well out of the park.

Schrödinger’s wave equations, which predict the behavior of quantum particles, assume that those particles are classical, not influenced by relativity. What Dirac managed to do was to transform the equations to deal with particles traveling at relativistic speeds. The price he paid for this breakthrough was the discovery that electrons should be able to exist in two states—with either positive energy or with negative energy. If so, the expectation would be that the negative energy state would be more stable, and every electron in existence would give off a blast of light and disappear into this strange negative energy state—something that clearly didn’t happen.

To fix this problem in what were otherwise very elegant extensions of Schrödinger’s equations, Dirac used a property of particles like electrons (which are members of a group of particles called fermions) known as the Pauli exclusion principle. This makes it impossible for two fermions to be near each other and in the same state. Dirac imagined there was an infinite sea of negative energy electrons—not detectable in the normal world—filling all of empty space. Because these negative energy electrons were already there, the normal, positive energy electrons couldn’t drop down into the negative energy state. They were kept away from the full negative energy sea by the Pauli exclusion principle.

However, Dirac’s model predicted that just occasionally one of those negative energy electrons would absorb a chunk of energy and pop into a positive energy state. It would leave behind a “hole” in the negative energy sea. That hole would behave as if it were a positive energy particle with the charge reversed to that on an ordinary particle—an antielectron. If a normal, positive energy electron dropped down to fill the hole, the result would be annihilation, just as is observed when an ordinary electron meets a positron. This was how Dirac predicted the existence of the positron.

The model worked, at least for fermions. There are other particles called bosons (protons, for instance) that also proved to have antiparticles but for which this model was not helpful, because the Pauli exclusion principle doesn’t apply to bosons. But many physicists were (and still are) uncomfortable with the idea of an infinite sea of negative energy electrons. It doesn’t have the neat sense of elegance that often marks a successful scientific theory. This is where Feynman's idea came in.

Many of Richard Feynman's successes in quantum physics came from taking a very visual approach. He would later devise diagrams for the interaction of light and matter than would revolutionize our understanding of this crucial behavior. But to handle the electron, Feynman came up with a different visual picture—one that portrayed electrons and their negative energy equivalents as two metro lines, running in opposite directions.

In principle, there is nothing in the Dirac equation that prevents negative energy electrons from running backward in time. Feynman imagined that this was the case, making it impossible for the forward-traveling electrons to switch tracks to become backward-traveling negative energy electrons. In this model, electrons don't all instantly annihilate, because they can't make the leap into time reversal. They are unable to drop down into a negative energy state.

The clever thing about this model is that it is absolutely impossible to distinguish between a negative energy electron traveling backward in time and a positive energy positron traveling forward in time. They are identical concepts as far as the equations go. So by Feynman's theory, positrons exist because that's how we, with our particular view of time's arrow, see what are, in fact, negative energy, backward-traveling electrons.

This theory works better than Dirac's original electron sea because it is equally applicable to bosons and fermions. If it's true, rather than being just a convenient mathematical description, it means that every time we detect a positron we are detecting a particle that is traveling backward in time. But unfortunately for time-machine builders, we can't harness this property. The particle may be, in truth, a negative energy electron slipping back through time, but we will always see and interact with a positive energy positron traveling with time's arrow. There is just no way we can ever use it.

If we can't use Feynman's time-reversed negative energy electrons, there is a final phantom possibility for communication through time. The science makes this approach, like advanced waves possible, but the outcome has never been observed. It may never be found—just because the physics makes something possible doesn't mean it exists—but it could also be discovered tomorrow. This idea predates the concept of advanced waves. In fact, it goes back further even than relativity. This is the idea of the tachyon (the name came later).

The tachyon is a particle that travels faster than light, and hence lives out its existence backward in time. The idea was first dreamed up by the German scientist Arnold Sommerfeld in 1904 in response to the symmetry in Maxwell's equations. An ordinary particle gains velocity as it gets extra energy and can never travel as fast as the speed of light. A tachyon would get faster as it lost energy and would be unable to get as slow as the speed of light.

One of the most worrying things about a tachyon flows from the relativistic equations that describe how speed influences size and mass. What we're dealing with here is "rest mass." This is what the mass of a particle would be if it were brought to a standstill, ignoring any mass due to the energy of motion. A photon has a zero rest mass, though in a sense the concept is meaningless, because a photon can't be stopped.

Once the speed of a particle exceeds light speed, some of the relativistic equations—including that for mass—produce results that are imaginary. This isn't imaginary as in an "imaginary friend" but in the mathematical sense. An imaginary number is the square root of a negative number, which is a fairly mind-boggling concept.

You have come across the square root: the number which, when multiplied by itself, produces the value it's the square root of. So the square root of 4 is 2, because 2 × 2 is 4. But what is the square root of –4? What do you multiply by itself to get –4? It's not –2. If we multiply –2 by itself, once again we get 4. All –2 provides us with is an alternative square root for 4. Two positive numbers multiplied together make a positive number. Two negative numbers multiplied together make a positive number. To get the square root of a negative number, we need something completely different—in essence a fantasy construct, called an imaginary number.

For easy representation, the square root of –1 is called i, so we can now label the square root of –4 as 2i. So far, so good. And lots of good math has been worked out for manipulating imaginary numbers. They turn out to be very handy for performing a lot of real-world calculations, provided the imaginary numbers disappear before the final result. It's fine to use an imaginary number to calculate a real outcome, as long as you don't end up with an imaginary value in the result of your calculation.

Imaginary numbers are often envisaged as operating in a dimension at right angles to normal numbers. If you think of the number line, with 0 in the center, heading of in the positive direction to the right and in the negative direction to the left, then the imaginary number line can be treated as running at right angles to this, heading upward for positive imaginary numbers and downward for negative imaginary numbers. A position off the axis in such a diagram is a "complex number," which has both a real and imaginary part. So it might be, for instance, 3–2i, which would be 3 on the real number line and –2 on the imaginary number line.

Often when imaginary numbers are used in science and engineering, they are just a handy way to manipulate something that requires two different dimensions like this. No one is suggesting that there is a tangible entity which has a value of an imaginary number. But if tachyons exist, then their rest mass is genuinely imaginary (though in practice they are physically incapable of being at rest, because they have to travel at higher than light speed).

Tachyons have a pleasing symmetry when compared with a conventional matter particle. As we speed up a conventional particle, we have to pump energy in. As it gets near the speed of light and its mass gets larger and larger, we need to inject more and more energy to increase the velocity. It would take an infinite amount of energy to get it up to light speed. Similarly, a tachyon requires more and more energy to slow it down. It would take an infinite amount of energy to get it down to light speed.

If there are any tachyons out there, the chances are that they aren't charged particles. This is because of a surprising little twist in the whole business of traveling faster than light. We're used to being told that nothing massive can travel faster than light—but what we mean by "faster than light" is the ultimate speed of light, the speed of light in a vacuum, 300,000 kilometers per second (186,000 miles per second). However, light doesn't always travel this fast. In fact it can go much slower. You can even see this slowing down happening, whenever light enters water or glass.

There's an old trick to amuse children of putting a pencil into a cup of water. Looking into the water, the pencil seems to be broken, changing direction at the surface of the water. Generally speaking, when light passes from air into a denser substance—water or glass, for instance—it bends in to be closer to a line at right angles with the edge of the glass, the process known as refraction. This is why lenses bend light to a focal point (the curvature of the lens bends different beams by different amounts, bringing them to a focus). It's also how a prism produces a rainbow as different colors of light bend by different amounts.

The whole business of light bending this way seems odd to begin with. Why should it suddenly change direction at the interface between two mediums? This was explained by the French mathematician Pierre de Fermat in the seventeenth century. Fermat is probably best known now for the challenge he threw down with "Fermat's last theorem." In a note scrawled in the margin of a book, Fermat claimed to have a mathematical proof. The note said, "I have a marvelous demonstration of this proposition which this margin is too narrow to hold." It wasn't until 1993 that this theorem was proved, with mathematical tools that were far more sophisticated than anything Fermat had available, so perhaps he was bluffing. His idea about refraction was less dubious.

In looking at refraction, Fermat made two assumptions. One was that light's speed was finite (this was before Ole Roemer had measured the actual speed of light). The other assumption was that light traveled slower in a denser material like glass than it did in the air. With these assumptions in place, Fermat could apply what has since been referred to as the Baywatch principle.

Generally speaking, the fastest way of getting from A to B is in a straight line. But that assumes that conditions remain the same all the way along the journey. But think of a lifeguard who sees someone drowning in the sea. She has two choices of route. She can head in a straight line toward the drowning person, or she can travel farther across the beach, so that she travels a shorter distance through the water. Because she is much quicker on the beach than in the water, the second option is faster. Despite the increase in overall journey length, it’s quicker to travel a bit farther on the high-speed segment to reduce the length of the low-speed segment.

Similarly, if light is to get to its destination as fast as possible, it shouldn’t always take a straight line. By taking the path it does, bending as it passes from air to glass, it minimizes the time taken in its journey. This approach, called the principle of least energy or the principle of least time, seems to be a fundamental aspect of nature. If you look at the way a baseball travels when thrown, it takes the route that minimizes the balances of kinetic and potential energy along the way. Similarly, the light bends in such a way that it minimizes its journey time as it passes from one material to another.

This visible effect reflects a slowing down in glass to around 200,000 kilometers per second. But light has been made much slower than this. In 1998, a team working at the Rowland Institute for Science at Harvard University under Danish scientist Lene Vestergaad Hau brought light down to around 17 meters per second, less than 40 miles per hour. You could drive a car faster than this light. And in further experiments, the team slowed the light to under 1 meter per second, around walking pace, and even trapped it within the apparatus for a considerable period of time.

This was using a special type of matter—almost an entangled cross between matter and light—called a Bose-Einstein condensate. The experiment shot two lasers through a vessel containing supercooled sodium atoms. Normally such a condensate would be totally opaque, but the first “coupling” laser blasted a sort of ladder through the condensate that the second light beam could claw its way along—at vastly reduced speeds. In the process, the photons of the second light beam—the “signal”—became entangled with the atoms in the condensate. As a long pulse of light flowed into the condensate, the front part of the pulse was slowed down by the entanglement, while the rear end plowed in at full speed. The result was that the light pulse was hugely compacted.

Producing this effect is not easy. To get into Hau’s lab you have to take off your shoes and generally be checked out for dust, just in case you contaminate the air and upset the precision optical systems. There’s even a plastic curtain around the table on which the experiment is based, largely to stop interference from passing onlookers. According to Hau, this was added after a German TV crew, visiting the lab, set up a smoke generator near the experiment when no one was looking. The shamefaced journalists had intended to make the experiment’s lasers visible to increase the visual impact of what otherwise was just a dull-looking piece of equipment: instead, they succeeded in temporarily disabling the experiment.

However, you don’t need to go to the extent of Hau’s remarkable experiments to get light down below its vacuum speed. As we have seen, a glass of water is enough to do that. And this is where things get interesting, and we have an effect that’s relevant to tachyons. The Einstein limit on speed of anything material, 300,000 kilometers per second, is the speed of light in a vacuum. But there’s nothing to stop a particle like an electron from approaching this speed as it travels through something denser than a vacuum—and that means there is every possibility that such a particle will travel faster than the speed of light within that medium. As we’ve seen, a particle traveling through glass, for example, would have to reach only two-thirds of the full speed of light to pass through the local light barrier.

If a particle does exceed local light speed, and it’s a charged particle, it gives off electromagnetic radiation, a process known as Cerenkov radiation. This is why some types of nuclear reactors give off a spooky blue glow as high-energy electrons zip through the liquid surrounding the fuel elements. These electrons are traveling faster than the speed of light in that liquid.

For an ordinary particle, giving off energy as a result of Cerenkov radiation—losing energy—means slowing down. But for a tachyon, giving off energy means speeding up. Any charged tachyon would get faster and faster, blasting out all of its energy in Cerenkov radiation to reach a strange state where it was theoretically traveling infinitely fast—present everywhere along its path simultaneously. So any tachyons that might be of use for sending messages through time would probably have to be ones without a charge, which is unfortunate, as charged particles are usually easier to interact with.

A good comparison is with the neutrino. The neutrino is a common particle that you are very unlikely to come across in everyday life. It was deduced back in 1930 that the uncharged neutrino existed, because nuclear decay seemed to have a missing element—there just wasn’t as much energy after the event as before, which suggested that an undetected particle was being emitted; but it wasn’t until 1956 that a neutrino was detected through its impact on other particles.

We aren’t quite sure if the basic electron neutrino has a mass—the standard model of particles assumes it doesn’t, though there is some suspicion that it may have a tiny one, but it hasn’t been definitively proved, so slippery are these particles. Because neutrinos interact so weakly with other particles, neutrino detectors are typically buried well underground to protect them from more heavy-handed particles and usually rely on using a large volume of liquid, which is surrounded by detectors that pick up the particles given off if a neutrino interacts with the fluid.

Because of the massive volume of nuclear interactions within it, the Sun pours out a torrent of neutrinos. It’s thought that upwards of 50 trillion neutrinos from the Sun pass through your body every second—it’s not surprising that they are sometimes referred to as ghost particles.

If tachyons were like neutrinos, then space could be full of them without our being aware of them. But if this were the case, then also like neutrinos they would be of very limited practical use for the would-be communicator. With neutrinos this isn’t an issue. If they are massless they probably travel at the speed of light; if they have a mass they move at rather less than light speed—so they provide no advantage for communication over the conventional photons used in radio or for laser signaling in fiber optics. But tachyons would, of course, be a different matter.

If tachyons *do* interact with ordinary matter they should be reasonably easy to detect. Just as the existence of a neutrino was deduced from the behavior of the particles it left behind, so a tachyon should have its own unique signature. A tachyon would differ from an ordinary particle because of the peculiarity of a tachyon’s mass. Remember, a tachyon has an imaginary rest mass and loses energy as it speeds up. This means that the resultant energy and momentum of any particles produced from a tachyon collision would be totally different from those of any sublight particles. But as yet, such collisions have not been detected.

We’re left, as far as tachyons are concerned, with an “invisible dragon” problem. This is the metaphor sometimes attached to psychic abilities or to ghosts, which always seem to disappear when subjected to controlled testing. It’s said to be a bit like a friend saying, “I have a dragon in my garage.”

“Okay,” you say, “let’s go and see your dragon.”

“Sorry,” says the friend, “it’s an invisible dragon. You can’t see it.”

“Fine,” you say, “we’ll feel it.”

“No, it’s not detectable by touch.”

“We’ll hold up sheets of paper, so its breath burns them.”

“It’s not a fire-breathing dragon, so that won’t work.”

“Right. We’ll put flour on the floor to detect its footprints, and scatter the floor with weight detectors to register the dragon as it passes by.”

“No, sorry, it has no weight and it leaves no footprints.”

“We’ll use infrared cameras to detect its heat.”

“That won’t work either; it doesn’t give off any heat.”

Whatever you suggest, your friend counters it by saying that the dragon isn’t detectable this way. There can never be any proof. You just have to take her word for it that the dragon exists. Tachyons are in a slightly better position than the dragon in that there is no theoretical basis for the dragon’s existence, while at least the tachyon is a hypothetical particle obeying clear physical laws. However, if it remains undetected and is impossible to interact with, it might as well not exist. It’s certainly no use for a communicator that works backward through time if we can never detect or influence it.

As yet the hypothetical concepts that support the phantoms of time that are tachyons and advanced waves have never been observed. But some time travel options don’t require strange new phenomena, just engineering that goes far beyond our current capabilities. We are looking a long way into the future here. The idea we are about to explore is as far advanced beyond our most recent space probes as a modern computer is compared with using two stones as a way of counting. But in principle there does exist a means to engineer our way into the past.

CHAPTER TEN

INTERSTELLAR ENGINEERING

> *If the "Principle of Relativity" in an extreme sense establishes itself, it seems as if even Time would become discontinuous and be supplied in atoms.*
>
> —Oliver Lodge (1851–1940), Presidential Address
> to the British Association (1913)

Much 1950s science fiction reflected the inspiring pioneering spirit of the American West. Just as the gold rush drove people to cross vast distances and risk their lives to mine for rare commodities, so, it was imagined, mining in space would be the driving economy behind traveling out into the solar system. And to make the simplest form of time machine work, all we need to do is pick up on those science fiction dreams of carving up asteroids and planets on a rather larger scale.

In truth, a massive scale.

In his failed campaign to become the 2004 Democratic Party candidate for the White House, General Wesley Clark made an impassioned plea for a new goal for the space program. In a speech given in New Hampshire, drawing on the experience of President John F. Kennedy's race for the Moon and how this goal had inspired a whole generation, General Clark suggested that the next great frontier was traveling faster than light.

Dismissing the idea of a manned mission to Mars and the other relatively sedate goals that NASA had at the time, General Clark said that we needed to build public support for exploration of a new frontier—and what could make for a more dramatic space challenge than the attempt to travel faster than light? The general had in mind making it possible to reach the stars, journeys of such length that faster-than-light travel would be almost mandatory. But though not mentioned by the general, such research would be intrinsically linked to the mechanisms of time travel.

There is no doubt that taking the engineering approach to faster-than-light flight or to time travel involves huge goals—in fact, it involves dreams, as General Clark suggested in his speech. The scale of effort required to produce an engineering-based solution totally dwarfs everything the human race has ever done in the field of construction. You have to be prepared to think big.

The first person to take on time using heavyweight technology (or at least who believed he had achieved a shift in time) did so by accident. This was the remarkable Nikola Tesla. Tesla was born in Smiljan in the Austrian Empire (now in Croatia) in 1856; he would become a U.S. citizen in 1891. He was a strange mix, managing to be both a scientist and a hugely successful inventor while at the same time, particularly in his later life, displaying strange behaviors and beliefs that seemed to verge on insanity, and that would have anyone else instantly labeled a crank.

It's a measure of the seriousness with which the scientific community regards Tesla today that the International System of Units has one measure, the unit of magnetic flux, named after him. His early work was hugely important for the electrical industry. He invented the fluorescent light and, most significantly, he championed the use of alternating current (AC) to transmit electricity. It was Tesla who made AC current usable by building the first practical AC motors and designing the AC system we still use today.

This resulted in a huge battle of wills with Thomas Edison, Tesla's early boss after the young Croat moved to America. Edison's growing electrical empire was based on direct-current electricity. Edison attempted to discredit Tesla's AC by showing how dangerous it was, using it to electrocute a range of animals from a dog through to an elephant, a series of demonstrations that would lead directly to the development of the electric chair. This was despite Tesla's correct suggestion that DC was more dangerous than AC because it would cause muscles to tense, locking a hand onto a wire if it was touched.

