PART III

Frontiers

CHAPTER 17

Faster than light: was Einstein wrong?

Peaceful coexistence

For a hundred years, physicists trumpeted the celestial speed limit. Einstein has shown, they said, that nothing travels faster than light. But for a generation now, there has been stunning experimental evidence that hints that some mysterious influences are travelling faster than light.

Contemporary physics rests on two great pillars. Einstein's theories describe the large-scale structure of space and time. Quantum theory describes the small-scale behaviour of matter within space and time: the behaviour of molecules, atoms and other particles. Roughly, one describes the container, and the other the contents. Although research continues, the two traditions are so much at variance that no one has been able to combine them into a single, unified theory or "theory of everything". Quantum theory emerged piecemeal over many years and its development was driven by experimental results and mathematical guesses. Like most committee efforts, quantum theory was a patchwork of conflicting motivations and strategies. There is one central obstacle to unification: even today no one really understands quantum theory.

For many years, relativity and quantum theory led a peaceful coexistence. The mysteries of quantum theory were dramatized by a series of paradoxes, but the theory worked very well and never threatened to contradict and overthrow its rival. But now things are changing. Recent experiments are revealing that quantum theory is even more strange than expected. Sometimes it appears as a great, conceptual black hole that sucks down into it every attempt to clarify the foundations of physics. Now Einstein is threatened with Newton's fate. The theories of classical physics worked well at low speeds but failed for objects travelling near the speed of light. Newton's theories got the predictions right in a limited domain, but were not fundamentally correct. In the long run, Einstein's theories may be celebrated for a host of startling, true predictions, but relegated to history for their partial vision.

The EPR experiments

The experiments that directly threaten Einstein's celestial speed limit involve measurements on pairs of particles some distance from each other. In short, the measurement on the first particle on the left mysteriously "influences" the other particle on the right. Wiggling the particle on the left produces a jiggle on the right. But the experiments show that any "influence" would have to travel faster than light. That is, the particles are far enough apart that a beam of light from the left-hand measurement cannot reach the right-hand apparatus until after it has completed its measurement and found the jiggle. What could cause this? Could some influence be travelling faster than light? The interpretation of every experiment in science rests on assumptions, and these claims are so astonishing that it is best to examine what lies behind them extremely carefully.

In general, when an association or correlation between two events or measurements is found, there may be three explanations. First, there may be a mistake. Perhaps the association was merely an

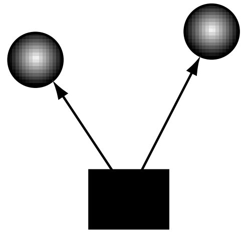

Figure 17.1 *EPR experiments. Two particles leave a common source. A measurement on the left disturbs the particle and influences the particle on the right. If the influence traverses the space between the particles, it travels faster than light.*

accident, a chance or spurious occurrence. If so, further repetitions of the experiments should reveal no further associations. Secondly, there may be a *direct link*. Measurements may reveal an association simply because the first event affects the second. Thirdly, however, there may be an *indirect link* between the events. Perhaps some third event, occurring earlier, sent out influences that created the later association between the pair of measured events. Philosophers say such events have a "common cause".

These three possible explanations provide the framework for the argument that the experiments show some faster-than-light influence:

Faster-than-light quantum influences

A.	A correlation between distant measurements is observed.	
B.	If a correlation is observed, there is a spurious association, a direct cause or a common cause.	(P)
C.	Therefore there is a spurious association, a direct cause or a common cause.	(from (A,B)
D.	There is no spurious association.	(P)
E.	There is no common cause.	(P: Bell's theorem)
F.	Therefore, there is a direct cause.	(C,D,E)
G.	If there is a direct cause, it travels faster than light.	(P: Aspect's experiment)
H.	Therefore, there is a direct cause that travels faster than light.	(F,G)

This momentous conclusion threatens to topple our understanding of relativity theory. The argument reveals that it rests on several key premises. The first, B, seems safe. The second, that the association is not spurious, is also simple: the experiments were repeated at a dozen universities and the associations were consistently found. The last two, however, are quite strong and require comment: everything depends on them.

There is now a strong consensus among both physicists and philosophers that there is no common cause (premise E). The basis for this is a famous mathematical proof published by John S. Bell. His result was perhaps the most important development in the foundations of physics between Einstein and the current period of frenetic activity. Indeed, more than anyone else, John Bell triggered the progress now being made. All but a tiny minority of physicists now accept that his proof shows that no possible common cause could produce the observed measurements. It has been studied exhaustively, and several simple expositions have been published (see Appendix E).

The next premise, G, gained dramatic support in experiments performed by Aspect and others at the Institute for Optics in Paris. Pairs of distant measurements within the laboratory were made extremely closely in time. Any cause, any force or wave, travelling from one to the other could not complete the trip within the small interval of time between the measurements. Yet the associations between the pairs of measurements were still observed, just as in other experiments. Aspect's and succeeding experiments have provided direct evidence that no signals travelling slower than light could produce the associations.

In this debate, "influence" is used as (what philosophers call) a "weasel word", that is, a vague word with a slippery meaning used to conceal ignorance. No one really knows what it is that might be travelling faster than light. It is not a cause that can be used to send signals and carries no mass or energy but is apparently not nothing, and so is an "influence" of some sort or another.

Controversy

If the premises based on Bell's theorem and Aspect's experiments are as secure as they seem, there is no choice but to accept the revolutionary conclusion that something is travelling faster than light. Oddly, many mainstream physicists accept both Bell's and Aspect's work but resist this conclusion. How can this be? At first, there was widespread confusion and misunderstanding about Bell's theorem in the physics community. Many physicists had not studied the issue in detail and simply refused to believe that Einstein could be wrong. Even as younger physicists began to realize that quite profound progress of some sort had been made, they tended to give two sorts of reasons for discounting the above argument.