Edison's argument was based purely on commercial factors; the science was on Tesla's side. Alternating current transmitted power with less loss than direct current, and inevitably over time it replaced DC in every country's power system. With his income expanding rapidly, Tesla was able to set up an experimental station in Colorado Springs, Colorado, to work on experiments where he pushed electricity to higher and higher power and frequency. His main goal was to find a way to transmit electrical power without any wires, with the related, and simpler, possibility of sending messages without wires—wireless telegraphy or radio.

Tesla's Colorado Springs base looked like a movie designer's idea of a mad scientist's lair. At its heart was a 200-foot tower with a great copper globe on top, which would be charged up to millions of volts. When Tesla was experimenting, the air around the site seemed to crackle with electricity—sparks flew from faucets in nearby houses and horses were said to be electrocuted as they stood in the fields. Lightbulbs placed hundreds of yards from the transmitter glowed eerily without any visible connection, picking up the massive electrical field that Tesla was producing.

It wasn’t at Colorado Springs, though, that Tesla had his brush with time travel. Four years before the move to Colorado, he was working in New York, first at 35 South Fifth Avenue, and then, when his laboratory burned down in a fire, at 46 East Houston Street. Here his experimental devices produced powerful rotating magnetic fields. Although there is no theoretical reason to suggest that such a field would be strong enough to distort space-time and make time travel possible, Tesla was convinced he had achieved a movement in time.

Tesla believed that the rotating magnetic fields were ripping open space and time. We know now that powerful magnetic fields can have a significant effect on the brain. The process known as transcranial magnetic stimulation (TMS) uses rapidly changing magnetic fields to start off small electrical currents in the brain, stimulating neurons to fire. Tesla seems to have experienced this, describing headaches, tingling, and disorientation. He felt a detachment from the flow of time and believed that the powerful magnetic fields were ripping him out of the time flow.

In March 1895, Tesla was struck by a high-voltage electrical bolt. Some have suggested this accident marked the beginning of his mental deterioration. But Tesla himself believed that the accident shifted him outside the conventional flow of time, giving him an overview of the fourth dimension that should have made it possible to reposition himself anywhere in the time stream. Tesla believed that the accident, building on his experience with magnetic fields, *was* a crude time machine.

Increasingly embittered by Guglielmo Marconi’s success with wireless telegraphy—Marconi obtained a patent that overthrew Tesla’s temporary patent on the wireless transmission of energy—Tesla never came back to his ideas on time travel, though he believed his experience showed the way to make time travel possible. He continued to experiment and to theorize on everything from death rays to vertical-takeoff aircraft, but it seemed that time travel had ceased to interest him.

Ironically, given the number of time-machine concepts that are based on relativity, Tesla proved less effective as a physicist than he was as an engineer and a publicist. He dismissed general relativity, producing his own theory of gravitation (which was never to be published) in the 1920s. He died in January 1943 at the age of eighty-six. Tesla was something of an enigma. On the one hand he was without doubt an engineering genius. His development of motors that could make use of alternating current, along with a whole host of other inventions, put him in the same league as Edison. But at the same time many of his scientific ideas were at best flaky, and he sometimes seemed to rank showmanship over science.

As well as ignoring relativity, Tesla refused to accept quantum theory, or even that light and radio were both electromagnetic radiation, though of different energies, propagating through space without the need for a medium. He steadfastly stuck to the idea of the ether, and his attempts to make possible worldwide communications using electromagnetism seemed largely to be based on the idea of setting up a vibration in the Earth, triggered by vast electrical discharges—hence his mad-scientist tower in Colorado and another massive high-voltage device in his Wardenclyffe experiments on Long Island.

Tesla's emphasis on show over science comes through in the way that he would demonstrate many remarkable effects with electrical devices without ever giving a detailed explanation. He always claimed to be on the verge of coming out with some amazing discovery, without ever going into details. It seems typical of the man that he had a box that he told all and sundry contained a deadly secret, a weapon of fantastic destructive power. When opened after his death, with considerable trepidation, it contained only a commonplace electrical device that enabled different resistors to be switched into a circuit. Given this tendency to make dramatic unjustified claims, it seems likely that Tesla's time travel concept was nothing more than fantasy.

In the end, there is no evidence that Tesla's experiments could manipulate time, and powerful though his experiments were, they are dwarfed in scale by the kinds of technology that may be needed to make time travel possible by engineering. The first person to go far beyond Tesla's experience, at least in thought engineering, was Willem Jacob van Stockum.

Born in Holland in 1910, van Stockum traveled with his family to Ireland at the age of ten and spent the rest of his short life in the English-speaking world. (He would die in June 1944 as a pilot, flying Lancaster bombers for the RAF over Europe.) In 1937 he published a paper that provided an exact solution for general relativity—at the time a rarity—for a rather strange object: an infinitely long cylinder of rotating dust.

As well as being unusual in being an exact solution to the complex equations of general relativity, this was one of the first times that general relativity had been applied to a rotating object, and the outcome was more than a little strange. If the cylinder of dust rotated fast enough, an observer orbiting the cylinder like a moon around a planet would find that he returned to the same position above the cylinder’s surface earlier than he’d been there on the previous rotation.

In effect, the cylinder’s enormous mass produced a distortion of space-time that was sufficiently great that when it was whirled around, it dragged space-time into a kind of spiraling loop, forcing the orbiting observer back to an earlier point in time. This type of time distortion is technically referred to as a closed timelike curve. We’ve seen how general relativity says that all mass distorts space-time, making straight lines curved. In this case the curve is twisted so much that it loops back in itself, so that the observer is dragged back to a point before the time at which he entered the curve.

Van Stockum’s paper describes a very simplistic and artificial situation. No one could create an infinitely long cylinder of dust. But his solution was the first hint that the possibility of practical time travel was emerging from a combination of general relativity and a large rotating object. This would be taken even further by the great, if more than slightly eccentric, mathematician Kurt Gödel. He applied relativity to the biggest rotating object you could imagine—the entire universe—and discovered that this too could set up closed timelike curves.

Gödel was born in Brno in Czechoslovakia in 1906, but his family was of German origin, speaking German at home. Kurt and his older brother, Rudolf, were brought up as if they were living in a German or an Austrian home. It seemed entirely sensible, then, that Kurt, who was already showing signs of great skill in mathematics, should attend university in Vienna, closer to Brno than a location like Berlin, and so more practical to keep up family ties. Kurt’s brother Rudolf was already there, making it the ideal choice of school.

Vienna continued to be attractive to Gödel, who stayed on for his doctorate and subsequent research. At the time he was no social recluse—quite the reverse. He seemed capable of partying all night and still coming up with quite remarkable new ideas. At one of the nightclubs he attended, Gödel met a dancer, Adele Porkert, older, more sophisticated—exactly the kind of woman his mother probably warned him to stay away from. Nonetheless, Adele became his wife, and they stayed together the rest of Gödel’s life. With Adele at his side, the partying went on, as did Gödel’s rapidly maturing ability to challenge the accepted norms of mathematics.

Gödel was to come up with what was arguably the most shocking proof in all of mathematics, a bewildering masterpiece called the Incompleteness Theorem. This states that in any system of mathematics there will be some problems that are inherently insoluble. According to Gödel, no matter how much effort is put into some problems, they can’t be cracked. And this he proved with mathematical exactness.

You don’t need to know the exact formulation of Gödel’s Incompleteness

Theorem to appreciate the kind of thinking that went into it. It is based on the same kind of approach that generates statements that are logically self-inconsistent. At the most basic we are looking at statements like “This is a lie.” If it’s a lie, then it’s true . . . but if it’s true, it’s a lie. A version of this kind of logic problem closer to Gödel’s theorem is this: “A barber shaves everyone in the village who doesn’t shave himself. Who shaves the barber?” But though the Incompleteness Theorem remains Gödel’s most famous contribution to math, his thoughts on time travel would come over a decade later.

In the mid-1930s, as the rise of the Nazis made Vienna an increasingly dangerous place, Gödel was invited to join the Institute for Advanced Study at Princeton, New Jersey, which already had Albert Einstein on its books. Gödel was not a Jew, but many of his colleagues were, and he was attacked in the street on the suspicion of being Jewish. It would seem that an escape to Princeton would have been very attractive, but Gödel did not last long there, returning home after only six months.

Meanwhile, as Austria became more and more dangerous, Gödel seemed blissfully unaware of what was going on around him. It seems that it was only in 1939, when the authorities informed Gödel that he had been declared fit for military service, that he realized the risky situation he was in. He and his wife just managed to leave the country for America before all possibilities of travel were closed down. It was already too late to take the Western route. Instead the pair risked the Trans-Siberian Railway, then traveled on to Japan and from there by boat to San Francisco.

Once they were in America, Gödel’s mental health, already weak, began to decline. He became more and more paranoid. While on a holiday, the distracted Gödel was suspected of being a spy as he paced along the seafront, muttering in German to himself. The locals thought he was waiting to contact a U-boat. Although he lived on for many years, not dying until 1978, he was convinced that there was a plot to poison him and would eat only if Adele had tasted his food first. When she was taken into a hospital and could no longer act as food taster, he refused to eat and in effect starved himself to death.

It was back in 1949 that Gödel came up with another solution to general relativity with implications for time travel, one that assumed that the universe as a whole was rotating. This helped with one of the earliest problems that finite models of the universe had. A universe with boundaries had a tendency to collapse. This was something that was acknowledged as far back as Newton’s time. Without something intervening, it seemed inevitable that the gravitational attraction between stars and galaxies would pull all things toward one another. The process might start gradually, but eventually every massive body in the universe would be attracted to the others in an immense cosmic collision.

Newton suggested that the only way the contents of the universe could avoid being dragged together in its center was if the universe was infinite. That way, there would be no center, and the forces pulling in every direction should balance out. But Newton was aware that such a model was easily destabilized. If just one heavenly body moved slightly out of place, a collapse would be precipitated. Newton argued that this didn’t happen because God was constantly tweaking the universe to ensure everything remained in place.

Gödel’s spinning universe, by contrast, could be finite without collapsing. His model prevented this from happening because the tendency of rotating bodies to fly off into space countered the gravitational attraction. It was a bit like the way being in orbit stops a falling body from hitting the Earth—but magnified to take in every object in the universe.

Like van Stockum’s cylinder, Gödel’s rotating universe opened up the possibility of traveling along a curve through space-time that resulted in looping back in time. The faster the universe rotated, the more direct these time loops would be. At the basic rate of rotation required to offset gravitational collapse, the universe would be rotating quite slowly, taking around 70 billion years to perform a complete turn. In such a universe, the curve required to loop back in time would be around 100 billion light-years long—not exactly a practical journey.

It’s true that the journey could be made a more manageable length if the universe rotated considerably faster, but this isn’t particularly helpful. The Gödel universe bears no resemblance to the real universe as we know it. In his model, the universe is static and rotating, whereas the real universe is expanding and shows no evidence of rotation. We would expect that a universe rotating fast enough to be like Gödel’s model would produce very noticeable shifts in the polarization of light from distant sources, and would leave a distinctive pattern in the cosmic microwave background radiation, the so-called afterglow of the big bang that is pictured in images from the Cosmic Background Explorer (COBE), the Wilkinson Microwave Anisotropy Probe (WMAP), and Planck satellites. No such polarization shifts and background radiation patterns exist.

Gödel’s model doesn’t require us to build an infinite cylinder like van Stockum’s device, but in practice it is no more usable for time travel. Gödel’s rotating universe doesn’t give us a practical mechanism, because it would require impractical journey lengths and because it bears no resemblance to the real universe; but it did keep alive the idea of using the effects of general relativity with large rotating bodies to produce paths through space-time that made it possible to loop back into the past.

It’s a very simplified representation, but in essence what such a massive rotating body provides is a way for someone to travel faster than light . . . without ever traveling faster than light. The massive rotating body drags light with it into a loop, and when the traveler enters that loop, she too is dragged around. Inside the loop, from the traveler’s viewpoint, she never exceeds the speed of light—so Einstein is kept happy. But from the outside, viewed from the destination where the traveler will eventually arrive before she departed, the traveler is moving faster than light and spiraling backward in time.

In the 1970s another physicist, Frank Tipler, would come up with a way to manipulate time related to van Stockum’s idea, using this kind of rotating space-time drag, but in a way that unlike Gödel’s would not need the whole universe to be spinning. Tipler wrote up this idea in a paper with the reasonably innocuous title “Rotating Cylinders and the Possibility of Global Causality Violation.” But those words “global causality violation” are nothing more or less than code words for time travel. It is now fairly respectable for scientists to discuss time travel, but back then it was career suicide, as it was considered so farfetched. To be able to violate global causality means to be able to overcome the relationship between cause and effect, to take the effect back before the cause—to travel in time without so naming it.

Let’s think again of a vast, massive cylinder (though no longer infinite in length). Imagine its effect on space-time. There will be distortion, a warping of space-time around it as there is around any massive body. As you rotate the cylinder it will drag space-time with it. Think of turning a spoon in a viscous fluid like honey. Dribble a little food coloring in the fluid and you will see a spiral whorl. Imagine rotating this so quickly that the thin line of food coloring comes back on itself—you can set up a closed loop. This is a simplistic image, but it gives the right idea for the process occurring here. It’s possible, in effect, to so warp the time dimension that it becomes more like space and it is possible to traverse it.

In principle such a time machine could work in either direction in time, depending on which way the traveler moved around the cylinder. And when Tipler calculated the density of material and speed of spin required for his cylinder, he came up with something relatively close to the vital statistics of a neutron star. We’ve already seen how the gravitational field of a neutron star (see page 95) can provide a mechanism for traveling into the future, but these strange stellar objects have another trick up their sleeve.

Something interesting happens as a neutron star forms. Think of a spinning ice-skater who starts with his arms extended and brings them down to his side. The skater’s spin speed increases because the angular momentum, effectively the amount of energy in the spin, is conserved. As the skater’s mass moves closer to amount of energy in the spin, is conserved. As the skater's mass moves closer to his center, the speed of spin has to increase to counter this shrinkage. Similarly, if the original star that became a neutron star was spinning (and all stars seem to be), its spin speed would get faster and faster as it collapses into ultradense form.

We have good evidence that this does happen from pulsars. These are stars that give off light in the radio part of the spectrum, and the radio signals from them come as steady pulses, a regular beat that seems so artificial that when the first one was spotted by British radio astronomer Jocelyn Bell and her professor, Anthony Hewish, it was given the code LGM-1 for "little green men 1." Bell and Hewish didn't seriously believe that they were detecting a signal from an alien source, but at the time there was no known natural phenomenon that could produce these high-speed regular pulses.

The best explanation for a pulsar is that it is a fast-spinning neutron star, acting like an interstellar lighthouse. A radio beam pours out from the collapsed star, sweeping around through space as the star rotates. The flashing (or more accurately the blips picked up by the radio detector) arrives at the rate of rotation of the star, and for some pulsars that is very fast indeed. They appear to be spinning around about once a millisecond. A body the size of Manhattan with the mass of a full-sized star is making a thousand rotations every second—which is less than a factor of three away from the speed needed to make a Tipler cylinder work.

So a neutron star pretty much fits the bill. Except we do need a cylinder to have the appropriate dragging effect on space-time—which means finding a minimum of ten to a dozen neutron stars, all rotating at the same speed in the same direction, and cramming them together to make a cylinder. This generates another tiny problem. If you make a cylinder out of such massive objects, it won't be stable. The gravitational pull of all that matter would suck the whole thing into a sphere, and such a concentrated sphere, with the mass of ten to twelve neutron stars, would most likely slip into forming a black hole. Not to mention the other issue that the gravitational pull of the cylinder would be so large that anyone approaching it close enough to get the time travel effect would be ripped apart by tidal forces.

So the challenges facing interstellar engineers wanting to make a Tipler cylinder are, to say the least, nontrivial. They have to locate at least ten neutron stars and drag them together. As we've seen, the nearest known neutron stars are between 250 and 326 light-years away, not exactly on our doorstep. This requires travel over vast distances, plus the ability to manipulate something the weight of a star from place to place across tens or hundreds of light-years. We would then need to force ten of them together, equalize their rotation, and spin them up to maybe three times the revs.

Finally, we would have to apply some massive force, probably an antigravitational force, to keep the stars in a cylinder—and we would have to have some way (again we're talking antigravity) to protect our time travelers from being dragged apart by tidal forces around the cylinder. All in all, Tipler's cylinders are a nice idea that fits well with General Clark's dream of a massive engineering project in space, but it isn't going to happen. We need to find an alternative approach that requires less stellar engineering.

There is one other possibility that involves circling an extremely long object that has, in principle, the chance to be used as a time machine and doesn't require us to manipulate neutron stars, but this does involve the existence of a wholly hypothetical and very strange form of matter: the cosmic string.

Although related, this is on an entirely different scale from the strings you may have come across in "string theory." String theory is an attempt to unify all the forces and particles of nature into a single explanation. In string theory, each particle is made up of an incredibly tiny loop of material that can vibrate in different ways, producing the different particles that make up matter and that carry forces. Although a simple description of the theory is very appealing, it is mathematically complex and has real problems when applied to a working description of nature.

Apart from requiring the existence of multiple spatial dimensions on top of the three we experience, string theory is unable to make any sensible predictions that can be tested—a problem that has led at least one leading scientist to describe it as "not even wrong." But the existence of cosmic superstrings is an extra, separate possibility.

Cosmic strings are hypothetical structures that are remnants of the early years of the formation of the universe. They have never been observed, but their existence is postulated by some of the theories on the nature of matter and the universe. A cosmic string is a vastly long filament stretching through space. In fact, a cosmic string isn't allowed to have ends, so unless it loops around on itself, it has to be infinitely long. Though extremely thin, it is also very massive at around 10,000 trillion tons per centimeter.

If cosmic strings do exist, physicist Richard Gott has suggested a way that they can be used for time travel. If you could get yourself a pair of cosmic strings and set them moving apart at high speed—near light speed—Gott says, the distortion they would make in space-time would be such that by spinning around the pair of strings at high speed (it would have to be high speed to get around them—remember, they are moving away from each other at nearly the speed of light) you would travel backward in time.

Like string theory, this is a case where the basic picture seems quite simple—but once you get into the detail it proves horrendous. First, we don’t even know if cosmic strings exist. They are much more hypothetical than black holes. We would expect that cosmic strings would give starlight alternative routes around them that would introduce delays or warps in the light’s travel—so they would produce double images of stars. And we certainly do see double (or even multiple) images of stars in space. But there are other, simpler explanations for this effect arising when general relativity says that massive bodies in space will act like lenses, bending and splitting rays of light.

If there are cosmic strings, the chances are we would have to travel millions or even billions of light-years to come across them. And the logistics of manipulating two such strings to be near each other, then moving them apart at near light speed, makes the concept of building vast neutron-star cylinders seem like a trivial project. So this is likely to remain a theoretician’s dream.

Taking on vast structures could definitely produce a time machine, if we were capable of the engineering feats required. But massive cylinders and cosmic strings aren’t the only ways to use a distortion in space-time to make time travel possible. There is a natural phenomenon that could provide the answer for us without any construction required.