First, everyone agrees that no energy or mass travels between the particles from one measurement to the other. Physicists tend to believe (with good reason) that everything that exists has mass and energy. Thus they argue that if no mass or energy is transferred, nothing at all is transferred. This objection is countered by other physicists who argue that these experiments are very, very strange. They may be telling us that there are indeed things in the universe with no mass or energy (so-called "pilot waves" or "information"). No one has a clear idea about what these might be but clearly, the proponents say, *something* is producing the associated measurements in the experiments.

Secondly, everyone agrees that no messages can be sent from one thing being measured to the other. Usually a cause travelling through space – like a radio wave – is ideally suited to send messages and signals. But in these key experiments, no message can be sent. Many physicists believe that this is evidence against the existence of any faster-than-light causes. But this objection is mistaken. In quantum theory, the results of measurements are fundamentally random. These experiments cannot be used to input and output messages because the result of the first measurement is random. Since we cannot control the input to the system, we cannot control the output. It is a garbage-in garbage-out (GIGO) effect. Thus the failure to transmit messages is due to quantum randomness and not necessarily to the absence of faster-than-light causes.

Many or most mainstream physicists still deny that these experiments threaten relativity theory, but for reasons that seem weak. Philosophers tend to divide into two camps. Some, such as Arthur Fine and Bas van Fraassen, accept the curious associations but, crudely put, say there is simply no explanation for them. They give various arguments but essentially say that explanation has here reached a limit. Nothing travels faster than light and nothing slower than light could produce the associations, and that is the end of the story. This position is made plausible by their general philosophical views, but is obviously frustrating in this special case. Other philosophers hold that something is indeed travelling faster than light. This position was defended for years by the respected but eccentric physicist David Bohm, and was carefully analysed by Jim Cushing. In its various incarnations, this view has won serious reconsideration by philosophers and younger physicists.

An ability to signal would imply a faster-than-light causal process, but the failure of signalling does not imply the absence of causal processes.

Revisiting the majority and minority interpretations

The EPR experiments have momentous implications for the interpretation of relativity theory. In short, they favour Lorentz's minority interpretation.

According to the mainstream interpretation, faster-than-light causation is impossible. There are several reasons for this. One is that the formula for mass increase suggests that anything approaching the speed of light would acquire infinite mass and energy. If the EPR measurements do instigate faster-than-light influences, then there is a lot of explaining to do here. Another reason is that faster-than-light influences would seem to make the paradoxes of time travel a real possibility. If simultaneity is really relative, then such influences could change the past and kill off our grandmothers, and so on.

On the other hand, the minority interpretation can comfortably accommodate such influences. It says that only the present, only the absolute now of the ether, exists. It therefore immediately rules out the time paradoxes: the past cannot be changed if it no longer exists. The minority interpretation insists that the relativity of simultaneity is merely apparent, an artefact of our measuring processes, and faster-than-light influences would favour this view. For a century now, Lorentz has been belittled for clinging to his deeper, explanatory interpretation of relativistic physics. Physicists favoured economy and observability over intuitive understanding. These EPR experiments may mark the rehabilitation of his more philosophical approach.

The EPR debate has, however, produced one significant shift in recent presentations of the mainstream interpretation. It used to be common to assert flat-out that nothing can travel faster than light. Now textbooks are more coy. They say that no "cause" or no "signal" can travel faster than light. This sounds like a minor change, but actually opens up a loophole: the possibility that some things that do not transmit signals travel faster than light.

I conclude this chapter with an odd historical footnote. These historic experiments, which provide the first credible evidence against the mainstream interpretation of relativity theory, were first proposed in 1935 by Einstein himself. As Einstein was developing his theory of special relativity, he also published some papers on the behaviour of atoms and electrons. Some historians, like Thomas Kuhn, now say that these papers were the real start of quantum theory. Before Einstein, Planck had groped towards the basic concept, but it was Einstein who should be regarded as the founder of quantum theory.

Einstein is thus credited by some historians with launching both the quantum and relativity revolutions.

Later in his life, however, Einstein became quite disenchanted with the odd patchwork of ideas that the quantum theory had become. In 1935, he co-authored a now famous paper with two younger physicists, Podolsky and Rosen, which came to be known as the "EPR" paper. The argument of their paper is complicated, but for our purposes can be summarized briefly as follows:

The EPR argument against quantum theory

A.	If quantum theory is true, then some causes propagate faster than light.	(P)
B.	But no causes propagate faster than light (as relativity has shown).	(P)
C.	Therefore, quantum theory is not true.	(from A,B)

Clearly this conclusion is an attack on quantum theory. Essentially they are saying that because quantum theory conflicts with relativity, quantum theory must be nonsense. Most remarkably, however, they detailed specific experiments in which quantum theory seemed to predict faster-than-light causation. These experiments are now known as "EPR experiments".

Partly because of his public attack on quantum theory, which was then both successful and fashionable, Einstein became a sad and isolated figure. For the last 30 years of his life, he was often regarded by other physicists as a has-been, and became the subject of whispered jokes. Even his attack on quantum theory was misunderstood and trivialized. The story circulated widely that Einstein had an old-fashioned mental block against randomness in physics. His line that "God does not play dice" served as a caricature for his views. In hindsight, Einstein knew long before others that the key issue was these "spooky" faster-than-light influences. But even his best friends, like Max Born, could not follow Einstein's reasoning and chided him for being so confused.