CHAPTER ELEVEN

ALICE THROUGH THE WORMHOLE

> *Time ends. That is the lesson of the “big bang.” It is also the lesson of the black hole, closer at hand and more immediate object of study.*
>
> —John Wheeler (1911–2008), “The Lesson of the Black Hole,” Proceedings of the American Philosophical Society 125 (1981)

It’s probably a good thing that not many people now remember the Disney movie *The Black Hole,* as it wasn’t very good, but the concept of black holes themselves, and the possibility of using one as a sort of gateway in time and space, remain strongly present in the general awareness and in the rich mythology of cosmology.

Ask someone on the street what a black hole is, and he will probably tell you about a dark star with a vast gravitational pull, dragging in everything around it, making it a kind of interstellar vacuum cleaner, a monstrous all-consuming giant, sucking in anything that dares to get anywhere in the neighborhood—all too possible, because the black hole itself is a thing of mystery: dark, scary, and quite possibly brooding.

As we’ll see, this caricature of a black hole is almost entirely wrong. It’s possible that black holes don’t exist at all, but assuming that they are out there, they aren’t entirely dark and they don’t act as a cosmic vacuum cleaner any more than any other star does. Yet they are amazing—downright weird, in fact. And the idea that they could exist has been around for a remarkable 250 years.

The first suggestion that a black hole was possible came from English astronomer and geologist John Michell, working at Cambridge University. Michell, born in 1724, was one of a new generation of scientists who could be confident that light had a measurable speed. Until 1676, no one was sure whether light got from place to place instantaneously, or at a rate that could be measured. It wasn’t that people hadn’t tried to pin down the speed of light, but it proved challenging.

Galileo, for example, made a gallant attempt to put a figure on light’s speed. His approach depended on pure darkness. The night in the countryside around Padua was stygian as Galileo and his assistant set out to make their measurement. It’s hard to appreciate just how absolute the darkness was when looking back from the present. Now the sky glow of artificial light reaches most of our world, but this was the unsullied black night of the Italian countryside in the seventeenth century. In this kind of darkness, the naked eye could make out a candle flame 10 miles distant.

The assistant rode off a measured distance and stationed himself, ready for Galileo’s signal. Probably using his pulse as a clock (we don’t have details of the experiment), the great man unmasked his lantern, adding a yellow-white star to the view of his assistant. Immediately, the assistant uncovered his own lantern, and light was sent on the return journey, ready for Galileo to spot it and mark the time. The result was a disaster. There was no consistency in timing. Galileo returned home a failure. He commented that he had found it impossible “to ascertain with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous, it is extraordinarily rapid.”

For once, the man whose faith in the invincibility of science resulted in a life-and-death battle with the hierarchy of the church was frustrated. Even if he had owned a timepiece that had been accurate enough to measure the time light takes to travel that sort of distance—perhaps one-hundred thousandth of a second—the delays introduced by human response times at both ends of the experiment far outweighed anything else. Galileo recognized this human contribution. He tried the experiment again with his assistant standing next to him—and the measured time was the same. The whole measurement was down to reaction time. As an attempt to fix the speed of light it was a failure, but at least Galileo had tried.

Some would have argued his effort was a waste of time. The French philosopher-scientist René Descartes, for example, believed that light took no time at all to travel, working as a form of pressure, rather as if a source of light were at one end of a pool cue and the other end was on your eye. The moment the source pushed, your eye detected the light. Descartes, rather unwisely, commented: “[Light] reaches our eyes from the luminous object in an instant; and I would even add for me that this is so certain, that if it could be proved false, I should be ready to confess that I know absolutely nothing about philosophy.”

Descartes didn’t have to indulge in the philosophical equivalent of eating his hat, as it was in 1676, twenty-six years after his death, that the otherwise obscure Danish astronomer Ole Roemer found a big enough instrument to make light’s journey time measurable. With wonderful irony, given the failure of his own experiment, it was Galileo that made the Dane’s measurement possible. Galileo had discovered Jupiter’s four biggest moons in 1610. Ole Roemer was trying to use the movements of these moons as a celestial timepiece as part of the huge effort going on across Europe to try to measure time accurately at sea. This was essential to be able to calculate longitude for safe navigation.

The crude mechanical clocks of the day simply didn’t keep good enough time to make it possible to determine location with any precision—so Roemer was searching for a celestial clock. It needed to be something clearly observable around the world, yet unchanging in its timekeeping at different longitudes. After taking careful measurements over a number of months, he came up with what initially seemed a disappointing result. The gap between appearances of the moons as they circled Jupiter was getting longer and longer. Not ideal. If the moons of Jupiter were a clock, it was a clock whose mechanism was running down.

It was only after Roemer had taken many measurements that he realized what might be happening. Eventually, after many weeks, the process reversed. Now, it seemed, the moons were appearing a little earlier with each orbit. And that change in the timing occurred when the Earth was at its maximum distance from Jupiter. There had to be a connection between the two alterations, the change in the moons’ timing and the change in the Earth’s direction with respect to Jupiter.

Roemer knew that as the Earth and Jupiter followed their paths around the Sun (another piece of information he had to thank Galileo for, even if it wasn’t the Italian’s original idea), the two planets spent part of the year getting closer to each other and part getting farther away. When the distance between Earth and Jupiter was on the increase, the light had to travel farther. Assuming light had a measurable speed, it would take longer to arrive at the Earth. When the two planets were getting closer to each other, that timing should decrease. The changes in time for the light to turn up accounted for the apparent shift in the moons’ timing. All Roemer had to do was compare the way the timing shifted with the varying distance to Jupiter to find the speed of light.

Using the measurements the astronomer Cassini had produced for the size of Jupiter’s orbit, Roemer managed to calculate the speed of light at around 220,000 kilometers per second. He was a little off—the actual figure is close to 300,000 kilometers per second—but his measurement was close enough to get a feel for light’s speed, and impressive given the uncertainty over exact distances and the crude timing mechanisms he had available.

This speed, 220,000 kilometers per second, was immense. When you consider that the fastest travel anyone would have experienced was on the back of a galloping horse—a rate of around 0.015 kilometers per second—it was unimaginably fast. It was hardly surprising that Galileo didn’t notice any time elapsed in his experiment. However, it did mean that light’s speed had a finite value. Descartes was wrong. And this is where we return to black holes and John Michell.

Knowing that light traveled at around 220,000 kilometers a second, Michell could compare this speed with another known figure—the escape velocity of the Earth. This was a concept that arose from Newton’s formula for gravitation. To overcome the pull of gravity on the Earth’s surface and escape into space, something has to travel at a certain speed. This is around 11.2 kilometers per second, or 25,000 miles per hour. Leave the Earth at 11.2 kilometers per second or more and you will get free; travel any slower and you will be pulled back to the surface.

This sounds unlikely. Everyone has seen video of rockets launched into space, and they seem to claw their way into the air painfully slowly. They certainly don’t take off at 25,000 miles per hour. But escape velocity is the speed at which an object would need to travel if it was thrown into the air with no additional force applied to keep it moving. I seem to remember Superman hitting a baseball into space in one of the movies or on the TV show. That ball would have to travel at escape velocity because once it left the bat, the only forces on it would be air resistance and gravity, both slowing it down. But as long as a rocket’s motors are firing, it is fighting the force of gravity. If the upward motion can be maintained, the rocket will escape at any speed. Michell, though, was thinking of the full 11.2-kilometers-per-second escape velocity.

Michell put the idea of escape velocity together with the knowledge of the speed of light. Obviously, the escape velocity for a much bigger, heavier body like the Sun is significantly higher than that for the Earth—we now know it is more like 620 kilometers per second. But what if you were dealing with a star that was much heavier still? Eventually, as you piled more and more weight into the star, the escape velocity would exceed the speed of light. The star should go dark. Light would not travel fast enough to escape the star’s gravitational pull.

At the time, Michell’s idea, published in the *Philosophical Transactions of the Royal Society* in 1783, was considered entertaining speculation, but nothing more. After all, who could ever envisage a body massive enough to have such a vast escape velocity? It was on a par with considering how many angels could dance on the head of a pin. And it wasn’t certain that light had any mass for gravity to act on—an essential for Newton’s law of gravitation and the idea of escape velocity to work. It took Einstein’s general relativity in the twentieth century to make the idea worth revisiting, though the man who would do so probably had no idea that Michell even existed.

This was German physicist Karl Schwarzschild, who seems to have used Einstein’s newly published equations as a way of distracting himself from the heat of battle. It was 1916. Schwarzschild was on active service with the German army in the First World War. Yet he found time to consider what the equations of general relativity predicted for particularly massive stars. Relativity explained the effect of gravity as a warping of space. Near a heavy body, space was curved. Schwarzschild realized that with enough mass, a star would warp space so much that light leaving it would be bent back in on itself. It would never escape. He had reinvented Michell’s dark star with the mathematical tools of modern physics and in a way that didn’t depend on light having mass.

Despite his more rigorous approach, Schwarzschild, like Michell, believed that he was dealing with an unrealistic picture. It was neat theory, but he was sure it didn’t reflect reality. To take the example of the most familiar star, the Sun is around 1.4 million kilometers (870,000 miles) in diameter. For its mass to be concentrated enough for it to become one of these hypothetical dark stars, it would have to be squashed smaller and smaller until it was just 6 kilometers (3.8 miles) across. To get a picture that’s easier to imagine, think of the entire mass of the Earth squeezed into an object the size of a grape. That’s the sort of concentration of matter needed to form a black hole. This hardly seemed likely to happen.

Again, the idea remained as something of a theoretical oddity until the 1930s, when two physicists, Subrahmanyan Chandrasekhar from India and Robert Oppenheimer from the United States (later the “father of the atomic bomb”), constructed models of the evolution of stars that suggested there was a practical way for such a collapse to happen. We accept the way that gravity keeps us in place on the surface of the Earth, pulling us, and everything around us, toward the planet’s center. The same thing happens on a star, only more so with its huge mass. All the material in the star is constantly being pulled inward with a force that is hard to resist.

When a star, like our Sun, is still very active, the nuclear reactions within it that produce its light are constantly pushing outward, giving a counterforce to that of gravity. The star is in equilibrium, where the outward pressure from the nuclear reactions balances the inward force of gravity. But eventually the star’s fuel begins to run out. The outward pressure drops, and gravity takes charge, forcing the star to contract in size.

However, the energy of the nuclear fusion taking place in the star isn’t the only thing that keeps the particles within it apart. There is also the requirement called the Pauli exclusion principle, which we met in Dirac’s sea of negative energy electrons. This requires similar particles that are close together to have different velocities. The result is that as the particles are forced closer together they attempt to escape, driving outward and resisting the collapse. In most cases, the contraction of the cooling star ceases. But there is one exception.

If the star is particularly massive—around 1.5 times as massive as the Sun or more—then the force of gravity will overcome the resistance and the collapse will continue. In some cases the result will be a massive explosion, a supernova, producing new elements and spreading them across the galaxy. It's believed that this is how all the heavier elements on the Earth were first formed. But if an explosion doesn't happen, in theory nothing can stop the collapse. The star will get smaller and smaller. Space in its vicinity will take on a tighter and tighter curvature until light can no longer escape. The star will have become what in 1967 American physicist John Wheeler would name a "black hole."

The boundary at which light cannot escape (which means nothing can escape, as nothing travels faster than light) is known as the event horizon, and this is the apparent size of a black hole, should one be formed—but the horizon isn't the actual black hole itself. Once this process has started, it is, as far as theory can predict, unstoppable. It will shrink smaller and smaller until it becomes an infinitesimal dot, a singularity where the strength of gravitational pull heads off to infinity and our physical theories, with their dependence on finite mathematics, fall apart.

The geometry of black holes is more than a little mind-bending. In effect, a black hole is similar to the Tardis in the TV show *Doctor Who*—it is bigger on the inside than it is on the outside. Although the event horizon, the visible limit of the black hole, may be only a few kilometers across, the radius of the black hole—the distance from the event horizon to the singularity at the middle—is likely to be vastly greater than this.

This strange, apparently contradictory structure is because of the way that the singularity at the heart of the black hole warps space. The warping is so extreme that the distance from the singularity to the event horizon is much, much larger than the radius of the sphere formed by the horizon. It's easier to imagine the two-dimensional equivalent, a rubber sheet so distorted that it becomes like a very long, pointed cone. The radius of the event horizon is the radius of the circle at the top of the cone, level with the sheet. But the internal radius to the singularity stretches down to the point of the cone.

At the time the theory of black holes was developed, no one had ever detected a black hole, so many cosmologists thought they were objects that were possible in principle but were never actually formed. Einstein, for example, was convinced that black holes could not exist in reality. This view gradually changed. There is now good indirect evidence that black holes really do form part of the stellar population. Most astrophysicists think that there are examples of them across the universe, and that the majority of galaxies—perhaps all of them—have a huge black hole at their center, in part responsible for the formation of the galactic structure.

This evidence *is* indirect. We’ve never seen a black hole. This might appear a very obvious statement. By definition a black hole sounds as if it should be invisible. But leaving aside the possibility of seeing a black hole as a dark gap in space, just as we see Venus as a black spot when it transits the Sun, black holes should not be truly black. If, for example, a black hole is in a binary relationship with another star, a common enough stellar formation where two stars orbit each other, we would expect to see material from the partner star spiraling into the black hole—and there is some evidence for this kind of phenomenon.

Even an isolated black hole should produce some light in a process called Hawking radiation. The idea here arises from quantum physics. In empty space, quantum physics predicts, pairs of particles, matter and antimatter, should constantly be popping into existence for a brief moment of time, then disappearing before they can be detected. If this happens near a black hole’s event horizon, one of the particle pair could fall into the black hole while the other particle flips out into space, producing (admittedly faint) radiation that should be observable.

Because we don’t have detailed direct observations, black holes could still be theoretical constructs that don’t actually form. There are alternative theories that could explain the things we attribute to black holes, like the mass in the center of galaxies, without black holes themselves ever forming. But the ideas behind the formation of black holes seem sound, and it is much more likely that they actually do exist.

Although black holes are quite capable of stripping material from a companion star, it ought to be stressed that they aren’t the sort of insatiable cosmic maws often portrayed in fiction. In the end, a black hole is a star, with exactly the same gravitational pull as it had before it collapsed. No more, no less. Its gravitational effects are identical to those of any other star of the same size. Yes, it’s a strong pull—get too close to the Sun, for example, and it will be difficult to get away—but it’s entirely possible to be in a stable orbit around a black hole, or to fly away from it, just as is the case with an ordinary star. Provided, of course, you don’t go past the event horizon.

There is something seductive about the idea of a black hole. Get close enough and it seems to be a one-way tunnel into which anything can disappear and nothing can emerge. In some ways it is reminiscent of the way we see death, making it easy to think, “Surely there’s something on the other side?” Isn’t it possible that a black hole is not a cosmic trash can, but some kind of portal? What if you could fly into a black hole and emerge somewhere else?

This isn’t an entirely crazy idea. The singularity at the heart of a black hole is an incomprehensibly powerful distortion in space-time. Think of it as a narrowing tunnel heading off . . . somewhere through another dimension. Could you use the singularity as a portal to jump to another part of the universe? And if so, would this make it a time machine? First we have to see just how practical traveling through a black hole would be. It wouldn’t be easy.

Imagine traveling in a spaceship into a black hole. As you got closer and closer to the singularity, the gravitational pull would get more and more powerful. As with a neutron star (see page 95), but even more dramatically here, the difference between the gravitational pull at the front of your ship and the pull at the back end would become intense. The effect of these tidal forces would be to elongate your ship (and everything in it, you included), dragging it out like a piece of spaghetti. You would be stretched to death in the ultimate version of the medieval torture instrument, the rack.

Because life near a black hole is never simple, this tidal effect would have the surprising property of growing smaller if the black hole you encountered was bigger. This is because the amount of tidal force that you would feel would depends on two factors: it would be proportional to the mass of the black hole divided by the cube of the event horizon’s circumference. The tidal effect would be smaller if you were dealing with a more massive black hole. So maybe, if the black hole was big enough—perhaps the supermassive black hole that is thought to be at the center of the Milky Way—you can last long enough to make some kind of jump through the black hole as a portal.

There would be problematic time effects as well as the tidal forces. From your point of view, time would proceed perfectly normally as you passed the event horizon, but to an outside observer, as you approached this point of no return, you would get slower and slower as general-relativity effects slowed down time for you relative to the outside world. In principle, as far as an outside observer is concerned, it would take you an infinite time to cross the event horizon.

Assuming you survived the gravitational stretching so far, once you passed that horizon, your biggest problem would become apparent. There would be no way out. A black hole is a one-way street. Once you were inside the event horizon, even if the tidal forces weren’t big enough to kill you yet, they soon would be as you got closer to the singularity and forces soared up toward infinity. To make matters worse, everything else entering the black hole—every fragment of dust and gas—would be accelerated to near light speed, turning them into deadly missiles. But ultimately, there would be no way out. A singularity isn’t a gateway; it’s an end to everything. Good-bye world.

On its own, then, a black hole isn’t much use for any form of travel. But there is a way to extend the potential of a black hole to make it potentially traversable and relevant to time travel. This was originally dreamed up in the 1930s and called an Einstein-Rosen bridge, though the idea has been much developed since and now tends to be referred to as a wormhole. The idea is apparently simple: to use not one but two black holes, merging the distortions they make in space-time.

Just think of that common two-dimensional image of the way mass distorts space-time under general relativity. We think of the mass as causing a dip in a rubber sheet—the more concentrated the mass, the sharper that dip. The singularity at the heart of a black hole is, in effect, an infinitely concentrated mass—so we can imagine the rubber sheet of space having a sharply pointed dip that heads off to infinity, stretching the fabric of space-time all the way to the edge of reality. It’s a space-time equivalent of Gabriel’s horn (see page 238).

If you could somehow link this space-time hyperhorn to another such distortion, caused by a second black hole, it might be possible to bridge two points in space-time, linking the two dips in the fabric of reality. If there were some way to travel through one black hole into the other, you would be at another point in the universe (or even in a different universe), potentially at another point in time, without traveling through the intervening space-time. It’s a bridge, or a tunnel that links two points in the space-time continuum.

In fictional terms, the wormhole moves us away from the likes of H. G. Wells’s *Time Machine* or Dr. Who’s Tardis to the creaky but affectionately remembered 1960s TV sci-fi show *The Time Tunnel* . Here, a lab-based tunnel (with suitable 1960s psychedelic effects) drops a pair of time travelers back in time, where they are bounced from era to era, unable to return home, while the base seems unable to retrieve them but can watch and send some items to help.

Note, by the way, that when we consider wormholes in space-time, we are deep into hypothetical mode. The physics of black holes is well understood, and we believe that they exist widely throughout the universe. The physics is equally sound for using wormholes, but we have no evidence, even indirect, that they exist in reality. They may. As we will see later, a future human race with advanced technology may also be able to create them from scratch. But rather like the tachyons in chapter 9, it is entirely possible for the physics of black holes to make wormholes theoretically sound without their actually existing.