In 1964, 30 years after the EPR paper, it was John Bell who revived Einstein ideas and crucially pushed physicists toward conducting the experiments that Einstein had proposed. Even then, however, Bell's paper was lost by the journal and not published for two years. Almost 15 years passed before serious experiments were performed in the early 1980s. These EPR experiments proved that Einstein's premise A was probably correct. Although Einstein has had the last laugh, it may be small comfort. In the long run, quantum theory may undermine relativity theory. We will remember Einstein not for positively creating his own theories but for his penetration into the quantum theory's mysterious, destructive power.

> Einstein saw that quantum theory implied faster-than-light signals and therefore was in conflict with relativity, but he concluded there must be some flaw in quantum theory.

CHAPTER 18

The Big Bang: how did the universe begin?

One philosophical question is so exquisitely compact, so breathtakingly deep, that it can only be regarded as a miniature masterpiece. It seems that Leibniz was the first to express it in the haunting words "*Why is there something rather than nothing*?" It is clear that not even "God" could be the answer here, for even if God created all things and even the universe itself, we could still ask why God existed. If the divine existence is pronounced "necessary", we could ask in turn "Why this necessity?"

Some philosophers find Leibniz's question so frustrating and unanswerable that they declare it to be absurd, a grammatical confusion of some sort. Others, however, have felt its sharp bite, its evocation of the "miracle of existence". Modern scientists tend to shun this sort of question altogether. They concentrate instead on "how" questions. They trace how one event caused another, or how one body emerged from more primitive ingredients. *Teleology*, the study of purpose, of ultimate origins and fate, has been expelled from science.

Nonetheless, every human society has struggled to answer questions about the origins of our world, and have believed in what anthropologists call *creation myths*. From the Judaic story of Adam and Eve in the book of Genesis in the Bible, and the Greek myths of Chronus and Zeus, to the Japanese tales collected in the Nihongi, each explains the emergence of our world from a primordial chaos. Modern society prides itself on explaining the world's formation in a scientific way, and the cornerstone of that explanation is the Big Bang.

The first indication that the universe had erupted out of some large explosion was a discovery made in 1929 by the astronomer Edwin

Hubble. Using the largest telescope then available, he made the surprising announcement that distant stars and galaxies are moving rapidly away from us: *the universe is expanding*. In fact, the farther away objects are, the faster they are receding. The most remote objects are moving at large fractions of the speed of light. Through the Second World War and the 1950s, several explanations of these facts were debated, but the controversy was finally settled by surprising new observations.

In 1965, two young radio astronomers from Bell Laboratories in New Jersey were constructing early "satellite dishes", and struggling to eliminate some hissing static in their receiver. They were mystified by its source. It seemed to be coming from all directions in the sky with the same intensity, and this led the engineers to conclude that the source must be within their own equipment, since no transmitter could produce a pattern like that. They checked all their connections, and even cleaned the "white dielectric material" pigeons had left on their antenna, but made no progress at all.

As luck would have it, one of the astronomers heard through friends that physicists from nearby Princeton University (where Einstein had died tens years earlier), had just finished some new, very speculative calculations. The physicists argued that, if Hubble's observations could be explained by a giant, primordial explosion, there should still today be a faint "afterglow" of radio waves filling the entire universe. They were able to calculate the main frequency and intensity of this radiation. The two teams quickly realized that the static in the satellite dish approximately matched the characteristics of the afterglow calculated from theory. Unknowingly, the astronomers had detected the remnants of the Big Bang. The astronomers and the physicists later received the Nobel prize for their historic discovery of this *cosmic microwave background radiation*.

All this jump-started study of the universe's origins. Speculations about the "beginning" had been regarded by mainstream physicists as mere science fiction, but this new hard experimental data moved the subject to the frontlines of scientific research. Since the 1960s, several lines of observational evidence have all converged to make a very strong case for a Big Bang about 15 billion years ago. Most scientists now regard this theory as very well confirmed. For one reason, detailed models of the early fireball can be used to calculate the kinds of debris it spewed out, and precisely predict the proportions of hydrogen and helium that should remain in the stars and galaxies around us. Astronomers have found that the amounts of these elements observed through the universe closely correspond to the predictions. This in turn suggests that we have a good understanding of what happened during the early Big Bang. There is an astounding match between theory and experiment.

If this theory is correct, the original explosion was so hot that only stray particles and the simplest atoms could survive. Any larger atoms formed by random mixing would have been ripped apart in collisions, or bombarded by intense radiation and broken down again into simpler fragments. Thus only the lightest elements such as hydrogen and helium emerged unscathed from the Big Bang. This raises an intimate question. Our bodies are mostly composed of much heavier elements like carbon; likewise Earth contains silicon and other relatively large atoms. Where did these come from?

The generally accepted view is that these were formed much later than the Big Bang. As the universe cooled, scattered atoms were pulled together by gravitational forces, congregated and formed stars. After some billions of years, these stars would age, and some would collapse and explode. Such a *supernova* would be violent enough to ram together simpler atoms into larger clumps, and would fling minute portions of these heavy elements out into empty space before they were broken down again. After generations of stars were born and died, significant amounts of heavy elements would remain floating through space. If these dust clouds again formed new stars, their outer fringes might congeal into planets. Eventually the heavy elements might form complex structures like our bodies. Thus, astronomers believe, Earth and our bodies are ancient ash from stars exploding like fireworks.

Leibniz would insist on asking what came before the Big Bang, but this question makes physicists nervous. They tend to insist in turn that their science merely traces causes: it can only investigate empirical questions. Since the Big Bang was so hot and so turbulent, probably no causal process can be traced back through its origin. Although a few are brave enough to speculate, most would say that whatever came before the Big Bang can be no part of science.

The Big Bang was some 15 billion years ago, Earth was formed some five billion years ago and humans evolved in the past five million years.