Let’s assume, however, that nature has conspired to help us and we discover a pair of black holes whose dips in space-time have penetrated each other, so we have a form of bridge. We still have a number of problems to face. As we enter the first black hole, we are still heading toward a singularity. We are still going to be ripped apart and bombarded by incoming material traveling at near light speed. But it is possible there is a way around this. We just need a black hole that's spinning. In the early 1960s, mathematician Roy Kerr pointed out something that should have been obvious from day one. In space, on the whole, things spin.

It shouldn't have come as too much of a surprise to astronomers. We are a human race who inhabit a planet that spins once a day as it travels on its yearly orbit around a spinning Sun, meanwhile being orbited by a moon that spins as well. This isn't entirely obvious, as the Moon always presents the same face to us—but given the way the Moon orbits us, it has to spin to do this. It just happens that over millions of years that spin has been synchronized with its orbit by the tidal forces of the Earth's gravitational pull.

For that matter, every star that has been checked out appears to spin. It seems to be their natural state. So why should we assume that a black hole isn't spinning? What's more, it should be spinning very quickly indeed. Like the neutron star but even more so, we have the ice-skater effect of increasing spin speed as the radius decreases. The angular momentum, which depends on the distance from the center, mass, and velocity, is one of those physical quantities that is conserved. Reduce the radius and the velocity has to go up.

According to Kerr's calculations, in some circumstances, a ship could pass through the center of a black hole undamaged. The reason a spinning black hole makes transit vaguely possible is that the singularity, the inescapable point of infinite density, would be spun into a ring. Any traveler trying to pass through the wormhole would not come into contact with the singularity, but would shoot through the middle of the ring. If the ring was big enough, the traveler might not undergo so much gravitational pull that he was stretched to death.

So let's imagine that by having two spinning black holes, we manage to get through both of the singularities unscathed. We are now in the second black hole, somewhere else. Perhaps the other side of the universe. Perhaps in a different universe altogether. Unfortunately, we still have a teensy problem. We are still inside a black hole. There is no escape, no way out. However hard we try to accelerate away, we will gradually lose momentum until we shoot back through ring singularities, and so bounce back and forth like a galactic office toy, never emerging to the outside world.

To be able to get out, we need something dramatically different, in effect an anti–black hole. Not a black hole made of antimatter. Antimatter has the same gravitational effects as ordinary matter, so an antimatter black hole would still be inescapable (even if you could avoid coming into contact with the antimatter and annihilating). We are looking for something much more dramatic: the equivalent of a black hole that runs backward in time. It has a similar structure, but everything is pushed out instead of being sucked in. This is what is sometimes referred to as a white hole.

The white hole still has a singularity at its heart, but it is a very different kind of singularity, a singularity of creation rather than of destruction. Such singularities are not forbidden by the laws of physics in some circumstances, but they have never been observed. As far as we can tell they don't exist in nature. Or to be precise, such a singularity has existed only once as far as we know. The last time this type of singularity is thought to have existed, it was at the heart of the big bang.

Because the big bang represents the start of everything, such a singularity has the possibility of existing, but later in time—now, for instance—there are problems with the second law of thermodynamics. As we have seen (page 55), this law tells us that entropy—disorder—stays the same or increases in a closed system. A white hole seems to defy the second law of thermodynamics because it reverses the action of a black hole. Instead of ripping structured bodies into random constituents, it seems to assemble them and spew them out.

It is possible to fudge your way around the thermodynamics problem—remember, the second law applies only to closed systems, and it is possible to argue various ways in which the white hole could take energy from elsewhere to balance out its entropy problem. This would be similar to the way the Earth can have increasing order as life forms, due to the energy taken from the Sun.

Assuming we have ourselves a black hole and a white hole and somehow manage to merge their warps in space, in theory we seem to have a one-way tunnel through time and space. We enter the black hole and emerge from the white hole somewhere else. We still need to avoid the singularities, and somehow to survive the torrent of high-energy matter that is zapping into the black hole (and quite possibly out of the white hole), but we have something closer to our imagined picture of a wormhole. But there is still an issue to face.

From the white-hole end of the wormhole, you should be able to look back and see the singularity. If the traveler can get out, so can light. Although it's not a well-supported theory, mathematician Roger Penrose has suggested that singularities are so unnatural that we will never be able to see them—they always will be shielded by something like the event horizon of a black hole. The exit point of a white hole breaks this shield. This problem doesn't make black hole/white hole wormholes impossible, but it does make them seem more unlikely. This problem could be avoided if the singularity was spun into a ring—

you might then see through it rather than seeing the singularity itself.

Ideally, though, we would like to get rid of the singularities altogether. They are, frankly, an embarrassment and certainly an inconvenience. Luckily, it is possible to keep a wormhole and lose the singularities if we can get hold of a pair of white holes. If these should happen to meet up—or if we could somehow engineer a merging of their distortions in space-time—the two big-bang-style singularities would annihilate each other. The result would be a tunnel between two points in space and time with no deadly singularities in the way. It would be a tunnel that was open both ways—there wouldn't be a single travel direction. This would be a true wormhole, a shortcut through space-time that would give us a fleeting glance of a potential time machine.

But "fleeting" is definitely the word. Such a wormhole is inherently unstable. Relativity predicts that the wormhole would naturally break apart again so fast that even traveling at the speed of light, it would be impossible to get all the way through. And in that collapse, the wormhole would form a pair of inescapable, black-hole-style singularities. Any would-be traveler would be doomed. To make matters worse, should anything material manage to get into the wormhole in the short time available, it would cause the whole structure to collapse even sooner.

If you are trying to use a naturally occurring wormhole, there is also the problem of where the wormhole is going to take you. Bearing in mind that the extension of space from each singularity in effect penetrates the whole universe, we don't know where such a bridge of two singularities' space-time warps would emerge. One possibility is that it would extend into some other universe (a bit of a problem if there is only one universe, though eminently possible if you accept the cosmological idea that our universe is just one of many bubbles of inflation in a wider multiverse). If it did, such a wormhole, even if you could get through it, wouldn't be of any use as a time machine. The effect of traveling through it would be to detach you from our universe, rather than shift you in time within it.

The basic Einstein-Rosen bridge or wormhole, left to its own devices, just won't deliver. But the idea of using wormholes for travel was given a huge boost thanks to Jodie Foster and a movie. Science popularizer Carl Sagan wrote a novel called *Contact*, made into a film starring Foster. In the story, aliens send us instructions to build a device to travel to distant stars by passing through an artificial, constructed wormhole. Sagan originally intended to use a black hole as the means of travel, but he couldn't see how it could possibly work. For the novel, he didn't need to go into detail about how this would be done, but for fun he asked physicist Kip Thorne to come up with a more realistic way to make interstellar travel possible.

Until then, those thinking about Einstein-Rosen bridges and wormholes had assumed that they would be a natural phenomenon, but Thorne was, in effect, reverse engineering the problem. He looked at what's necessary to *make* a wormhole that passes from one part of the universe to another. If we think of that much-misused rubber sheet representing space-time, Thorne wanted to twist it around so that the rubber sheet was like a letter U lying on its side. He then wanted to make a funnel-shaped opening in the top of the sideways U and another funnel in the bottom of the U, joining the two together to make the wormhole.

The actual distance in space-time between the entry and exit points of the wormhole would be the distance all the way along the U-shaped rubber sheet, but a traveler heading through the wormhole would only cross the distance between the two arms of the U, potentially vastly exceeding the speed of light as far as the actual distance was concerned. Thus, traveling through a wormhole like this could be used to travel backward in time.

Thorne already had the basic mechanisms of a wormhole to work with, but as we have seen, if it were possible to construct a true wormhole from a pair of white holes, it would collapse incredibly quickly. What was needed was an engineering solution, some way to hold the wormhole open, stopping it from collapsing out of existence. This called for exotic matter—matter that bears the same relation to ordinary matter as a white hole does to a black hole. Such matter would apply a negative gravitational force to the wormhole, holding it open. We are talking about applying antigravity.

At first sight, this is the end of the line, as antigravity seems even more unlikely a concept than time travel, and there is no point replacing one impossible problem with another. Using antigravity did not seem a particularly practical solution. But that is based on the assumption that antigravity isn't possible—and we have been increasingly aware of effects that can, to all intents and purposes, be described as antigravity.

The best-known such effect is dark energy. This is a concept that has arisen out of observations of the way the universe as a whole is behaving. The big bang theory in its modern form envisages that a tiny universe went through a vast expansion in size—much faster than the speed of light—during an inflationary process, followed by more sedate expansion as it grew to its current size.

Until the 1990s everyone assumed that this expansion would gradually slow under the influence of gravity, as all the bodies in the universe attracted each other. The final outcome would be either a reversal, so that everything would come back together in a cataclysmic big crunch; or, more likely, that the expansion would very gradually peter out, never quite stopping but getting slower and slower forever.

With new telescopes and space observatories, it became possible to look far back in time (because of the finite speed of light, a view into distant space is also a view into a distant time) and hence to follow the expansion of the universe for a long time. The result of these studies came as a shock. The expansion of the universe is not slowing down as the gravitational attraction between the matter in the universe pulls things together. Instead, it is speeding up. The expansion of the universe appears to be getting quicker.

The expansionary force, driving the universe apart, was given the name "dark energy" to parallel the already existing concept of dark matter. This is not a trivial effect. In fact, it makes up the biggest component of the universe, dominating everything else. Dark energy is thought to amount to around 70 percent of all the matter/energy (remember, the two are interchangeable thanks to $E = mc^2$) in the universe, far outweighing the conventional matter and dark matter out there. But this is a repulsive force. Unlike gravity, it is driving everything apart. It is the equivalent of antigravity.

Unfortunately, vast though this effect is, it is difficult to see how it could be harnessed. Even if it could, the amount of dark energy available in the vicinity of a single wormhole would be tiny—the total amount is so vast only because it acts across the scale of the universe. Add to this the fact that we don't know what dark energy is, or what is causing it, and the chances of making practical use of it become slim.

However, the general concept behind dark energy gives us a clue as to what might provide a possible route to antigravity. One way of looking at dark energy is that it is negative energy. Antigravity should be produced if we can get an area of space into a state of negative energy. Remember Dirac's sea of negative energy electrons that introduced the idea of positrons and antimatter. The concept of negative energy is not an alien one to modern physics.

We know that the presence of a particle of matter distorts space as it produces a gravitational effect. Einstein's $E = mc^2$ equation tells us that any matter is the equivalent of positive energy. Mass is positive and c^2 is positive, so the energy associated with mass has to be positive as well. If we take away all matter from a region of space, then the space should have zero energy. What we want to do is to go further than this and take away more somehow, leaving behind negative energy.

There are a number of ways of generating negative energy that are more than just theory, with practical experiments already carried out to back them up. All of these have one substantial flaw. We'll come back to the flaw, but let's take a look at the negative energy generators first. The best known is without doubt the Casimir effect. This is a quantum effect in the vacuum of space that arises from the uncertainty principle.

As we have already seen, Heisenberg's uncertainty principle, one of the essential elements of quantum theory, says that there are pairs of properties that can't both be known about in detail for quantum objects. The best-known pairing is momentum and position. The better you know a particle's position, for example, the less you can say about its momentum. Know exactly where it is located, and it could have any momentum.

The same uncertainty principle also applies to the pairing of energy and time. If we take a bit of empty space and examine it closely over a very precise, narrow period of time, then we are forced to be very vague about just how much energy that space contains. When that energy soars to high levels, as it sometimes must, it can temporarily produce pairs of particles—matter and antimatter—out of nothing.

These are the same pairs of particles that it is thought would produce Hawking radiation near a black hole. These particles aren't observed, because they immediately annihilate and return to being energy before they can interact with anything. But though they are "virtual" particles in the sense that they aren't observed, they do exist. In some circumstances they can become separated, or one particle will undergo a reaction, leaving the other particle observably present.

Another set of virtual particles that inhabit apparently empty space are the virtual photons that are considered to act as carriers for the electromagnetic field. Again, these particles are not usually observed, but provide the mechanism for the electromagnetic field to operate at a distance. It is virtual photons, for example, exchanged between the nucleus of atoms and the electrons around the nucleus, that keep the electrons in place. Because of their short-term existence and the uncertainty principle, virtual particles can have positive or negative energy, and this possibility produces the Casimir effect.

The effect, first suggested by Dutch physicist Hendrik Casimir, working with Dirk Polder, most typically arises when you have two flat metal plates very close together in a vacuum. If the plates are close enough to each other (and that means nanometers apart or less), they limit the options open for virtual particles in between them, compared to the virtual particles forming outside the plates. If you think of the particles as waves (always possible with quantum particles), only those particles that could form a half wavelength, a wavelength, and so on between the plates could appear there. So there is less energy between the plates than outside them. But the net energy outside the plates is zero. The result is a force pulling the plates together that is the equivalent of a negative energy.

This, incidentally, is why it is very difficult to craft nanomachines (invisibly small robots) from metals: when one is constructing on this scale, the Casimir force is strong enough to make parts stick together and fail to function. The closer the plates, the bigger the force—but it is not easy to produce a sufficiently large negative energy this way, or by using variants where a single reflective plate is moved through a vacuum, which also generates very small amounts of negative energy.

The Casimir effect is sometimes used as an illustration of zero point energy. This is the minimum energy of a quantum system, in effect, the energy of the vacuum. Zero point energy has been used as the basis for dramatic schemes to produce free energy from nowhere—perpetual motion machines. But these have no basis in scientific fact, as there is no way to access the "energy of the vacuum."

To get energy out of something you need a "sink"—somewhere else that has less energy. Take a simple example. If I put a ball on top of a mountain and let go, it will roll down because there is a sink, a point of lower energy. If everywhere around had the same energy or more, the ball would go nowhere. With a heat engine, the sink is usually the temperature of cold water, though to get maximum efficiency out of a heat engine you really want to get that sink as close to absolute zero as possible. Again, if there is nowhere with lower energy than your starting point, you can't get energy out.

So to harness zero point energy you would need a sink that had lower energy than zero point—which by definition is the minimum achievable energy. Schemes to extract free energy from zero point energy are inherently attempting the impossible. The energy is there, but you can't use it.

Zero point energy also gets dragged into pseudoscientific energy-based "healing" schemes like Reiki, making it easy to suspect that the Casimir effect is similarly lacking in scientific credibility. But this effect is quite different from zero point energy schemes. Rather, it is a widely observed and well-supported phenomenon which does not claim to produce usable energy on any practical scale. If you see a device that claims to work by extracting energy from the Casimir effect, be very suspicious.

Physicist Michio Kaku describes how he imagines a time travel device using the Casimir effect would work. Kaku is a leading light in string theory and M theory, the powerful but highly speculative science that suggests that reality is a four-dimensional membrane floating in a higher dimensional environment. Kaku is an interesting and inspiring character who is hugely optimistic about what will eventually be possible when a civilization reaches much higher levels of technology than our own. He is sure that it is only a matter of time before *Star Trek*–like technology is possible.

It's important to bear in mind these contrasting aspects of Kaku's nature—the superb physicist and the enthusiast for science-fiction dreams—when considering his description of a time machine. He believes it will consist of two chambers, each made up of a pair of concentric spheres separated by a very small distance. In preparation for the time trip, the chambers need to be "hooked up" to a wormhole linking the two (not exactly a trivial requirement). A time differential is then built between the chambers, using one of the techniques we'll come to in a moment.

Then comes the application of the Casimir effect. In a retelling of his idea by Jenny Randles, he then puts a huge voltage across the two spheres, to somehow create a strong Casimir effect. The trick, she says, is "generating a sufficiently huge electromagnetic force that would induce massive electrical fields between them." Randles suggests that the metal plates would have to allow as much of the "energy field" as possible to pass between them, perhaps by using a superconductor to enable this.

Then, she says, the machine "must" distort space-time to create a wormhole between the two chambers, stabilized by the Casimir effect. But unless this was a different idea, it isn't what Kaku himself describes. Kaku merely says that the Casimir effect is set up by "imploding the outer sphere." He doesn't describe producing a wormhole using electromagnetism, but instead, possibly harvesting one from space-time foam (see page 218). Perhaps Randles had in mind creating the space-time foam using the electrical field. When I asked him for details, Kaku pointed out that the implosion is significant because the Casimir effect is proportional to the inverse fourth power of the separation distance.

This means that as the distance becomes very small indeed, the amount of negative energy should hit a massive peak. If, for instance, you reduced the gap to one-hundredth of its previous value, the negative energy goes up by a factor of 100 million. Imploding the outer sphere seems to entail closing the gap very rapidly—not an easy option. But if you could make that implosion very even for an extremely short time, the gap would be immeasurably small and the negative energy massive.

This is the moment when Kaku's time machine would be active and the time traveler would make the trip, zapping through the wormhole while the negative energy briefly held the wormhole open. Such is the level of the surge that there should be time to get through the wormhole, even though there would be no way of passing through during the instant when the negative energy peaked.

However, this idea still has a significant problem attached. Before the traveler could pass through, the wormhole would have to be kept stable while the time differential was produced. This could take years. And all the evidence is that wormholes have a natural tendency to collapse and need constant stabilization. Maybe Kaku came to this conclusion: when he provided me with details, he pretty well ignored the concept of implosion.

Instead, he pointed out that to provide enough negative energy to stabilize a wormhole using the Casimir effect, the separation distances between the inner and outer spheres would have to be very small—perhaps on the order of the Planck length. This is a very special measurement in quantum theory that we met when looking into the nature of time (see page 65), and one that could lie at the heart of existence.

The Planck length is around 1.6×10^{-35} meters. It is calculated using only three fundamental constants: the speed of light, Planck's constant, and the gravitational constant. Planck's constant provides the relationship between the energy of a photon and its frequency when treated as a wave of light. (Technically, the Planck length actually depends on the "reduced Planck's constant," which is Planck's constant divided by 2π.) The gravitational constant first appeared in Newton's law of gravitation and describes the relationship between the masses of two bodies, their separation, and the force of gravity between them.

Some have speculated that the Planck length represents the fundamental "graininess" of the universe—that there is no meaningful distance below this, and that we live in a digital world with "pixels" at this level. This is the level at which our conventional ideas of distance collapse, because the quantum effects become so significant. If Kaku is right, then producing a stable gap of this size would require engineering feats far beyond our current capability. As he puts it, "This is for a very advanced civilization, not for us."

If the Casimir effect won't generate the negative energy needed to stabilize a wormhole, another option is using laser pulses. If a pulse of laser light is sent into a suitably designed crystal with reflecting ends, which forms a cavity in which photons can set up a resonant pattern (rather like way an organ pipe generates sound), the result can be a "squeezed coherent state" that comprises pairs of lower-frequency pulses, one of positive energy, the other of negative. It has never been done, but if these negative energy pulses can be separated off (not a trivial task, as the pulses are typically a million billionth of a second long), the result could be a stream of negative energy.