CHAPTER 19

Black holes: trapdoors to nowhere

Anyone hauling a boulder to the top of a skyscraper and dropping it on to the street below would expect a catastrophic impact: flying shards of rock and road, streaks of sparks and smoke, the clap and crack of the reverberating bang. Similarly, when a planet, comet or any other material falls into a star, the resulting explosion is often dramatic. It can produce blinding flashes, bursts of high-energy X-rays and gigantic glowing flares of fiery gases.

But, in early 2001, astronomers observing a strange object 6,000 light-years from Earth with the orbiting Hubble Telescope reported that they had seen the opposite. Massive clumps of hot gases many times larger than Earth were being sucked down into a large, invisible object. As they raced downwards, the accelerated jostling heated them, and they glowed and pulsed with incredible energies. Then nothing. The gases just disappeared. There was no explosion, no flashes, no flares – just nothing.

Einstein's theory of general relativity predicts the existence of *black holes*: bodies so dense that their gravity captures everything close by and prevents it from escaping. Not even light, the fastest and most nimble signal known, can climb up and away from a black hole. They are colourless, invisible, wholly black patches in the sky. For this reason, physicists doubted for many years that black holes could ever be seen at all. And if they could not be observed, they doubted they were a serious part of empirical science. For many, they were just science fiction.

Since the 1970s, evidence has slowly accumulated that black holes do exist. Nonetheless, all the observations were necessarily indirect and circumstantial, and sceptics insisted that other interpretations of the data could not yet be excluded. In the past few years, however, the richness and variety of observations have sharply strengthened the case. Many feel there is now overwhelming evidence that black holes exist and are common throughout the universe. The Hubble observations of the disappearing gases were, for one recent example, widely regarded as the tell-tale "signature" of a black hole: nothing else could have so completely swallowed and contained such a violent explosion.

The formation of black holes can be understood in a simple way. The parts of any body attract each other with a very tiny gravitational force. Usually, other forces keep the parts apart and ensure that bodies remain stable. But consider a star shining in the night sky. It is mostly a kind of gas composed of very simple atoms. In its dense centre, these atoms bump into each other and fuse together in mini-nuclear explosions. These generate the heat and light that makes stars so hot. Since heat causes expansion, the energy released pushes the other atoms in the star outwards. Thus the star is stable because of a certain balance: gravity pulls the atoms together, some of them collide and explode, and the resulting energy pushes the atoms away from each other. The inward and outward forces are in equilibrium.

Over billions of years, however, the star will burn up all its atomic fuel and become dim. With fewer explosions inside, gravity will gradually win the war, and compress the star further and further. In very large stars with enormous numbers of atoms pulling each other inwards, no other processes are able to resist the force of gravity, and the star will shrink until it is very tiny. Although the gravitational pull of a single atom by itself is very weak, many atoms concentrated in a small space exert gigantic forces. These would be so strong on our tiny star that nothing could escape its grasp: it has become a black hole.

Even light cannot be reflected off such an object. A portion of any light that struck it might bounce off and begin to race away. But the gravitational pull would be so great that, like a ball arcing upwards and falling down again, the light would gradually turn around and be reabsorbed. This is what makes black holes invisible.

Even though general relativity predicts black holes, Einstein always denied their existence. He repeatedly sought to find physical principles that would block their formation. We can get a glimpse of his reasoning by returning to the rubber sheet analogy for curved space.

A weight on the rubber sheet will bend the rubber downwards and produce a deep well. Crucially, if the same weight is compacted into a smaller space, it creates an even deeper well with steeper sides. This is because there is less rubber directly under the weight and supporting it, and less rubber that needs to be stretched downwards. This can be compared to pushing down on a thin sheet with the flat of your palm and your fingertip: the latter creates a deeper hole with the same force.

According to general relativity, gravity will compress some stars into ever smaller and smaller spaces. This means that the wells in the rubber sheet get ever deeper and narrower. *Eventually, as a star shrinks, the curvature of the well will become infinitely steep*. Thus a black hole is called a *singularity*, which means that the numbers describing it have all gone off the scale and become infinite. When the numbers in their equations blow up and become infinite or develop other pathologies, mathematicians say they have become “singular”. What does it mean to say the curvature of the well in the rubber sheet has become *infinite*? The short answer it that no one really knows. We can imagine this as a rip or rupture in the rubber sheet: a place where it is no longer smooth but suddenly has no definite depth, no steepness that we can measure and assign a finite number to.

This is probably what set Einstein so firmly against black holes. His theory made the curvature of spacetime the most basic thing in the world. He pictured the curvature as continuous and smooth, and gave equations that precisely described its flexing. A black hole is not only physically bizarre, but it also represents some kind of breakdown in general relativity. Although the theory predicts that large stars will be endlessly compressed and form black holes, it cannot describe their ultimate, infinite state. Einstein’s theory cannot reach into the central core of a black hole.

Zeno’s paradoxes entangled Greek philosophy in paradoxes of the infinite. Here we see infinity rearing its head again in our most advanced science. Einstein believed that, if black holes were real, if actual infinities infested his spacetime curvature, his theory would be wrecked. They would show that spacetime curvature was not basic, or that it came to an “end” where it was not defined, or that there was something beyond spacetime. He died believing that predictions of black holes were some kind of miscalculation, some minor misunderstanding that future generations would put right. Thus the confirmation of the existence of black holes has created an important mystery for interpreters of general relativity. If black holes are real and physical, then probably actual infinities are too. In fact, the physicists Stephen Hawking and Robert Penrose proved theorems in the 1970s that roughly say that singularities are inevitable and unavoidable. Since then physicists have begun to grapple with the meaning and mathematics of these infinities more seriously.

John Earman, a leading philosopher of physics, treats this issue in his book *Bangs, Crunches, Whimpers, and Shrieks: Singularities and Acausalities in Relativistic Physics*. He begins with a concession:

> Einstein is surely right that, whatever the technical details of a definition of spacetime singularities, it should follow that physical laws, in so far as they presuppose space and time, are violated or, perhaps more accurately, do not make sense as singularities. This is good reason for holding that singularities are not part of spacetime.

Earman goes on to say, however, that singularities are not a breakdown in general relativity. The theory works well in ordinary, smooth spacetime. Singularities can be regarded as the boundary of spacetime, as its end-points, and perhaps we should not hold it against general relativity that it fails there:

> Contrary to Einstein, I do not think the fact that General Relativity predicts spacetime singularities is necessarily a cause for alarm, and I certainly do not think the prediction of singularities is a signal that the theory self-destructs.

In sum, Earman argues that singularities can be quarantined. They exist and are predicted by general relativity, but will not infect those regions of spacetime free of infinities.

Einstein believed that his theory described the ultimate reality. Thus suggestions that general relativity works only in certain portions of the universe are catastrophic. Earman reflects the views of many contemporary physicists. They expect that general relativity will someday be superseded just as Newton's theories were. Both Einstein and Newton were correct, but only in limited domains. Someday, they believe, a quantum theory of gravity will replace general relativity and, they hope, make sense of singularities.

In the meantime, the hunt for black holes has produced new and breathtaking evidence that they exist, are common and are sometimes unimaginably huge. Astronomers distinguish between black holes that weigh about as much as our Sun and "supermassive black holes". For example, there is a powerful source of X-rays called Cygnus X-1. This system wiggles and gyrates in a way that suggests it is a pair of bodies rotating around each other. One of them, however, is invisible. Observations suggest that it is a black hole weighing about ten times the size of our Sun. This is puny, however, compared to the monsters detected at the centres of galaxies. Galaxies are great, swirling collections of stars that are brighter and more concentrated near their centres. In recent years, compelling evidence has emerged that stars attracted down into the centres of galaxies conglomerate into black holes. These weigh a million or a billion times as much as our Sun. The black hole at the centre of our own Milky Way galaxy is three million times as massive as the Sun.

Black holes exist and give rise to infinities, which suggests that general relativity is not an ultimate theory.

CHAPTER 20

Why haven't aliens come visiting?

Where does life come from? The *theory of evolution* describes how one species slowly develops out of another, how humans evolved from apes, but does not explain the ultimate origin of life. Charles Darwin, who first published his theory of evolution in 1859, was always baffled by this mystery. At one point, even though he was an atheist, he even desperately suggested that God must have "breathed" life into the earliest organisms.

For most scientists, this mystery was solved by the famous experiments of the chemists Stanley Miller and Harold Urey, performed in 1953 at the University of Chicago. In a large, glass beaker in their laboratory, Miller and Urey approximately mimicked the conditions on Earth long before there was any life. They added some simple inorganic chemicals, heated them and shocked them with bursts of artificial lightning. After a week, they opened the beaker to see what products had formed. To their surprise, they found large quantities of amino acids, the simple organic molecules that are the building blocks of our bodies. Although these were not alive, this result proved for many that mere random mixing on the primitive Earth would produce organic molecules and eventually lead to simple life-forms. That is, given enough time and a chemical beaker the size of Earth's surface, *evolution would begin spontaneously.*

Physicists tell us that Earth formed about four-and-a-half billion year ago, and recently fossils of very simple one-cell organisms have been found in Australia that date from less than a billion years later. Since even these organisms were the products of a long period of evolution, the fossils also suggest that evolution started very early, and therefore relatively easily and quickly.

Taken together, the theory of evolution and the experiments of Miller and Urey may solve the mystery of our origins, but they also pointedly raise another question: does intelligent life exist elsewhere in the universe?

If the universe contains a mind-boggling 50 million galaxies each with some 100 billion stars, the sheer force of numbers suggests there is a high chance that we are not alone. The scientist Frank Drake tried to calculate the number of advanced civilizations in the universe using the now well-known *Drake formula* he devised, and found that the universe was so vast that many life-forms must have evolved. But the formula depended on guessing the answers to questions that we were almost entirely ignorant about. How many stars have planets? How many of those are hospitable to life? Even if conditions were right, how frequently would life evolve? What portion of living creatures would develop intelligence, and what portion of them would go on to master technology? Drake made some very conservative estimates, and still discovered that in a universe so vast intelligent life should be common. But his research was widely regarded as speculative, and many decided we were just too ignorant to come to any firm conclusions.

During the 1990s, this debate shifted dramatically. Astronomers invented telescopes and other detectors so sensitive that they were able to search the sky for planets orbiting nearby stars. These are extremely difficult to observe because they are tiny, dark and orbiting around very bright stars. Searching for planets is like looking for moths flying outside a distant lighthouse. Nonetheless, astronomers made an historic, unexpected discovery: *planets are very common*. It is not too much of an exaggeration to say that they found them almost everywhere they looked. Dozens and dozens have been detected around stars not too far away from our Sun. This is surprising and important. Even if planets with conditions favourable for incubating life are a small fraction of all planets, there are still many, many planets where life might evolve across the universe. Thus, this discovery raises the probability of extraterrestrial life, and has led many to change their opinions and entertain the question more seriously.

Critics of the search for extraterrestrial life, however, have some very strong arguments of their own. One has become known as the *Fermi paradox*, named after Enrico Fermi, the physicist who created the first controlled nuclear chain reaction. If, he argued, the universe is so large that advanced civilizations are plentiful, then we should have encountered them by now. At least, we should have obvious evidence of their existence. Even if there are no junk spaceships atop mountains and we are not ruled by intelligent jellyfish, there should be signs of some sort. Although some civilizations might have prohibitions about contacting us, many others would not. This paradox, the tension between statistics that suggest life is plentiful and the deafening absence of clear-cut evidence, has intrigued and bothered many. Where are they?