Even this is a relatively small effect, though bigger than the alternatives. But it might be enough. If you could set up a very small black hole, this would act as a kind of negative-energy amplifier. The effect we have already seen described, Hawking radiation, is the equivalent of positive energy flowing away from the black hole while negative energy flows into the black hole. The smaller the radius of the hole, the bigger the flow of negative energy. If you could fire a burst of negative energy from such a squeezed laser into a tiny black hole, the result could be to open up a wormhole, with the inflow of negative energy widening the entrance and stabilizing the wormhole.

We're most of the way, then. If we can get hold of a suitable wormhole (or construct one), stabilize it with negative energy, and keep it wide enough open to pass through, we just need to make sure that emerging from the other end of the wormhole has taken us on a journey that enables time travel.

One way to force this to happen is to set up a special-relativity differential between the two ends of the wormhole. This assumes that it is possible to pick up one end of the wormhole and move it about. To do this, we could shoot electrons or other charged particles (generally speaking, a charge is needed to manipulate quantum particles easily) into the wormhole while it is still small. We use the charge to keep the nearer end (say) of the wormhole steady, while whizzing the distant end around using some sort of accelerator.

An accelerator is one piece of the technology that might be required for wormhole time travel that we already understand quite well. Probably the most famous accelerator today is the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, but all accelerators operate in the same basic fashion. A series of large electromagnets are switched in such a way to give a push to a charged particle. Linear accelerators send the particle along a straight path, but the kind we would need to wiggle our wormhole pass the particles around a ring. In the case of the LHC, this ring is enormous—an 84-kilometer-long tube. As the particles shoot around the ring they are accelerated more and more, getting closer and closer to the speed of light.

If we keep a body rotating around the ring at nearly the speed of light, significant relativistic effects can be generated. Imagine putting the charged distant end of a wormhole in an accelerator and speeding it around time and again, building up a time differential compared with the other end of the wormhole. If the process were undertaken while the wormhole was still small, it should be relatively easy to generate a reasonable time shift between the two ends.

Accelerators like the LHC also potentially have a role in the creation of wormholes. If we can't find a suitable wormhole to operate on in space, we would need to create one from scratch. If the inflationary powers of negative energy were to work, this might be a more controlled way to proceed, starting with a very small wormhole. It has been speculated that the LHC could generate tiny black holes, which might be manipulated; but it has also been suggested that it could generate complete wormholes with roughly equal probabilities to the mini–black holes.

According to mathematicians working at the Steklov Mathematical Institute and the Lebedev Physics Institute in Moscow, some of the extreme head-on collisions generated by the LHC could create localized shockwaves that would distort space-time sufficiently that a rip would occur, causing a tiny wormhole to pop into existence. This depends on ideas on the quantum nature of gravity that aren't fully formed, so it is a very speculative notion, but fascinating nonetheless.

If the Russian theory holds good, such wormholes should be appearing briefly, naturally, all the time—for example, in the collisions that constantly occur between cosmic rays and matter—but usually we aren't on hand to keep the wormhole alive. This depends on a picture of space-time under the stress of high-energy events that is a kind of foam, in which all manner of quantum effects, including miniature wormholes, are constantly, briefly, occurring, then disappearing.

Described by Kip Thorne as a "random probabilistic froth," this bubbling quantum foam is envisaged to be the nature of space-time in the vicinity of a singularity, such as in a black hole, and could be created by high-energy collisions. If tiny wormholes were generated in the LHC (initially, all we would see would be the particles produced when they collapsed), it might be possible to stabilize them using exotic negative energy, shift them into space, and use them for time travel.

As an alternative to using an accelerator to generate a time differential, we could set one up with a conventional twins paradox journey, sending the far end of the wormhole off on a spaceship at near the speed of light for a length of time, then bringing it back to Earth. Say the journey took one year from the pilot's viewpoint but twenty years from the Earth, so the ship landed twenty years after it took off. Looking through the wormhole from the "Earth" end, we would see that the journey took place in one year. If the ship took off in 2050, by 2051, the observer from the Earth end would see the ship back on the ground on Earth—but the view would be of 2070.

Another way to generate a time difference between the ends of a wormhole is to use general relativity. As we have seen, general relativity says that mass warps space-time—not just space, but time, too. Get close to a heavy mass and your clock will slow down. This is measurable even on a skyscraper—there is a tiny difference between clock speeds at the top and bottom of the building—and is even more obvious with GPS satellites. As we've seen, these gain around 46 microseconds a day because their clocks run faster than clocks on the Earth's surface. It's not just that the clock isn't working right—time is running faster on the satellite.

These effects are caused by the Earth's gravitational pull; but if you make the gravitational effect massive enough, you can get a noticeable slip into the past. As we have seen, in theory a neutron star—a highly collapsed star that doesn't quite make it to being a black hole—could apply enough of a gravitational pull to be used as a time machine for traveling into the future. Likewise, we could use a neutron star as a time engine for one end of a wormhole to set up a differential that would allow us to journey into the past.

As before, we would have to pin down one end of the wormhole at our start point and drag the other over to a neutron star, where its time would gradually drift out of synchronization with the time that was registered at the other end of the wormhole. The wormhole would become a gateway through time.

Let's assume the neutron star is quite far from the end of the wormhole that is parked back near Earth. But through the wormhole the distance between the two points is very close. A big time differential builds up between the two ends because of the difference in gravitational effects. At least, that is reality as seen from outside the wormhole. If you look through the wormhole, then the entrance is only a few meters away from the neutron star, and you still feel the same gravitational effect. So depending on whether you look through the wormhole or through normal space, you will see the same time or a different time.

This means that, as with the special-relativity example, by taking a journey that loops around through the wormhole, back through space, and so on repeatedly, you will travel back in time. But reverse your journey around the loop and you will travel forward in time. These wormhole time travel devices are among the few examples that are reversible like the classic fictional time machine.

Sadly, though, like pretty well all real time travel technology, the wormhole time machine lacks the flexibility of the typical fictional device. In fiction we see someone set the destination time on a dial, pull a lever, and be transported from A to B through the time stream. Our "real" time machines are more like a railroad than like traveling by car. You can't choose your destination—in using the machine, you go to whatever destination has already been set up, following the "rails" of the time differential.

The same wormhole could, however, be used for multiple trips, provided the machine was kept active. If you traveled forward from 2051 to 2070 in the example above, you could walk around to the departure end in 2070. As time was ticking on, through the 2070 departure end you could see 2089 and step through to that. You could keep jumping forward in increments of the time differential as long as the machine was kept running. But going back, you could never pass back earlier than 2051.

For practical reasons, if using a general-relativity time machine, you might want to drag the far end of the wormhole away from the neutron star after the differential had been set up to make it feasible to pass through without being damaged by being close to the star. This would shorten the external length of the wormhole, but would have no effect on the length of the passage through the wormhole.

Although you might have moved the two ends of the wormhole by light-years, it is quite possible for the distance through the hole to remain constant. Imagine a U-shaped loop of space-time on its side, rather like a looped piece of ribbon, with the wormhole linking top and bottom near the “fold” in the material. You can slide out the material, keeping the wormhole in place, making the loop longer and longer. The distance along the loop of material—the distance between the ends of the wormhole through normal space—can increase or decrease while the length of the wormhole remains the same.

Wormhole technology still requires speculative theory—we don’t know, for instance, that firing negative energy pulses into a tiny wormhole will stabilize it, and we don’t know for certain that tiny wormholes will be created by the LHC or found “wild” in space—and also brings with it the need for unthinkably complex engineering prowess. The general-relativity wormhole device, for example, requires us to find a neutron star and to drag one end of our wormhole to it across what is probably many light-years of space.

As we have seen, the nearest detected neutron star is around 250 light-years away. Our fastest current spaceships would take around 4 million years to reach this—not yet a very practical approach. However, at this stage the important thing to emphasize is that while not necessarily practical, this is a theoretically possible mechanism for building a time machine. There is nothing in the laws of physics that rules it out.

I have seen it said that these methods that use special or general relativity to set up a time differential between ends of a wormhole are the only ways to use the wormhole to travel into the past. (At least, the only controlled means. In principle a wormhole, being a bridge in space-time, could link two randomly selected points in time.) In his book *Cows in the Maze*, mathematician Ian Stewart says that to travel back in time using a wormhole, it’s necessary to wave one end of the wormhole around at nearly light speed.

When I asked Stewart to clarify this, he said, “It depends on how the time frames at the two ends match up, and that involves some assumptions. The usual one is that the two ends are simultaneous, in the frame of reference of one of them. So if we stepped through to Alpha Centauri, and at the same time sent a light signal by the normal route, then we'd have to wait 4.5 years for it to turn up. Going through the wormhole and back would then give the same elapsed time as if you'd not bothered to go at all, so no time travel."

But this view is disputed by no less a figure than Stephen Hawking. In *A Brief History of Time,* he makes it clear that traveling faster than light always brings with it the ability to travel back through time, curiously also using the example of travel between Earth and Alpha Centauri. He envisages a message from Earth reaching a congress on Alpha Centauri through a wormhole, carrying the result of a race on the Earth. "But then an observer moving towards the earth should also be able to find another wormhole that would enable him to get from the opening of the Congress on Alpha Centauri back to earth before the start of the race. So wormholes, like any other possible form of travel faster than light, would allow one to travel into the past."

Having said this, Hawking has recently suggested that wormholes could never be kept stable long enough to be used. The reason he gives is feedback. We're used to positive feedback when a microphone gets too near an amplifier. Any small ambient sounds get picked up by the microphone and come out of the speakers louder. The amplified sounds are then picked up by the microphone and amplified again—the result is the familiar squeal.

Hawking suggests that something similar would happen with a wormhole. Natural radiation would pass through the wormhole—that's fair enough. He then suggests that the radiation would travel back to its point of origin, reenter the wormhole, and get into a reinforcing loop, producing feedback "so strong that it destroys the wormhole."

Stephen Hawking was picking up on a challenge posed by physicists Robert Geroch and Robert Wald to Kip Thorne back in 1988, when Thorne was working on the theory of wormholes and time travel. Geroch and Wald suggested that electromagnetic radiation would pass through the time travel wormhole, emerging at an earlier time. It could then travel back to the entry point at light speed and join itself, passing through the wormhole again, building up and up, just like feedback from an amplifier, but with the advantage of time travel to help synchronize the reinforcement.

In the version of the time travel wormhole where the distant hole is moved around at high speed to generate the time difference, you would also get the Doppler effect kicking in—if the source is moving, the speed of light can't change, but the energy can. The motion could result in even higher-energy electromagnetic radiation being added into the repeated circuit. Because energy, like mass, distorts space-time, the rapidly growing beam (faster than rapidly—it takes no time at all to build up, because of the time shift) would massively warp space-time through the wormhole, destroying the bridge.

It might seem that these physicists have failed to notice a fundamental difference between sound and light. Audio feedback works even if the microphone isn't pointing at the loudspeakers, because the sound from the speakers will be picked up (at reduced intensity) even if the microphone is facing away from them. In the case of the wormhole, isn't it enough to make sure that the two ends of the wormhole face in opposite directions, so radiation emerging from one hole is heading off in the opposite direction to the other hole?

The physicists who wanted to shoot down Thorne's time travel device were ready for this argument. It wasn't a problem for them, because we are imagining the entrance and exit of a wormhole incorrectly. They aren't two-dimensional holes in space, but three-dimensional. The end of a wormhole distorts space outward like a flower that bends out in a curve, and as such will receive some of the radiation emerging from the opposite end.

Thorne soon came up with a counterargument. The exotic matter threading through the wormhole that is used to keep it open will also splay the radiation out at the far end. Instead of traveling in a tight beam, the photons will shoot off in a whole range of directions, becoming more and more diffuse. Only a tiny fraction of them will find their way back to the entrance to the time travel wormhole, and they wouldn't be enough to set up a feedback loop.

This defense against self-collapse wasn't enough to get Thorne off the hook, though. Another physicist, Bill Hiscock, suggested to him that electromagnetic radiation wasn't the only bug in the system. It was possible that a similar feedback effect could occur with electromagnetic vacuum fluctuations, the tiny quantum variations in electromagnetic energy in the vacuum that occur as virtual particles pop into and out of existence.

Thorne initially assumed the same defense would work as prevented electromagnetic radiation from blowing his time travel wormhole apart. The exotic matter would defocus the quantum variations, sending them off in all directions. But to his surprise, the math produced a different picture. It seems that though the "exit" end of the wormhole would disperse the fluctuations, the "entrance" end would refocus them, so that the energy of the vacuum fluctuations would build toward infinite intensity, blowing the wormhole apart.

After much calculation, Thorne and a colleague decided that this wasn't a problem. The surge in quantum variations, they believed, would happen so briefly when time travel was first established that it wouldn't have time to destroy the wormhole, and then, almost instantly after, it would be dispersed. Stephen Hawking disagrees and believes that a relativistic effect would mean that there would be enough time for the wormhole to be destroyed. The exact details depend on an understanding of quantum gravity, something that is yet to be properly described, so any attempt to work out the results are inevitably speculative and will be subject to change.

Either way, this feels like the sort of problem that it should be possible to address, if Thorne is proved wrong and Hawking right. The feedback effect doesn’t seem to be an insuperable problem when put alongside all the other practical difficulties to be overcome in producing a wormhole time machine.

If we do ever construct a wormhole time travel device, as with other time machines dependent on relativity, we would be able to travel back no further than the moment when the device was first created, and in practice we would probably fall far short of that, for getting near that limit implies moving impossibly close to the speed of light. This doesn’t in any way rule out such a device’s creation, but it does stop its being used to travel back to great historical events.

But along with rotating neutron star cylinders, the science and technology involved in wormhole manipulation seems far, far beyond anything that is likely to be possible in the next hundred years or more. After all, we would have to find or create a wormhole to make this possibility a reality, something we are yet to come close to. And then we would have to go through all the processes to enlarge it, stabilize it, and set up a time differential to be able to make a time journey through it.

Although none of this is impossible, as we have seen, there are huge difficulties to overcome in making it feasible, difficulties that go far beyond the technology we could envisage producing in perhaps even thousands of years. In the meanwhile, though, one man believes that we don’t have to venture into space or deal with anything as tricky (and perhaps even imaginary) as wormholes. He is sure that we can tame time on the desktop.

CHAPTER TWELVE

THE MALLETT MACHINE

> *My quest from then on was to prepare myself so that one day I could design a machine that would take me back in time to before May 22, 1955. I wanted to see my father again.*
>
> —Ronald Mallett, *The Time Traveler* (2006)

It's rare to find much similarity between scientists in the movies and inhabitants of the real world. The scientists you are likely to meet in universities around the world are just like ordinary people. They might tend to be a little more precise in the way they speak about things—dare I say it, a little more geeky than the average person—but they don't stand out as distinctively odd human beings.

By contrast, movie scientists are rarely normal. Most are driven by some extreme urge. Perhaps they want to dominate the world, or ever since their brother died of cancer they have been desperate to find a cure. Everything they do in their working lives (and they rarely have much else) is an attempt to move closer to their dream. Here's a typical movie scenario. Ronald's father died when he was young, something he bitterly regrets. All his life he has wanted to be able to meet his father again, to talk with him. It has driven Ronald to become a scientist—and now he is determined to invent a time machine. It seems painfully far-fetched. But this is the true story of Professor Ronald Mallett of the University of Connecticut.

In 1955, when Ronald Mallett was ten, his father died. With his love of gadgetry, Mallett senior had been a huge influence on the boy. His death meant more than the loss of a key member of the family and a devastating reduction in income—it also meant that Ronald lost the stimulus of the kind of father who built a voice-activated toy train at a time when such technology seemed closely allied to magic.

Two years later, uncomfortable in a new life in Pennsylvania, where being black was suddenly a stigma that it had never been in his early years in the

Bronx, Ronald came across a comic-book version of the classic story that opens this book—H. G. Wells's *The Time Machine*.

The story presented a whole new concept to the boy. It seemed to say that it was possible to travel through time just as easily as we move through space, provided you built the right structure. Using his father's tools and the contents of the basement, Ronald tried to reconstruct the machine from the illustrations in the comic. Despite all his effort, it didn't work. But rather than be put off, this inspired him to find out more about the science that the comic book said made time travel possible. He would go back to 1955 and warn his father to get checked out by the doctor. He *would* see his father again.

Initially inspired by science fiction, young Ronald eventually came across a reality in science to back up his desire. As we have seen, Einstein's relativity had shown that the speed of light was a constant, which forced the flow of time to be less fixed than had previously been assumed. Ronald realized that relativity provided a means to travel in time. But the obvious way of doing so, using time dilation, would move you into the future, not the past. He wanted to get back to 1955. This would require a faster-than-light journey—something that science labeled impossible—or some other way to get around the time barrier. Mallett continued to hunt for a means to fulfill his dream.

After a short stay in the air force, working with early electronic computers, Mallett went back to college and in 1973 received a PhD in physics from Penn State University for a thesis on a cosmological application of Einstein's general relativity. It was no accident that the subject of his thesis was time reversal in a de Sitter universe (a particular type of curved-space universe). Although this "time reversal" was not literally time travel, but rather a look at what happens to the equations of motion when the time variable is reversed, it was close enough for Mallett to feel it was a useful addition to his mental armory.

After a couple of years in industry, where he first worked with lasers—an introduction that would prove valuable later—Mallett moved to the University of Connecticut as an assistant professor of physics, working on general relativity. Bearing in mind that general relativity showed that time slowed under the influence of gravity, Mallett felt that there might be some opportunity here to develop a theory that would lead to a time machine—though he was careful not to mention this to his colleagues, who back then would have thought him crazy. Maintaining a good image was essential because assistant professors did not have tenure—they could be fired—and he needed to progress up the academic career ladder to a tenured position before he tipped his hand.

In his second year at Connecticut, Mallett discovered the idea of rotating black holes as potential time machines. He was also aware of an effect of massive objects on space-time called frame dragging. This is the effect we have seen used in van Stockum's and Tipler's vast hypothetical cylinders. Rather than creating a static "dip" in space, like the picture of a bowling ball on a rubber sheet usually used to describe the relationship between gravity and warped space, a rotating mass creates a swirling dip, like a gravitational version of water swirling into a drain.

Mallett wondered if there was a connection between these two hypothetical properties of a rotating black hole—the frame dragging and the ability to act as a gateway into the past. This stayed with him as his work continued on relativity and black holes, but he struggled to find a way forward. After all, it was fine to know that a rotating black hole could initiate frame dragging and produce a mechanism for time travel, but he was not likely to lay his hands on a black hole any time soon.