In the past five years, astronomers have made another historic discovery that may resolve the Fermi paradox in a particularly ominous, unpleasant way. It is a strange story. During the Cold War, the United States launched spy satellites to monitor the entire Earth for secret tests of nuclear bombs. Researchers were surprised by repeated bright flashes of light detected simultaneously by satellites on opposite sides of Earth. After years of secret work, they concluded that the flashes were coming from outer space and disclosed their strange discovery to astronomers in 1973. Since they consisted largely of high-energy light, or gamma rays, these mysterious flashes were called *gamma-ray bursts*.

Astronomers were baffled. The flashes occurred randomly about once a day, and were extremely bright, but no one could locate a source. A similar phenomenon occurs at a birthday party when the room suddenly fills with a camera flash, which fades in an instant. Those looking away from the camera will find it difficult to say exactly where the flash occurred. Since the satellites were not lucky enough to be pointed directly at these flashes, they were unable to pick out a source. At the time, however, astronomers favoured one conclusion: their source must be nearby. House lights seen from afar at night are dimmer the farther away they are. But these flashes were so bright, they must originate within the solar system or somewhere else near our Sun.

After 25 years of inconclusive debate and further observations, collaborators at the Italian Space Agency and the Netherlands Agency for Aerospace Programs sent aloft a satellite specially designed to locate the origins of these strange flashes. It was equipped with cameras with very wide lenses that could continuously monitor very great swaths of the heavens. On 28 February 1997, the satellite caught its first image of a flash. It immediately relayed the precise direction to ground-based telescopes, which swung into action. Within 24 hours, they had pinpointed the source, and made a breathtaking discovery: the source was outside our galaxy. This fact may take some time to sink in. These flashes are extremely bright but come from very, very, very far away. Their sources are extra-galactic. Usually, distant lights are dim. How could this be?

Astronomers could hardly believe their calculations. To fill such great volumes of space with flashes so bright, an explosion would have to compress to within a few seconds all the energy that our Sun emits in ten billion years. It would have to be more powerful than a supernova, an exploding star. It would be the most powerful explosion in the universe.

Astronomers are now debating what mechanism could liberate such incredible energies, and have developed several competing theories. In the meantime, the broader consequences of their discovery are chilling. These gamma-ray bursts are so powerful that they would completely destroy objects near their source, and in fact wipe out life in a sizeable portion of any galaxy in which they occur. That is, any planet roughly in the same neighbourhood of such an explosion would be scoured clean and left a barren, orbiting stone. They thus provide one unhappy answer to the Fermi paradox: although life may arise frequently around the universe, we do not encounter advanced civilizations because they are regularly annihilated by gamma-ray bursts. Without an understanding of their mechanism, we can only guess the chance that a burst may originate closer to home, within our own galaxy. But since life has survived on Earth for billions of years, we have been very lucky so far.

Children growing up today may look to the starry heavens with feelings very different from those of previous generations. Their parents could enjoy the sea of twinkling stars. They were assured that the Sun would shine stably for several more billions of years and that crashing asteroids were unlikely. The discovery of this intergalactic lightning, however, suddenly makes the universe seem a much more hostile place. Moreover, since they travel at the speed of light, these bursts give no warning. If there has been such a massive explosion in our own Milky Way Galaxy, and near our own solar system, the shock wave may now be hurtling toward us with the fury of 10,000 nuclear bombs.

Gamma-ray bursts may be the answer to the Fermi paradox.

CHAPTER 21

The inflationary and accelerating universe

The most exciting and profound new physics, the first glimpses of twenty-first-century physics, are now coming from astronomy. Stunning new, supersensitive instruments and dazzling theoretical models have combined to squeeze revolutionary data from the faintest observations. From satellites in outer space and camps 800 metres from the South Pole, astronomers are mapping the shape of space and reaching back to the birth of time.

Despite its many successes, the Big Bang model led to some new, deeply perplexing puzzles. Suppose our telescopes look at very distant objects in opposite directions. They might be so remote that nothing could travel from one to the other. Even at the speed of light, the journey would take longer than the 15 billion years since the Big Bang. Yet the universe in opposite directions looks pretty much the same; in fact, it is *exceedingly* uniform. The cosmic microwave background, for example, comes to us from the farthest corners of the universe, but is the same whichever way we look, to within one part in 10,000 or more. This is suspicious. What could have coordinated or matched conditions in regions so far from each other? Since this coordination seems to have extended beyond the horizon that light could reach, it was called the *horizon problem*.

There are other big problems. Imagine throwing a stone straight up into the sky. Three things might happen. Ordinarily, the stone will rise upwards, slow down and fall back to Earth. If it were thrown up with enormous speed, however, it would escape Earth's gravitational pull and zip out to infinity. Balanced between these two possibilities, there is a third. If the speed were exactly right, the rock might be slowed down by gravity but never quite enough to make it fall backwards. Its speed would be slower and slower. Far above Earth, where its gravitational field becomes ever weaker, the rock would barely crawl upwards but still manage to continue on toward the stars. Like someone travelling at one kilometre per hour, then a half, then a quarter, and then an eighth of a kilometre per hour, the rock would go slower and slower but never stop altogether. Obviously, this third scenario is extremely unlikely, and depends on the stone's initial speed being exactly on the knife edge between falling back and escaping to infinity.

The Big Bang hurled all the matter and energy of the universe outwards and, likewise, there are three possibilities for what might happen next. First, the matter might expand outwards and then fall back: the *Big Crunch*. Second, it might expand outwards for ever until all the matter and energy were thinly dispersed in a cold and dark infinite space: *Heat Death*. Thirdly, if the critical balance were just right, the universal expansion might slow down to a crawl but never quite fall back. In this case, the universe would become more and more stable. As the mass–energy became more evenly distributed, the curvature of space would become flatter and flatter: the *flat universe*. The problem is that this last scenario is extremely unlikely, but astronomical observations indicate that our universe is indeed flat. How could a huge, violent, turbulent explosion be so finely poised between the Big Crunch and Heat Death? Some called this the *fine-tuning paradox*.

In 1981, Alan Guth, a young physicist, then at Stanford University, proposed a wild theory that would resolve both these and other outstanding problems with the Big Bang in one fell swoop. In a word, he proposed that, early in the first second of the universe's existence, the framework of spacetime expanded extremely quickly. Like a balloon suddenly inflated to a gargantuan size, the universe puffed outward in an instant. This process was dubbed *inflation*. It is not a rival to the Big Bang theory but a modification and addition to it. Guth suggested that the distance between any two points would expand at a rate faster than the speed of light. This does not mean that any *thing*, any mass or energy, travelled faster than light. At each point, light would still travel along at 300,000 kilometres per second, but there might suddenly be much more space between it and its source. The distance between any two points would be stretched extremely quickly. After this brief burst during the initial explosion, the universe would settle down into the steady expansion discovered by Hubble.

Inflation would solve the horizon problem because things that are now very far apart and mysteriously coordinated were once cosy neighbours. This would also solve the flatness problem. Just as any region on a balloon's surface becomes flatter as it inflates, the process of inflation drives the curvature of space to near-perfect flatness. Although it would solve several puzzles about the Big Bang, many cosmologists were sceptical about this extravagant idea. Although Guth had been led to the idea by applying accepted physics to the early universe, the whole seemed rather speculative.

The world keeps surprising us. The great advantage of the inflation hypothesis is that it not only predicts that far-flung regions of the universe will be uniform, but it makes quantitative predictions about the minute residual departures from uniformity. Extremely tiny fluctuations in the microwave background radiation were measured in the early 1990s by the COBE satellite, and were an astonishingly close fit to the predictions. There were still many doubts about inflation among physicists, but in 2000 there were several new and historic reports of observations that further supported the inflation model. Astronomers and physicists triumphantly celebrated the combined achievement of their far-reaching theories and high-precision measurements. Inflation is now probably accepted by most of them, and will be taught as part of the standard Big Bang theory.

Just as it seemed as if contemporary physics was penetrating to the innermost secrets of nature, in 1998 astronomers made a preposterous announcement. The observations were so bizarre and so unexpected that most scoffed at them. It was widely expected that more data or more careful analysis would expose some mistake. When, in 2000 and 2001, more observations were reported, however, they in fact strengthened the case for the first, absurd claim. There is no agreement yet about how to explain these mysterious observations, but if correct they throw the foundations of physics into turmoil. Physicists have been heard to whisper that to make sense of it all we will need a new Einstein.

Imagine that our stone is again thrown overhead, arches high into the sky and then *accelerates out of sight*. That would be absurd. Gravity is pulling the stone downwards. It should be losing energy. How could it speed up? But astronomical teams based at the University of Berkeley and Harvard University have announced just this. The Big Bang threw all the matter in the universe outwards. Both Newton's and Einstein's theories of gravity predict that the expansion must be slowing down to some degree: the mutual gravitational attraction of all the matter in all the galaxies should be pulling them inwards. But measurements of distant supernovae show just the opposite. All the matter in the universe appears to be *accelerating* outwards. Its speed is picking up.

This new acceleration is entirely different from inflation. Inflation is a brief expansion of spacetime that lasted for an instant during the primordial fireball. If the galaxies are even now accelerating away from each other, some new force acting over long distances is at work. This new force would apparently be as permanent and real as the other known forces. But what force could be strong enough to push all the matter in the whole universe outwards? Are there new kinds of forces that our physics knows nothing of? Where would the energy come from? Could there be something "outside" the universe that is attracting our galaxies? Is general relativity just wrong altogether, and a misleading guide to interpreting these observations?

Since ordinary mass produces gravitational attraction, and since mass is energy, physicists say that energy produces attraction. Thus this new, mysterious repulsion, the new push outwards must, they say, be produced by "negative energy". The paradoxical name is really just a label for the mystery. There is no consensus about what new physics will be needed to explain our accelerating universe, and some, perhaps, still hope that the observations are some kind of error.

We return to Einstein again. In 1917, two years after completing general relativity, Einstein applied the theory to the question of the shape of the universe. At that point, however, he believed that the universe was more or less stable; this was a holdover from the traditional belief in the "fixed stars". His theory kept contradicting this belief. As the mass and energy in the universe moved around, the shape and curvature of the universe altered too. Einstein's theory was predicting that the universe would evolve and change over time. Reluctantly, Einstein published a paper showing how his theory, born of so many difficult years of struggle, would have to be modified. In brief, he showed that the theory could be tweaked or fudged to counteract any expansion or contraction of the universe. By adding an entirely new variable, he could stabilize the universe. He called this the *cosmological constant*. When Hubble discovered the expansion of the universe a decade later in 1929, Einstein was red-faced. If he had believed his beloved theory, he could have *predicted* Hubble's historic discovery. He deleted the cosmological constant from his equations and said it had been the "biggest mistake of my life".

What goes around comes around. Now that physicists are struggling to make sense of our new inflating and accelerating universe, the cosmological constant is suddenly back in vogue. By reinserting the constant in the general theory of relativity, and twiddling it up and down, physicists can make their theory match both inflation and the new acceleration. As one physicist said, the constant has become a "panacea": a universal cure for all cosmological puzzles. In fact, to counteract a contracting universe, the cosmological constant would represent just the sort of "negative energy" needed to explain the observed acceleration. Thus it may be possible, by restoring the constant to Einstein's theory, to extend the theory to handle the new observations. Einstein's biggest mistake may be the new physics of the twenty-first century. Time will tell.