It was about this time, in 1998, that Mallett noticed the significance of an obscure aspect of general relativity. We normally think of gravity being produced by bodies with mass, but general relativity points out that light can generate a gravitational field too. Back when this was first realized it was considered a nicety—no one had a way to produce a tight beam of light, rotating around in a way that could generate frame dragging. But Mallett knew better.

From his engineering work, he was aware of a device that was exactly that tight rotating beam: a ring laser. (In the most common form, the laser traverses four sides of a square, entering through a half silvered mirror, and then bouncing around four angled mirrors that keep it on a tight circuit.) After days of agonizing calculation, Mallett concluded that such a ring *could* produce frame dragging with the potential of forming closed timelike loops—gateways to the past. The result of his work was published in 2000. At this stage there was no mention of time travel—but Mallett had taken one step toward the possibility of making his dream a reality.

Taking the next step was not going to prove easy. Mallett struggled with the complex equations of Einstein's general relativity, for which he would need to produce a specific solution if he was to show that the frame-dragging effect applied to time as well as to space. He toyed with using two light beams, traveling in different directions, which would have simplified the math, but it turned that out they also had the potential to cancel out the frame-dragging effect.

Instead, Mallett tried a different mental picture from the simple ring laser bouncing off four mirrors. He envisaged using fiber optics to channel the beam—this way the light would circulate more smoothly, and could be brought into a spiral to enhance the effect. A colleague suggested applying the effect to a beam of neutrons passed through the middle of the spiral rather than to a single neutron, as Mallett had first imagined.

This was beginning to sound like a real experiment. But Mallett is a theoretical physicist and knew that he had not the skills or the resources to build an appropriate device. Instead, he wanted to crack the math that would demonstrate that his idea could work. For months he labored with the notoriously complex gravitational field equations, which look surprisingly simple when written in a single line of math, but hide many levels of complexity through the use of multidimensional entities called tensors.

Finally, working on a simplified model of a perfect spiral of light without the reflections involved in a fiber optic cable, he managed to wrestle the equations into a solution. The equations predicted that with a strong enough frame-dragging effect, there would be a movement backward in time.

In principle, Mallett had the mechanism for a time machine—and not just a time machine that could transmit information, but one that could produce a physical tunnel through time. However, there was one flaw in this design, at least as far as Mallett's initial inducement to devise a true time machine was concerned.

The manipulation of space-time by the frame-dragging effect builds up with time. As the machine continues to run, it's as if there's an anchor in space-time that it links to. In principle, after the machine has been running a year, it will be possible to pass back a year in time. But no further. Like all relativity-based time travel, Mallett's theory provided no way to travel back in time to before the point the machine was switched on. It would not allow him to go back and speak with his father.

Although Mallett is a theoretician, he still wanted his frame-dragging device to be built. First he worked with experimenter Chandra Roychoudhuri to demonstrate that the spatial aspects of frame dragging were occurring, as this could be tested with a much weaker effect than could the impact of frame dragging on time. As Mallett pointed out, you need frame dragging to create the closed timelike loops that enable time travel, so if you can't get an experiment to produce the frame dragging at all, there is no point in proceeding further.

As almost always happens with experiments, practicalities had to shift the approach away from the original theoretical concepts. Making a spiral of light was not a realistic possibility. Mallett and Roychoudhuri returned to the original idea of sending a light beam around a square (though they modified this to use four lasers rather than one), then extended the design to a whole tower of these laser rings—over two thousand of them in all—to amplify the effect to the extent that it should be detectable. They would then shoot a particle down the middle—

both neutrons and photons were considered—and see how the swirling light beams influenced the particle's properties.

Ronald Mallett describes his life and work movingly in the book *The Time Traveler*, written with Bruce Henderson. When I contacted Mallett around five years after his book was written, there was limited progress to report. He has added the Penn State Electro-Optics Center to his experimental collaborators and is still trying to secure funding. He estimates he will require $1 million to start work and around $10 million to complete it.

If the experimental process proceeds, the hope is first to show physical frame dragging, then low-grade time travel. This would be tested by sending decaying particles through the device. If the decay times were extended, it would seem that the particles had at least been slowed down in time. This has a parallel in the natural world, where muons, particles produced in the upper atmosphere, undergo time dilation because of relativity. Muons are produced in the atmosphere when cosmic rays—high-energy particles from the depths of space—crash into the upper atmosphere.

Muons have a very short lifetime and few should make it to ground level, but they travel so fast that special relativity plays its part. Because of their relative speed, the time the muons experience is significantly slowed down, by about a factor of five, and as a result they are observed.

It is only after this second level of testing that Mallett envisages actual time travel on a measurable scale. The delay is in part because it would require very expensive equipment, and it is necessary to have the step-by-step tests to justify going the whole way. He simply wouldn't get funding without succeeding in those first steps. There is some danger that Mallett, who was sixty-five in 2010, will have retired before he gets that far—but should the initial experiments prove positive, it is likely his experimental colleagues will continue, whatever Mallett's involvement.

Other physicists have raised some issues with Mallett's theoretical basis for his time machine. They point out that the approach he has used for calculating the impact of frame dragging was subtly different from the actual experimental design. In the theory he makes use of a "line source," a nonrealistic concept that will warp space-time in a way that is unlikely to be seen in an actual experiment—this is referred to by the authors as a "pathological space-time." The skeptical scientists also suggest that the amount of energy required to make a measurable impact through frame dragging is far beyond the capacity of the lasers that will be used, a concern that hasn't fully been answered. But there is still enough hope in Mallett's idea to make it worth taking to an experimental phase.

Bearing in mind how we opened this chapter with Mallett's story presented as if it were a movie script, it comes as no surprise to hear from Ronald Mallett that his story has been optioned by Spike Lee, who has acquired the film rights to make a feature-length movie of Mallett's attempts to be reunited with his father. It illustrates just how much this is a story about people and their desires as it is about science. It's hard to imagine that a Hollywood version would leave Mallett's work hanging in the air quite so much as he seems to be for the moment, though.

If we are to believe the timeline presented in his book, it is surprising how late Ronald Mallett discovered that his device, like all time machines that depend on relativity, would not penetrate further back in time than the moment when the machine was first built. This is such a basic phenomenon that it seems likely that Mallett reveals it late in his story to keep up tension, long after he was aware of this limitation of using frame dragging. It meant that in practice he would never be able to use such a device to visit his father. And given some of the paradoxes of time travel, it's probably just as well.

CHAPTER THIRTEEN

KILLING GRANDFATHER

> *The third [argument of motion is] to the effect that the flying arrow is at rest, which result follows from the assumption that time is composed of moments: if this assumption is not granted, the conclusion will not follow.*
>
> —Zeno (ca. 490–425 BC), quoted in Aristotle, *Physics*

If time travel ever occurs it takes us straight into the world of paradox. Sometimes the term “paradox” is used loosely to imply something that sounds merely unlikely but is in truth impossible. However, a paradox isn’t an impossibility; it is just something that seems unbelievable, but is consistent with the rules being applied.

There are true impossibilities. The old problem about what happens if an irresistible force is applied to an immovable object is such a fallacy, and is not a true paradox. There is no such thing as an irresistible force or an immovable object. To be irresistible, a force would have to be infinite. If not, the object has the potential to apply a bigger force in the opposite direction. And to be immovable, an object would have to be anchored to something absolute by a field of infinite strength. But there is no spatial absolute, nor a field of this nature.

It is also possible to come up with simple, logically inconsistent statements that cannot be true. You can’t have a glass that is empty and full at the same time. At least, you can’t unless you stretch the definitions. A glass can be empty of beer yet full of air. In fact, an “empty” glass usually *is* full of air. But taken literally, a glass can’t be crammed full of atoms and have a vacuum inside it at the same moment.

We have to be careful in physics about taking this argument too far. It’s a fundamental of quantum physics that a particle can be in more than one state at once, or in more than one place at the same time. Quantum objects can appear to defy logical consistency—but that is because we assume that the location of a particle is an absolute property, so something must be either here or not here. All the evidence is that, at least at the quantum level, location isn't really like that.

A paradox is different from a logical impossibility. To step away from time travel for a moment into the more precisely defined world of mathematics, there are plenty of paradoxical entities that crop up in the world of infinity. A good example is the structure often referred to as Gabriel's Horn. This is a very simple three-dimensional shape, formed by plotting the values of 1/x for every x greater than 1 and then spinning the resultant curve around the axis to make it three-dimensional, like a lathe turning an object that is going to be carved.

The shape that is produced is a bit like a long, straight hunting horn (or a wizard's hat that has no brim), but one where the pointy end keeps on getting smaller and smaller all the way to infinity. Now despite being infinitely long, this shape has a finite volume. This isn't as surprising as it sounds. It reflects the way an infinite series like 1+½ + ¼ + ⅛ . . . and so on, all the way to infinity, can add up to a finite value, in the case of that series, adding to a total of 2. Similarly, the volume of Gabriel's Horn is pi. Just 3.14159 . . .

You might wonder, "Pi what?" It depends on the units we were thinking of for our original 1/x from which the shape was generated. If the 1 was 1 meter, then it's pi cubic meters. If it was 1 inch, it's pi cubic inches.

The really interesting thing about Gabriel's Horn, though, is that despite having a finite volume, the surface area of the "horn" is infinite. So think about it. It would take just pi units of paint to fill up the whole horn. But if you started painting the surface of the horn, however much paint you had—even a billion times as much—you would run out of paint before you had finished painting the whole structure. Now *that's* a paradox!

It is paradoxical because it seems incredible, yet it is a fact that falls out of the math—there is no doubt about the truth of the horn's paradoxical nature within the mathematical structure. I ought to say, in case the idea is nagging at you, that physically it would be a different matter. Remember that the horn gets narrower and narrower as it heads off to infinity. Before long (and when we're dealing with infinity, any specific number is before long) the horn would be so thin that you couldn't get a molecule of paint to stick to it. You couldn't physically manage to paint anything more than a finite portion of it. But mathematically there's nothing wrong with the statement.

As soon as we decide that we have made time travel possible, a whole host of paradoxes leap out of the woodwork. This doesn't mean that time travel isn't possible—they are purely paradoxes—but they do give us pause for thought when we follow through the implications that arise. Take, for example, the idea that having the ability to time travel enables us to create something out of nothing. Not just something as diffuse as energy, or as vague as “matter,” but an actual object or collection of information with structure and content. This ability is sometimes referred to as a closed causal loop.

Think of your favorite piece of music. With time travel, we can make that piece a phantom, a self-producing composition that sprang into existence fully formed without ever being written. The process works like this. Let’s say that your favorite is Ravel’s *Pavane pour une infante défunte*. You download a copy of the piano sheet music from a Web site and print it. (The piano version of the piece came before the orchestration, so let’s be purist.) Then you whisk the sheet music back to 1899 to the Conservatoire in Paris, France, where Ravel is studying under Gabriel Fauré. You slip that casually obtained sheet music under his door.

Ravel finds the music, and after marveling at the beautiful quality of the printing, he begins to hear the piece in his head. “This isn’t half bad,” he thinks. He needs a piece for his composition class and hasn’t managed to come up with anything. Perhaps he was out on a night on the town and hasn’t done his homework. So he quickly copies out the piece in his own hand and presents it to his supervisor at the Conservatoire.

At this moment, the *Pavane pour une infante défunte* has become a ghost, a piece of music that was never written by a human being. Ravel didn’t write it; he just copied it from the version you gave him. You didn’t write it; you just downloaded it from the Internet. And whoever put it on the Internet didn’t write it; he or she just copied it from a printed version that was (back a few generations) copied from Ravel’s handwritten “original.” It’s a loop in time for which there is no beginning and no end. This is a paradox, having more in common with Gabriel’s Horn than with the immovable object or the glass that’s empty and full. It’s just that once the loop is set up, no one wrote the piece of music. Probably the best way of looking at it is that an alternative Ravel in an alternative reality wrote the piece, before it was injected into the loop. But there is nothing here to cause us the logical concerns that point to a fallacy.

It’s possible to argue that setting up such a loop isn’t physically possible because it defies the second law of thermodynamics. A piece of music has lower entropy than a random set of notes. When the music is added to the universe, it would seem that the entropy of the universe is reduced, with no accompanying exertion of energy. In practice, however, for the loop to be set up, we needed to take the piece of music back through time, which would require more than enough expenditure of energy to counter the reduction in entropy.

The other problem with this example is that time machines didn’t exist (as far as we are aware) in Ravel’s day, and with all of the relativity-driven mechanisms this means we can’t get back as far as 1899. But that’s just a matter of choosing the right piece of music (or book or whatever created item you would like to inject into a time loop). As long as it’s a work that is produced after the time machine is constructed, this should be a practical thing to do.

Note that this isn’t a universal mechanism for creating anything you like with no mental input. It works only for artifacts that have already been created at the time in the artifact’s future when you decide to set up the loop. So, for example, if you wanted to use this mechanism to create a sequel to your favorite novel, it would work only if you started the process at a point in time when such a sequel had been written. Similarly, you couldn’t use this method to create a pocket nuclear generator, because a pocket nuclear generator doesn’t already exist. You can apply the technique only to something that exists now and has a clear point of origin within the range of the time machine.

There might seem to be another catch. What if Ravel had looked at the piece of music but had not liked it? Or perhaps he would be too principled (or scared) to copy what he would assume was someone else’s work and pass it off as his own. If you accept an unfolding-reality version of time this would be possible. And if that did happen, when you returned to the future you would find Ravel had no longer written *Pavane pour une infante défunte.* Either someone else would have written it, or it wouldn’t exist at all. You could be responsible for destroying your favorite piece of music.

However, in a block-universe model this couldn’t happen. Because the piece existed in the future, Ravel would have to have written it . . . because he did write it. In such circumstances, either he did copy it from the printout you supplied, or he ignored what you pushed under the door—perhaps never saw it at all—and just happened to write an identical piece. Unlikely, for sure, but not entirely impossible. When it comes to the original version, Ravel did write this piece at that time, in that frame of mind, so it doesn’t seem unreasonable that he could do so without your help.

The example of the Robert Heinlein story “All You Zombies” mentioned in the first chapter is another closed causal loop. In that story, the main character (with the help of both a time machine and multiple sex changes) is his own father and mother, so pops into existence with no historical cause. There is a subtle difference here, though. The “Zombies” character is a more satisfying closed loop than the Ravel music because there is only a single entity. With our sheet music there are many copies going into the future. The music will continue to exist after the moment you began your intervention. But the self-creating character in Heinlein’s story ceases to exist at the point of his/her final journey into the past. This is a being who exists only between the furthest point in the past where she/he emerged and the start of that final journey. Before and after those points in time the character has no existence. He/she is truly a closed loop.

So to the most dramatic, and most worrying, of the time paradoxes, killing a grandparent before your own parent is conceived. I'm not quite sure why it's a grandparent. It would be enough to kill a parent or even yourself at a young age. Perhaps it's because you didn't know your grandparent when he or she was young, so it is a less painful thing to do. Murdering a grandparent is the traditional way of representing this paradox, so let's go for it.

Note, by the way, that this is rather different from the scenario in the movie *The Terminator* and its sequels. In those stories, the aim is to remove an individual (John Connor) from the future, where he will be a major factor in the war against the machines. The cyborg Terminator is sent back into the past to kill Connor's mother (or in later movies to kill the young Connor). This would change the future and so from the block-universe viewpoint is paradoxical, but it doesn't involve Connor in killing himself or his own parents, so it isn't a traditional time travel paradox. (*The Terminator* does feature a *Pavane pour une infante défunte*–style paradox, though. The remains of the original Terminator, destroyed in the first movie, are used by the corporation that will eventually build the thinking machines as the inspiration for their products.)

So to explore the grandfather paradox in full, let's forget the Terminator and put you in the role of killing a grandparent. Perhaps you are an extreme scientist who wants to test the realities of time paradoxes, or perhaps you don't intend to kill your grandparent at all, but your arrival in the past triggers an accident that gets someone killed. You get in your time machine and head back to a time when your grandparents were alive, but your parents were yet to be born. Picking any grandparent—say it's your mother's father—you murder him (or accidentally cause his death). So now your mother won't be born. And that means that you won't be born.

Fair enough, but if you weren't born, then you couldn't go back in time and kill your grandfather. So your grandfather didn't die. So you were born. So you could go back in time . . . and on and on it goes. Here, certainly in the block-universe viewpoint, you have hit a logical inconsistency. According to that picture, the future is fixed—and you were in it. You both exist and don't exist. You seem to be in a state of quantum superposition.

Perhaps that is the only way to keep the grandfather paradox in a block universe. Somehow making the time trip allows you to enter a state of quantum superposition. Generally speaking, such a superposition doesn't last forever. After a while it will collapse into one of the two possible states. If you exist, then something will have prevented your undertaking the killing. If you don't exist, then your grandfather will have died in some different way and you never existed. You were just a ghost in the system.

In the “unfolding now” version of time, things are a little different. There a number of possibilities in this picture to explain the paradox. One is that by killing your grandfather you started a new path into the future, but it isn’t your future. When you return, your grandfather will still exist in your future. It will be as if nothing ever happened. Another possibility is that a new future will evolve, bringing with it a version of you that isn’t connected to your grandfather—so the person you killed wasn’t actually your grandfather.

Science-fiction stories often provide useful testing grounds for the logical contortions we face when dealing with time travel paradoxes. There are a couple of escape routes sometimes posed in science fiction that might help. In principle any change in the past could have huge consequences for the future. But it could be the case that some form of damping implies that whatever change you make will have run out of steam and won’t directly change your future, even though it may have a substantial impact on the world as a whole.

You could also envisage a mechanism where the grandfather paradox isn’t a loop. You go back and kill your grandfather, so you never existed. This means you never made the journey, and the moment you take the action, you snap back to the instant that you were about to travel. Every time you try to travel to the past and make a change that will make it impossible for you to exist, you find yourself back just before you made the journey. Your journey into the past will never begin.

This wouldn’t stop you from making *any* change, just those that would result in your not existing or otherwise not being able to make the journey in the first place. There is usually a logical escape from these time paradoxes, and I find this an entirely satisfactory solution to the grandfather paradox. Do something that prevents the “now” you started your journey in from existing, and your entire time journey unzips to the moment before you take the trip into the past. Time to try again.

The interesting thing in such a scenario is whether you would remember that this had happened or not. If you did remember traveling to the past, killing your grandfather, and then ending up back in the present before making your journey, you would be like the protagonist in the movie *Groundhog Day*. Bill Murray’s character is aware that he is living the same day over and over again, so he can learn from his mistakes and change his and others’ lives. Similarly, if you remembered your aborted journey into the past, you could change your tactics.

If you didn’t remember what had happened, however, there would be a much gloomier prognosis. Left at exactly the same point as when you first undertook the journey into the past, with nothing to indicate to you that you should change your plans, you would undertake exactly the same actions that flipped you back to your start point. It’s possible that some quantum fluctuations might change things enough that at some point you would escape, but otherwise you would be left in an eternal loop, forever flipping back to the moment when you made the same mistake over and over again.