CHAPTER 22

Should we believe the physicists?

> It must have been around 1950. I was accompanying Einstein on a walk from The Institute for Advanced Study in Princeton to his home, when he suddenly stopped, turned to me, and asked me if I really believed that the moon exists only if I look at it. The nature of our discussion was not particularly metaphysical. Rather, we were discussing the quantum theory . . . (Abraham Pais, 1982)

There is an old debate in philosophy about whether the world outside our minds exists at all. In the early-seventeenth century, Descartes pioneered the new mechanical and geometrical view of material reality in which every event was determined. But he also believed that we each had a soul and that our will was free. Thus he had to insist that matter and the soul were entirely different: the mind–body split was born. Descartes's critics soon pointed out that a soul confined within the "veil of perception" had no direct evidence that its perceptions were true. Perhaps they were mere illusions or some sort of cinematic film projected by God? Bishop Berkeley went so far as to suggest that there are no bodies outside the mind, and that perceptions were the only reality: "to be is to be perceived". Samuel Johnson thought this was all twaddle. He famously rebutted Berkeley by kicking a stone, as if to say that its reality was painfully obvious.

During the past 30 years, there has been a resurgence of these sorts of questions. Oddly, however, the doubts today grow out of science itself. A number of philosophers, sociologists and historians, and even a few physicists, have proposed that scientific reality is for us a product of social processes or somehow mind-dependent.

Debates over quantum theory have sometimes strongly encouraged these doubts about external reality. A central plank in the theory, the famous *Heisenberg uncertainty principle*, says that the position and speed of a particle cannot be precisely measured at the same time. Initially, this was thought to be a consequence of the smallness of physical particles: any observation of position would *disturb* them and blur their speeds. This interpretation is now known to be false. Instead, there is a consensus now that particles *do not have both a position and a speed at the same time*. That is, when a particle has a precise speed, it has no position in space. Since it is hard to imagine what a particle without a position would be, some draw the conclusion that only observed properties exist. There is no hard little particle moving about independently of our observations. This interpretation was pondered by Einstein in the above quote, and has been advanced by physicists like Bernard d'Espagnat, John Wheeler and others. John Bell's result, discussed earlier, is sometimes interpreted as a proof of these strange views: it suggests to some that properties observed in the "wiggle-jiggle" EPR experiments *could not have existed prior to their being observed*. That is, particles have neither a position nor a speed until observation somehow materializes them.

As the history of science became established as an important academic discipline, it also cast doubt on claims that science had discovered the true nature of reality. In his famous book *The Structure of Scientific Revolutions*, Thomas Kuhn argued that scientists before and after revolutions lived in different "worlds". Their concepts were so radically shifted that they perceived different things, even when making the same observations. The philosopher Larry Lauden went on to make a notorious argument. Since we know, he said, that every scientific theory in the past has been overthrown and proven false, we can infer that even our present ones will be overthrown and are false. Thus there is no reason to believe that scientific theories truly describe reality. Many professional historians of science prefer to study science as a human activity. They regard claims that science has any privileged insight into nature as ahistorical and naive.

Some contemporary sociologists known as *social-constructivists* have been the most loud and hostile critics of science. A loose group led by Bloor, Barnes, Collins and Pickering, known at times as the Edinburgh School, led an attack on science beginning in the 1980s. French sociologists like Bruno Latour continued these onslaughts through the 1990s. They tend to start with the presumption that social reality, our interactions, conversations and writings, are primary. The concepts we use are social products and influence what we see and are able to see. Claims that science is able to escape from the web of social influences and penetrate to some reality beneath seem, to them, suspicious. They analyse such claims as attempts to grab and assert power. In his 1984 book, *Constructing Quarks: A Sociological History of Particle Physics*, Andrew Pickering, a physicist who became a sociologist, suggested that experiments were no longer *tests of theories*. Instead, experiments on subatomic particles had become so complicated that theory was needed to build the equipment and interpret the measurements. Experiments presupposed theory; they were no longer adversaries. In this situation, decisions about which theories to accept could not be decided by experiment alone and, he said, reflected the political rivalries of different communities within physics. "The world" of physics, he concluded, "is socially produced".

Since modern society is so dependent on and dedicated to science and technology, tremendous controversies have erupted over claims that science does not reveal the true nature of reality. Advocates of these views have sometimes been shunned and marginalized. Within philosophy, the debate has stabilized and its protagonists have settled into two warring camps. The *anti-realists* are led by prominent philosophers like Bas van Fraassen and Arthur Fine, while the defenders of science, the *scientific realists*, are led by Ernan McMullin and others.

The very vigorous debate over scientific realism, the belief that science describes reality, has been healthy and productive for both sides. It has generated far-reaching historical and sociological analyses of science. It has discouraged the naive *scientism* or "science-worship" that was common during the Cold War, and which still predominates outside academia. It has forced philosophers to examine their presuppositions, and pushed their theories deeper. In the past, both in philosophy and in science, times of radical questioning and scepticism have often been very fertile. Breathing space was opened up for entirely new viewpoints.

The philosophy of space and time presented in this book generally presupposes that scientific developments have taught us something new and deep. It thus presupposes scientific realism. Scepticism, however, is useful for ambitious philosophers.

Kuhn distinguishes between technology and science, that is, between doing things and knowing things. He agrees that technology has made progress in a sense, but claims that the conceptual justifications for technology have not. After a scientific revolution, new theories are used to rationalize the practices we keep. Thus the practical success of science is not an argument for the correctness of its descriptions: many bad theories have led to successful techniques.