The idea that history might reject the paradox and leave you back before you took the action is reminiscent of a concept that Stephen Hawking has suggested. This way that nature could conspire to avoid this kind of paradox is what he has called the “consistent histories” approach. Based on the “self-consistency principle” proposed by Russian physicist Igor Novikov, this says, in effect, that laws of nature would get in the way of any attempt to make a change in the past that would alter the future. It might be possible to travel into the past, but you would only be able to perform actions that resulted in the unfolding of history as you remember it.

So, for example, you could go back 65 million years in a time machine and wipe out the dinosaurs, because the fossil records seem to indicate that the dinosaurs did go extinct over a brief period of time around then. You wouldn’t be changing history. If, however, you left a big sign, made out of a material that would survive the 65 million years since the end of the Cretaceous period when the mass extinction event occurred, saying something like “I killed the dinosaurs,” either you would fail to get the sign in place or, despite your best efforts, it would never be found in the future. How do we know that? Because it hasn’t been.

The other possibility that Hawking mentions is the alternative-histories idea, the concept I have already hinted at by suggesting that killing your grandfather could start a “new path into the future,” an alternative version of reality existing, in effect, in a separate version of the universe. This can be tied in with the interpretation of quantum theory developed by Hugh Everett III, sometimes called the “many worlds” hypothesis.

Quantum theory is great as science. If you plug in the numbers, it works—in the case of quantum electrodynamics, the theory of the interaction of light and matter, it works with astounding precision, matching theory and experimental results to many decimal places. But for a lot of people it’s not enough to have a theory that works; you also need to have an explanation of what’s going on.

So, for example, there’s the Young’s slits experiment. This was the apparatus that first showed definitively that light was a wave. It was the idea of Thomas Young, a remarkable polymath who was a medical doctor, made the first translation of Egyptian hieroglyphics, gave engineering the concept of elasticity, and produced mortality tables for insurance companies.

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Born in England in 1773, Young was something of a prodigy, teaching himself to read at the age of two (his parents didn’t realize he could do so until he asked for help with some of the more difficult words in the Bible). By thirteen he was fluent in six languages and could converse in several others. He was never a dedicated physicist, yet he had a strong interest in natural science, particularly in light, and for Young, it seemed that having an interest was enough to make him something of an expert.

In 1801, Young devised the slits experiment to finally lay to rest Newton’s idea that light was made up of particles. Young shone a narrow beam of light onto two slits cut into a piece of card, allowing the twin beams of light to intermingle and pass through each other before they fell on a white piece of paper. The result was a series of light and dark fringes projected on the paper. Young argued that, just as water waves from two sources interfere with each other, as some ripples cancel out and some reinforce each other, so the waves of light were interfering with each other, something that couldn’t happen if light were made up of individual particles.

This was fine, until quantum theory came along. Quantum theory pictured light as a series of quanta—in effect, particles. And still the slits experiment worked (it was hardly going to stop working just because a new theory came along). What’s more, as technology improved, it became possible to send photons of light through Young’s apparatus one at a time. There shouldn’t be anything for these individual photons to interfere with—yet the interference patterns still built up, just as if multiple waves were passing through the slits. And the same effect could be achieved with other quantum particles like electrons.

The traditional explanation for the appearance of an interference pattern with individual photons is a hand-waving one that says that somehow each particle is passing through both slits at once and is then interfering with itself. Quantum theory allows such particles to be in a “superposition of states”—until they are observed they don’t go through a specific slit; they go through both of them, allowing the pattern to be built. If you ever check which slit a particle goes through, forcing it into a single state, the interference pattern disappears.

Hugh Everett was an American physicist who spent most of his career working in the field of operations research (OR). This was a discipline developed in the Second World War to apply math, particularly probability and statistics, to complex operational problems. OR would be used, for example, to decide which pattern of depth charges would be most likely to destroy a submarine. Everett’s expertise with probability proved valuable in getting a grip on the probability-driven quantum theory. Everett speculated that the on the probability-driven quantum theory. Everett speculated that the conventional interpretation of what was happening to individual particles in Young’s slits was wrong. He believed that there were many different parallel realities, and this was being revealed in the experiment.

In some realities a particular particle would pass through the first slit; in other realities it would pass through the second slit. The interference pattern arose because there was interference between these different realities. This helped explain one of the puzzles at the heart of quantum theory. Quantum events have probabilities, but any individual particle behaves randomly with that probability. How does an atomic nucleus decide to decay at a particular moment? How, in a beam splitter like a window at night, does one photon decide to pass through while another is reflected?

In Everett’s many-worlds picture, the various quantum states don’t somehow choose to collapse into particular values when an observation is made (leaving the question as to how they “choose” those values); instead, all the possible values exist in parallel in different universes, and we just happen to experience a particular one. This still leaves the question of why we experience that particular reality, but this doesn’t seem to have been a worry for Everett.

If you accept Everett’s many-worlds hypothesis, which a minority of quantum physicists continue to do in a very vocal fashion, then it’s arguable that there isn’t a problem with going back and killing your grandfather. The many-worlds enthusiasts will tell you that in killing your grandfather you have flipped into an alternative universe. In your own universe, the one where you still exist, the killing never happened. So when you return to the future, your grandfather will still be alive.

With this picture, there is no paradox, nothing to sort out. But many would argue that the many-worlds hypothesis isn’t really science, just speculation. It certainly doesn’t hold up well against Occam’s razor, the rule of thumb that says when all else is equal we ought to go for the simplest explanation. There can be few more complex possibilities than the idea that the universe splits into two for every possible quantum decision ever made.

Others contemplating the confusion caused by the grandfather paradox have resorted to billiard balls to find a solution. There is something rather endearing about the way physicists tend to return to simplicity in this way. It’s reflected in an old joke that’s a great way to find out if you have any scientists in the audience. They’re the ones who will really find this funny.

> Three people—a geneticist, a dietitian, and a physicist—are trying to work out how to produce a winning race horse. The geneticist says, “Obviously we need to breed from previous winners, selecting for the characteristics that will enhance fast movement.” The dietitian can’t agree. “No, no,” she says, “it’s all about producing the correct balanced food intake.” The physicist has been

> listening to this with interest. “Hmm,” he says. “Let’s assume the race horse is a sphere. . . .”

In the case of the grandfather paradox, the physicist who said, “Let’s assume the grandfather is a sphere,” was Joe Polchinski, professor of physics at the University of Texas in Austin. The problem with the grandfather paradox we generally come across is that it involves humans and contemplation of the nature of free will. That makes it difficult to separate the physics from the decision making. As Kip Thorne puts it, “Now, even in a universe without time machines, free will is a terribly difficult thing for physicists to deal with. We usually try to avoid it. It just confuses issues that might otherwise be lucid.”

Polchinksi set up a thought experiment using billiard balls and a wormhole that can produce a simplified version of the grandfather paradox. He imagined a very short wormhole hovering handily just above the surface of a billiards table. We hit a ball across the table so that it enters the “future” end of the wormhole and exits from the “past” end a second or so earlier. We have set up the experiment carefully so the timing is just right for something very strange to happen. The ball comes out of the wormhole at an angle. It travels across the baize from the wormhole and collides with the earlier version of itself, which is currently heading toward the wormhole. The version of the ball that has been through the wormhole knocks the earlier version of itself off track, so it no longer enters the wormhole.

So now we’ve got a ball that stops itself from going back in time, so it isn’t there to defect itself, so it does go back in time, so it defects itself so that it doesn’t go back in time . . . and so on. We have an alternative to the grandfather paradox, but one where we can use the simple laws of motion to monitor just what is happening without any messy emotions and considerations of free will entering the picture.

Kip Thorne and his colleagues were fascinated with the billiard ball model Polchinksi had produced and soon found an escape clause. Just imagine that instead of the ball that has passed through the wormhole hitting the younger ball so hard that it never gets into the wormhole, it strikes it only a light glancing blow. This has a minor effect on its trajectory, but not enough to stop it from entering the wormhole and traveling into the past.

The ball will then emerge from the wormhole in a slightly different way—and as a result it *will* strike with the light glancing blow, rather than the knockout blow of the earlier grandfather paradox. Thorne’s team had come up with a remarkable result. Using *exactly* the same initial conditions—there was nothing experimentally different about the second scenario from the first—they had turned the grandfather paradox into a totally logical occurrence that doesn’t result in a breakdown of reality as we know it.

What they were suggesting was that in reality, if you undertook the experiment with the billiard balls, the outcome would always be the second one. If you hit the ball in such a way that it came back out of the wormhole and hit itself, it would take the route that resulted in its being logically consistent and would continue to enter the wormhole. There would be no paradox.

Thorne and his team were elated. But not for long. For they soon realized that there wasn't a single route that would work with the laws of physics. You could, for example, produce a route that tapped the front right of the younger ball, or that tapped the back left of the younger ball. In both cases everything would work out precisely to deflect the ball in a way that would not stop it from entering the wormhole. Either of these scenarios was entirely possible according to the laws of classical physics.

In quantum physics, we are used to different outcomes occurring according to probability, but not in classical physics. By introducing the wormhole, we could start the experiment twice with absolutely identical initial conditions, give the ball exactly the same shot from the cue, and yet have a totally different combination of moves to produce the same outcome. We can no longer predict how the ball will behave, given its initial position, the momentum it gains, the details of its environment, and the parameters of the wormhole. There are two equally possible outcomes.

Thorne soon realized that things were even worse. Although his students had set up a situation with just two possible outcomes, he devised a simple experiment with an infinite set of outcomes. Imagine a ball that, without the intervention of a wormhole, would just go in a straight line between the mouths of the wormhole. For simplicity we imagine the mouths facing each other along a line that crosses the ball's route perpendicularly.

Now, with the wormhole in place, it seemed at first that there were two possible trajectories. Either the ball could simply pass between the mouths, or it could emerge from the "past" mouth at right angles to its original trajectory at just the right time to knock itself into the "future" mouth. After the collision, the ball that had traveled through the wormhole would be diverted by the collision to head on in roughly the original ball's path.

However, another physicist, Robert Forward, pointed out to Thorne that there was not one, but an infinite set of such possible interactions, each having the two balls traveling at a different angle with respect to the original trajectory. Every single one of this infinite set of interactions was possible from the original conditions given standard, classical physics.

As Thorne puts it, "One is left wondering whether physics has gone crazy, or whether, instead, the laws of physics can somehow tell us which trajectory the ball ought to take.” As a solution, Thorne decided the only option was to stray into quantum physics. Here, we can imagine a ball—like a photon “deciding” whether to pass through a piece of glass or reflect off the surface—having a probability of taking each of the possible routes. In any one experiment it will take one of the routes, but overall the probabilities will rule.

It seems that a time machine may have the potential to make large, tangible objects act in a quantum manner, which in itself raises some eyebrows. It is not entirely satisfactory just to say that the billiard balls act as if they were quantum particles, because all our experience is that large objects don’t act this way. We normally find that statistically, the random quantum behavior of the individual particles evens out, reducing probability to apparent certainty. However, we have to face up to the surprising conclusion that time machines may extend quantum behavior to the macro world.

This isn’t totally without precedent. Arguably, for example, a laser takes a quantum phenomenon and uses it to change the way a light beam acts in the large-scale world we observe. Perhaps we have to regard a time machine as a sort of matter laser, a mechanism that takes quantum processes up to the observable level.

In a more general attempt to avoid paradoxes, Hawking and others have also suggested that there could be a physical law called the chronology-protection conjecture, also known as the causal ordering postulate (it is given that clumsy name so it can be referred as the “time COP”). This is slightly different from the consistent-histories approach in that it suggests that nature would conspire to avoid using relativity to change the order of two events with a causal link. If an earlier event causes a later one, the time COP says, you can’t use clever manipulation with relativity to change it around so that the second event comes before the first.

Imagine a very simple paradoxical device. We don’t need to have anything so complicated and perverse as going back and killing your own grandfather. Imagine that you have a radio transmitter that sends a message to a receiver that operates a control to turn the original transmitter off. The cause-and-effect link is there—sending the signal has the effect of turning off the transmitter. And the order is clear. First the transmitter sends the signal, then the transmitter is turned off.

Now let’s imagine that we use one of our relativistic time travel mechanisms to send that signal back just 0.1 seconds in time. This is the sort of thing you might imagine emerging from one of the technologies we’ve seen described. By keeping the time shift small, we make it a lot more practical. It’s not enough to win the lottery, but it is enough to test the time COP. And we don’t need to send anything physical through, just a signal, so we have the widest range of possible time travel technologies available.

Let’s set up our imaginary transmitter so it can be switched on and off by the radio signal it generates. Okay. Switch the transmitter on and send a “switch me off” signal back 0.1 seconds into the past. So 0.1 seconds before you originally sent the signal, the transmitter is turned off. But if it’s turned off, it can’t have sent the signal. So it’s still switched on. But if it’s turned on it could have sent the signal . . . and so on: a simple causal paradox of the kind we’ve already met.

If the time COP holds true, every time you tried to build the signal, something would go wrong. You would never get the transmitter working. Or the switching mechanism would fail. Or if you did manage to send a signal through and the switch was working, something else would go wrong at the moment that you tried to send a signal back. Perhaps there would be a sudden burst of static that disrupted the transmission. According to the time COP, something would always get in the way.

Some people have even suggested that this implied that the Large Hadron Collider at CERN could be a potential time machine. When the vast collider was first switched on there was a disastrous failure that prevented it from working for at least another year. Could this have been the time COP in action, preventing possible time paradoxes from being set up in the LHC? As it turned out, no, as in 2010 the LHC became fully operational without further problems.

The LHC is a red herring—there is no obvious way that at this stage of its operation it could be a time machine, although the possibility of its creating tiny wormholes (see page 216) might allow the COP to come into action in the future. Hawking’s postulate would be a neat way out of the time travel paradoxes. However, it ought to be stressed that this isn’t a scientific theory. There is no physics behind it. It’s just a hunch that Hawking and others have put in place to get around the difficulties that arise from the paradoxes. They believe it feels right, but don’t have the scientific justification to back it up.

Even if the time COP exists, it won’t prevent all time travel. It merely specifies that if two events have a causal relationship—the first event causes the second, like the signal causing the transmitter to switch off in my example—and if these events come in a particular order, then the first event will always precede the second, for all observers. It doesn’t matter how they have moved with respect to each other or what relativistic effects kick in; the first will always remain the first.

The COP doesn’t prevent the order of events from being switched if they aren’t linked in any way. Relativity is allowed to swap which is first and which is second if they are unconnected. But as soon as one causes the other, their order in time is fixed. (As long as they are in the right order, the time difference between them can vary. The basic relativity-of-simultaneity idea still holds that moving with respect to something will change your idea of when events occur, but won't change the order of cause and effect.)

More surprisingly, the COP doesn't stop a cause coming before an effect. If, somehow, it were always true in a particular circumstance that, say, a light came on before you threw the switch to make it happen, then the COP says this is fine—but it will remain the case however you mess around with relativity. In practice, of course, in the normal world without special manipulation, cause always does precede effect, so the time COP keeps the status quo and says that this will remain the case.

Stephen Hawking has suggested one way that the COP could work. He envisages that the warping of space-time implied by time travel will result in some of the virtual particles that are constantly forming and disappearing according to quantum theory becoming real. He envisages these particles repeatedly passing in a loop through the same point in the same time, building up energy until their presence is enough to curve space-time in the opposite direction and counter the ability to time travel.

If this is true, setting up the conditions to be able to time travel will cause interference in the ability to time travel—so it will never be possible to make a time journey. This is, in essence, the same feedback loop that we saw might be possible with a wormhole in chapter 11. However, there are a lot of ifs and buts here with no detailed physics. The postulate is possible but not hugely plausible. As Hawking says, “The possibility of time travel remains open.”

In the end, the time COP is just the physicists' way of saying, “This is how things ought to be.” It just doesn't make sense that we could swap effect to come before cause. It doesn't seem right that we should be able to kill our own grandfather, or build a device that can switch itself off before it sent the signal to switch itself off. But science isn't about what seems right—it's about how well the theories we have match experiment and observation, and sometimes the outcome is nothing like common sense. Richard Feynman is often credited with saying (though no one seems quite sure where and when), “If you think you understand quantum mechanics, you don't understand quantum mechanics.” It may well be that something similar applies to the manipulation of time.

It has been suggested that a time machine could be used to provide an easy get-rich-quick device. It works something like this. You get hold of an expensive diamond. You wait a bit, then take your diamond back in time and give it to your earlier self. (As an added bonus, your earlier version gets to meet the future "you.") Now you've got two diamonds. You can do this as many times as you like, doubling up your diamonds. Riches beyond your wildest dreams! This is rather like the closed causal loop we envisaged creating Ravel's *Pavane pour une infante défunte,* but here the loop returns to a point alongside itself, so we end up with two copies of the music.

An immediate reaction is that such matter duplication contravenes one of the most fundamental rules of physics, the conservation of energy, or more specifically the conversation of mass/energy, since we know from Einstein's formula that mass and energy are interchangeable. At the point in the past where we accumulate diamonds, we end up with more mass in the universe than when we started. But in practice, all we have done is transport mass from one point in the space-time continuum to another, something that isn't restricted by the conservation laws. If you take in the picture across all of space-time, you might be adding a diamond into the past, but it is ceasing to exist in the future. What's more, to be able to undertake that transfer, we will have to put enough energy into the system to ensure that there are no inconsistencies.

Unfortunately, even if there isn't a conservation problem, there is a fatal flaw in this approach as a way of accumulating wealth. Leaving aside the fact that the loop is constantly changing the past, which then changes the future, and so on—so the trick may be prevented by the sort of mechanisms we've already looked at—you can never spend your newfound wealth.

As soon as you convert your diamonds to cash you no longer own them. If you don't own them, you can't take them back into the past . . . and if you have already taken them into the past, you no longer have them to turn them into cash. The loop falls apart. This process works only for the ultimate miser, sitting on his looped stash of treasure and never letting it go (at least until he reaches the moment when he has to take the treasure back to its point of origin). If the mythical dragon with its hoard of gold and jewels existed, this would provide an ideal mechanism—but it doesn't do a lot for normal human beings.

There are many paradoxes that arise once time travel is possible. Some are entirely internally consistent and can be lived with, a bit like the paradox we are presented with by quantum theory when it tells us that a photon of light can pass through two different slits simultaneously and interfere with itself. Others seem likely to cancel themselves out before they can be a problem. So if there is nothing that truly gets in the way of time travel (apart from being able to build the technology), is it a real possibility? Will time travel always be a fantasy, or will it be something that future generations will experience?

CHAPTER FOURTEEN

FACT OR FICTION?

> *Genius and science have burst the limits of space, and few observations, explained by just reasoning, have unveiled the mechanism of the universe. Would it not also be glorious for man to burst the limits of time?*
>
> —Georges Cuvier (1769–1832), *Recherches sur les ossemens fossiles,* trans. R. Kerr (1812)

So far we have achieved a form of time travel in the laboratory that results in so small a shift that it can’t be used. We can journey into the future using relativity, but with our current technology it would take too long to make a worthwhile time slip. Quantum entanglement gives us a mechanism that can link back through time but that can’t carry a message. And the other possibilities for time travel await technological developments that are far beyond our present capabilities.

While Ronald Mallett’s time machine has the potential to bring a measurable time shift to the lab within a decade, as yet we have to be satisfied with accepting that there is nothing in physics that makes time travel impossible and that there is every chance to achieve it for real in the future. That doesn’t mean, though, that no one has ever claimed to have built a time machine. There are plenty of individuals who have proudly announced that the secrets of time are already theirs.

We saw (page 171) how the physicist Nikola Tesla believed he had slipped outside time in the 1890s, using powerful electromagnetic fields to distort the fabric of time. A number of others have since claimed to have achieved real time travel usually by the application of extreme electrical and magnetic fields, though few of these individuals have had Tesla’s scientific and engineering credentials.

Perhaps the best known of these modern contenders for the time travel crown is the Russian Vadim Chernobrov, who claims that a device he has built with a whole series of nested superconducting electromagnets has succeeded in making time slow in a small chamber by as much as forty seconds a day. Chernobrov is also described as a UFOlogist, and though his technology is more impressive than the weird and wonderful ideas of many of his competitors, this still remains very much a fringe activity without accepted scientific backing or verification.

If Chernobrov's time chamber really does make time flow at a slower rate, it is interesting, and would enable some useful experiments to be done, though the nature of the device, even if it did function, makes it less useful than many for practical time travel. First, it's a device for traveling into the future. The implication of having a clock inside the device that runs slow is that time outside the device is running faster than on the inside. So when a traveler emerged from the device she would find that she had jumped into the future.

However, this is the one form of time travel that is relatively easy to do. We all travel into the future naturally, and we can use relativity, whether it is the general-relativity impact of heavy bodies or traveling at high speed, to make small shifts in time in this direction. We may not yet have achieved forty seconds in a day, but it is entirely feasible—and hardly a useful vehicle for traveling into the far future. In a subjective sense, a good night's sleep gives a much bigger time jump than such a device.

A quick search online will bring up devices with names like "hyperdimensional resonators" and "bioenergizers" being sold on the Internet for the do-it-yourself time traveler to get started in fourth-dimensional action. Usually costing a few hundred dollars, these machines tend to come with a warning that the technology doesn't work for everyone. Their inventors may be entirely genuine—but these remarkable boxes are sold in a very similar fashion to fake medical devices, whose makers claim their technology is based on quantum fields or electromagnetic forces. Any result is more likely to be in the mind of the purchaser than in the real, physical world.

There have also been a number of individuals who have claimed to be time travelers from the future, but they have suffered from a variant of UFO vagueness syndrome. People who have studied UFOs and alleged alien visits to the Earth point out that it seems very strange that after so many supposed sightings and abductions, we still don't have decent images of UFOs and aliens—we're always reduced to fuzzy images of lights. We don't have a single "alien" artifact that wasn't in fact produced on the Earth. And whenever anyone claims to have spoken to aliens, he always seems more interested in discussing world peace and inner feelings than in telling us a single bit of science we don't already know.

Similarly, the self-proclaimed time travelers somehow never manage to bring back information from the future, like a prediction of a major world event, or a clear description of the next president but one, or knowledge that can be commercially used, all possibilities that would add credence to their claims. Perhaps the best-known example, calling himself John Titor, claimed to have traveled back from 2036 to 2000 (or possibly 1998).

Although Titor, unusually, did describe his technology in some detail, there were serious problems with this, most notably his apparent ignorance of the inability of such a time machine to travel back to before it was first built. He also made several predictions of "historical" events that failed to come to pass.

It's hard not to see such people as either practical jokers or delusional. We need to separate these backyard "working time machines" and "time travelers" from the very real scientific claims for the possibility of building a time machine that are based on current physics.

The same holds true for a range of conspiracy theories that claim the U.S. government—or some secret shadow government that pulls the strings—has already developed time travel technology and is using it to control the world. A number of these stories center on the Montauk Air Force Station on Long Island, suggesting that experiments in the second half of the twentieth century produced a working time tunnel. Yet, as we have seen, the technology to make time travel possible is still far from being developed. This is fantasy.

Just how practical time travel will ever be remains open to question. There is no doubt whatsoever that modern physics makes time travel theoretically possible. Admittedly, there could be flaws in the basis for time travel. Einstein's relativity and the intricately tested details of quantum theory could turn out to be entirely wrong. But that is highly unlikely, and on a small scale we have good evidence for the way that both special relativity and general relativity do modify the flow of time. More reasonably, time travel could prove to be theoretically possible but practically impossible in a useful timescale. "Don't hold your breath" seems like sound advice.

Personally, I am inclined to be optimistic. Just think of the way that technology has been developed in the last hundred years or so. The first practical internal combustion automobile was built in the 1880s. It's not much more than a hundred years since the first flight at Kitty Hawk in 1903. We didn't see PCs until the 1970s, while the general public has had less than twenty years on the Internet.

I see no reason why we couldn't have developments within the next one hundred to two hundred years that put practical time travel in the cards. I think it is unlikely to happen in my lifetime, but it wouldn't surprise me if my children see the first tiny experimental steps. I am not thinking of a device we could step through into the past, but perhaps a machine in the lab that could send a signal back in time by a sizable fraction of a second. I could be horribly wrong, though.

Future gazing (without a time machine) is notoriously difficult. Perhaps those tiny wormholes will emerge at CERN next year. Perhaps time travel will remain forever an elusive dream.

To consider the potential impact of a time machine if it were ever built, we could do worse than consider some of the issues, problems, and opportunities raised in science fiction. This approach does need one health warning, though. It is totally misguided to suggest that science fiction provides us with a way of predicting the future. Most of the time, science-fiction writers get the future, and future technology, horribly wrong.

Take Arthur C. Clarke. He is often feted as the ultimate example of a science-fiction writer who foresaw the future, famously writing about geostationary communication satellites before they existed. I think Clarke had great imagination and technological spirit—but his fiction gives no better guidance to the future than anyone else’s. Yes, he predicted a form of communications satellite, though to be accurate, this was in a nonfiction article. We shouldn’t forget, that he also showed a manned probe to Jupiter being built in 2001, along with a self-aware computer. Not to mention having the airline Pan Am operating commercial shuttles to a vast space station in the same year.

If you talk to those who write science fiction, very few claim that they are especially gifted at predicting the development of science and technology. What they aim to do, rather, is explore the way human beings are likely to react to different technological advances. Science fiction is about imagining human responses to the issues and difficulties posed by science and technology, not about foreseeing the future.

This isn’t a disadvantage here, though. We already know about the science—it’s the human reactions that make science fiction’s take on time travel well worth reading. We have already seen some of the paradoxes that can arise from time travel portrayed in science fiction, but one of the earliest problems that writers recognized would face the time traveler was the difficulty of a time machine materializing in a space that is already occupied by a physical object.

It would be more than embarrassing if your time machine appeared in the middle of a brick wall, or buried deep in a mountain. Leaving aside the difficulties of getting out if you were surrounded by stone, there are the implications of putting your atoms in a relationship to other atoms that they would not tolerate.

The chances are, if a time machine were to materialize interlaced with a solid object, that there would be immense forces at play attempting to move the atoms to a more acceptable position. The time machine (and the object) would be vaporized. For this reason I have seen it said that “time machines would have to fly to avoid materializing inside an object in their path in the past."

In reality, flying isn't going to be a lot of help. It might prevent the traveler from appearing in the middle of a chunk of rock, but he will still appear in the atmosphere. What happens to a nitrogen molecule (say) that is in the middle of your flesh when you materialize? Will it be forced out of the way, or will your body appear around it, embedding gas molecules and potentially causing fatal damage to your body's structure? Could atoms materialize so close to atmospheric molecules that they initiate nuclear fusion?

H. G. Wells in *The Time Machine* was the first to consider this (as he did so many of the implications of time travel), when he thought through the problem of traveling through solid objects. According to his time traveler, when his device was in motion there wasn't a risk, because "so long as I travelled at a high velocity through time, this scarcely mattered; I was, so to speak, attenuated—was slipping like a vapor through the interstices of intervening substances!" But when he came to stop he was aware that he could cause an explosion, as he was jammed into something solid.

In the end the traveler simply takes the risk and goes for it, surviving a decidedly bumpy materialization. In practice, a real time machine is more likely to be used in space than on the surface of the Earth, which reduces the risk of interacting with matter, even if it doesn't remove it entirely. But more significantly, the whole problem of "materialization" is one that comes from a fictional rather than a realistic time machine.

When a fictional time machine like the Tardis in the TV show *Doctor Who* materializes, it gradually appears, fading into reality. At one point in time we have space that is not occupied by the machine, a few seconds later it is there . . . and in the intervening seconds it gradually takes on solidity. This is a naturally risky approach. But pretty well every time machine based on real physics involves movement in time and space. It doesn't simply materialize in a place; it moves through space-time into that position. The travel in time is accompanied by a movement in space. The result would seem potentially less risky.

To the observer on the receiving end, the time machine would not appear out of nowhere. There would be none of the gradual materialization. If it were coming from the past, the ship would be seen approaching—if it came from the future it would suddenly be there with no gradual emergence.

We also ought to consider just where the point of emergence is going to be. Bear in mind that the Earth does not sit fixed in space. It is hurtling around the Sun, which is rotating around the Milky Way galaxy, which is moving away from the other galaxies (with the exception of one or two near neighbors like the galaxy in Andromeda, with which we are heading for a collision in a few billion years). So when we step back in time, will we arrive in a different location with respect to Earth?

It really depends on how the time machine itself is pinned down. For example, if you are traveling through a wormhole, it may be possible to tow the exit of the wormhole along with the Earth—meaning that it won't drift away from the planet over time. The same could be done with a cylinder-based time machine, while Ronald Mallett's frame-dragging mechanism will travel happily along with the Earth through its orbit.

In practice there is no reason to assume that a time machine would have some concept of absolute positioning—that it would somehow deposit you at the same "fixed" point in space that you departed from. Since Einstein's day we have not been comfortable with the concept of a fixed point—everything is positioned relative to something, and there is no reason why a time machine wouldn't operate in such a fashion.

Science fiction is also littered with get-rich-quick schemes based on time travel. We have already seen the difficulties of duplicating diamonds this way. A traditional alternative is the "compound interest rules the world" approach. In this you take a valuable commodity—say a bar of gold—back into the past, or you take with you some money from the period you are traveling to. You then invest your wealth in the past, flip back to the future, and make a bundle because what started off as a small amount will have ended up as a fortune.

Whoever thought of this scheme seems to have forgotten the impact of inflation and stock market crashes. Simply having money in the bank earning interest doesn't guarantee you a long-term fortune. A more practical scheme is either taking back an item that hasn't been invented yet (or just inventing it yourself in the past) or making use of some other form of foreknowledge from the future.

Assuming that a type of chronology protection doesn't get in the way, you should be able to make a tidy bundle by selling more advanced products than are generally available. Early in its lifetime, a product typically makes a lot more in absolute money terms than later on. When HP first brought out a pocket scientific calculator in the early 1970s it cost nearly $400. Today a calculator with similar capabilities can be bought for perhaps $20. There's an obvious opportunity for financial benefit here.

If chronology protection was an issue, you could just make sure you were the inventor of a well-known product, using the name of the person who is in the history books. Or if you didn't want to go to so much effort, it would be simple enough to use your future knowledge to make money. The basic approach would be to go back with details of winning race horses or lottery results and win by betting. Or you could be more sophisticated. Find out which artists from the other end of the time link are going to be big sellers in the future, go back and buy a few of their works cheap while they are in the starving stage (or buy first editions of rare books), and reap the benefits.

Of course there is a big flaw in the whole “make money out of time travel” genre. Once time machines exist and are generally known about, society will begin to make allowances. Bearing in mind that relativistic time machines will only travel back to the point where they were first constructed, the general public is likely to be aware of their existence at any point in the past you can travel to, with the possible exception of the first few weeks after construction.

Those wanting to make an easy buck out of time travel will not have long before, for instance, those involved in lotteries become aware of the problems caused by time travelers and change the way they sell tickets. If all the tickets had a randomly selected set of numbers, it wouldn’t matter if you knew the winning number in advance—you couldn’t choose to buy a ticket with that number on it. Betting on events, whether horse races or football games, would die out.

The same would probably apply to the stock market. Buying and selling shares and running hedge funds are forms of betting on the future. If the outcome was already known, the mechanism would collapse. It would still be possible to buy shares in a company, but the pricing would have to be fixed. However, all such considerations depend on the future as predicted taking place. As we have seen from the various paradoxes, it is possible that by bringing information back into the past we would change the nature of reality in a way that the prediction of a lottery number or a stock price changes the future, making it impossible to profit from the knowledge.

A common theme in science-fiction time travel is the idea of a group or organization whose role is to keep the timeline clean—to ensure that any tangles caused by time travelers are untangled to restore the original reality. In practice, such an organization seems highly unlikely. Apart from anything else, with many interpretations of time travel paradoxes, it is difficult to know what the “true” version of reality would be. But this doesn’t mean that those whose businesses could be ruined by a malicious time traveler wouldn’t take action, like the randomized lottery tickets, to avoid misuse.

Most stories of time travel leave us in an ethical vacuum where the time traveler can do as he or she pleases—but we know that in the real world of science things are very different. When science has major implications for human life, such as the medical use of stem cells, there is usually a very strong regulatory framework to ensure that its use is carefully controlled.

Time travel technology is not something an amateur can cobble together in the garage. When it does become possible, whether through Ronald Mallett’s approach or with the more advanced technologies that are way beyond our present capabilities, it will involve high-profile science, subject to checks and safeguards. The ethical implications are likely to be examined every step of the way and to play as large a role in decision making about time travel as is the difficulty of building the technology.

It is hard to resist playing with the implications that time travel would have for our lives. The border between science and science fiction is littered with near-possible technology. There are matter transmitters and faster-than-light drives, force fields, deadly rays, and time machines. These ideas have proved useful additions to the science-fiction armory for two reasons.

The first is that they open up a new frontier. It’s a very human thing to be unsatisfied with what we have and what we know at the moment. We are always looking for the chance to discover, to explore, to be first somewhere new, whether intellectually or physically. As General Clark realized when he held up faster-than-light travel as a goal for the American people, we need a new frontier to explore.

By its nature, the universe is on a scale that simply isn’t accessible using normal human transport. Much of the future technology portrayed in science fiction is envisaged as part of the toolkit necessary to take on the universe—to explore beyond our solar system or to colonize a distant world. We need the faster-than-light drives to reach our destinations, force fields to protect against debris and radiation, beam weapons for protection, and more. Similarly, a time machine has a dual role in opening up new frontiers. Its linkage with faster-than-light travel puts it at the heart of physical exploration, but surely also there can be no more exotic and exciting frontier than venturing out of the present, into the past or future.

The second reason that exotic, near-possible technology features so often in fiction is less as an enabling technology and more as the heart of the story. We see, for instance, stories that explore the moral issues of using a matter transmitter that kills a human being and makes an identical duplicate. But no other extreme technology has as much power to fascinate as that of time travel.

There are the paradoxes, the mind-bending oddities, of the way time travel can play with the certainties of cause and effect. But even more important, there is the opportunity to explore something that we experience every day and yet still find deeply mysterious. Who hasn’t thought, “If only I could go back in time and . . .”? Who hasn’t, with Ronald Mallett, wanted a last chance to speak to a loved one, or wondered what it would be like to travel into the future and see the technological wonders of the twenty-fourth century? Along with Augustine of technological wonders of the twenty-fourth century? Along with Augustine of Hippo we can say, “What, then, is time? Provided that no one asks me, I know. If I want to explain it to an inquirer, I do not know.”

Time travel provides a delight that the feats of no other near-possible technologies bring. What’s more, despite its apparent inaccessibility, we now know the many ways that physics can make time travel theoretically possible, if not yet practically feasible. For many years, physicists regarded time travel as a preoccupation of cranks, on a par with discovering the lost civilization of Atlantis or chatting to a Venusian. But no longer.

Time travel is real. On a small scale we can do it today. Should the human race survive long enough, it seems an almost inevitable part of our future. And if that doesn’t inspire a sense of wonder, nothing will.

In the end, only time will tell.

AFTERWORD

Shortly before this book went to press headlines about time travel echoed around the world. They spoke of neutrinos at the CERN laboratory passing the light speed barrier and shattering Einstein’s special relativity. As we have seen, neutrinos are particles produced in nuclear reactions that are almost impossible to detect. In the CERN experiment (which did not involve the Large Hadron Collider), neutrinos were sent down a 732 kilometre tunnel, and the timing of their arrival at the far end was out by a matter of 0.00000006 seconds, making it seem that they went very, very slightly faster than light. This is the evidence that was presented as damaging relativity, and that has produced statements like this from the BBC:

> The speed of light is widely held to be the Universe’s ultimate speed limit, and much of modern physics–as laid out in part by Albert Einstein in his theory of special relativity–depends on the idea that nothing can exceed it.

These results are, without doubt, interesting, but not earth shattering. The chances are still high that this is experimental error. Although the experiment has been repeated it still used the same equipment and location. The experiment would only have to get the length of the beam wrong by a tiny amount, for example, for the whole thing to be a mistake. Another group of scientists have already shown some evidence that suggests that these neutrinos could not be travelling faster than light. And there is further evidence in a different experiment, comparing neutrinos and light from a cosmic source, where there is no such disparity–so there is already contradictory evidence.

However, even if the outcome is true, and these neutrinos did get from A to B faster than light, the BBC’s version is simply wrong. Modern physics doesn’t depend on nothing exceeding light speed. Special relativity is certainly the basis of much modern physics, but light speed being a limit is a consequence of that theory, not a starting point. In fact we already have well established experiments in which particles travel faster than light speed in which particles travel faster than light speed.

This is a consequence of the quantum mechanical tunnelling we met in chapter seven that was demonstrated by Professor Nimtz. All the evidence is that there is zero tunnelling time with such phenomena. A tunnelling particle literally doesn’t travel through the space it tunnels through. So if you imagine a particle going 1 centimetre at the speed of light, tunnelling 1 centimetre instantly and going a further centimetre at the speed of light, it will have traversed the entire distance at 1.5c–one and half times the speed of light.

This may not be exactly what is happening in the neutrino experiment, but if it wasn’t experimental error, I do imagine it is going to be something similar. Not a collapse of special relativity, just a way around it. Special relativity has been tested so many times and has always delivered. It is demonstrated in experiments every day. Neutrinos travelling marginally faster than light would be truly fascinating, but won’t overthrow the science described in this book.

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