CHAPTER 4

How to build an atomic bomb

A few months after Einstein published his first paper on relativity in 1905, he sent in a sort of extended footnote to the same journal. His theory had an odd little consequence. It seemed so strange that he phrased the note's title as a question: "Does Mass Depend on Energy?" To leaf through the next four flimsy pieces of paper and contemplate all that followed is to feel the power of ideas. For better or worse, Einstein had unlocked the secret of the atom. Here was the destruction of Hiroshima and Nagasaki. Here were 40 years of fear and tension as Cold War superpowers pursued their policy of mutual assured destruction, insisting on arsenals so large that even after a first strike they could reduce their adversary to bouncing rubble. Here was the promise of infinitely renewable energy, and the curse of Chernobyl. Here was the first explanation of the Sun's ceaseless light and the starry heavens. Although it is true that chemists had stumbled upon radioactivity before Einstein, and might have developed atomic power without him, Einstein's theory was the torch that led the way. His ideas shaped a century we were lucky to survive.

Einstein concluded his short note by deriving the most famous physics equation of them all,

$$E = mc^2$$

(pronounced "ee equals em sea squared"): the only equation we will meet in the main text of this book. Here, E stands for energy, m for mass and c for the speed of light. In short, it means that energy can be converted into mass, and mass into energy. In some sense, they are just different forms of the same thing.

Just after deriving this formula, in the last lines of his note, Einstein raised the question of whether his far-fetched idea might have experimental consequences: "It is not impossible that with bodies whose energy-content is variable to a high degree (e.g. with radium salts) the theory may be successfully put to the test." That is, Einstein already glimpsed in 1905 the possibility that radioactive elements like radium or uranium might easily exhibit conversions of mass into energy. This was 40 years before Hiroshima and Nagasaki were bombed. Even now, thousands of nuclear missiles sit steaming in their silos poised for launch. A dozen countries are pressing ahead with their weapons programmes. Einstein's ideas haunt us still.

Faster speeds, greater masses

Energy is the "amount of motion". Suppose that two identical cars are racing down a road; the faster car has more energy. Suppose that a truck and a small car are travelling side by side along the road and at the same speed; the truck is heavier and therefore has more energy. It is harder to stop. Thus, in moving objects, more speed or more mass means more energy. As a car accelerates or as we push a body along, it gains more energy.

Einstein discovered that a moving object weighs more than the same object at rest; that is, an object with more energy also has more mass. As the speed of an object increases, its mass increases. As objects move faster and faster and approach the speed of light, their mass becomes nearly *infinite*. This effect is called "relativistic mass increase". There are various ways of describing this but the one adopted here is the simplest and most common.

Energy can also be stored inside objects. Suppose we hold the ends of an elastic band in our hands. As we move our hands apart, they have motion and thus energy. As the band stretches to its limit, our hands slow down and the band absorbs their energy. The energy or motion is clearly in the band. If we relax and let the band pull on our hands, they will move together again. This inward motion has the energy that was stored in the band. Thus the band is a device for absorbing, storing and releasing energy.

Stored energy also has mass. When the elastic band is stretched or a spring is compressed it weighs more. Likewise, a new battery weighs slightly more than a used battery. Like time dilation and length contraction, this mass increase is not noticeable in everyday life. The extra mass is only significant when bodies move at enormously high speeds. The motion of our hands stored in the elastic band is so slow that no device yet invented is capable of measuring the mass increase.

To summarize, with faster speeds bodies weigh more, that is, they have more mass. More precisely:

> *Relativistic mass increase:* Assume an apparatus at rest or moving at a steady speed in the same direction is used to measure the mass of passing bodies. A given body that is measured at several speeds will have higher masses at faster speeds.

The celestial speed limit

Imagine trying to run if every faster stride made your legs heavier and even sprinting speeds turned them into lead weights. Increasing a body's speed requires some kind of push or force. Increasing the speed of heavier bodies requires stronger and harder pushes. If a body's mass approaches infinity, then further increases in speed would require forces that approach infinity. But no rocket engine and no explosion can produce *infinite* forces: nothing finite and limited can produce something infinite. Thus no force existing in the universe can push a body all the way up to the speed of light. In short:

Argument that the speed of light is a maximum

A.	If a mass reaches the speed of light, then an infinite force exists.	(P)
B.	No infinite force exists.	(P)
C.	Therefore, no mass reaches the speed of light.	(from A,B)

The first premise, A, is part of relativity theory. The second, B, seems secure because an infinite force would require infinite energy, which is not available in any finite portion of our universe.

Thus Einstein discovered that physical laws impose a speed limit on all movements: no body can attain or reach the speed of light. This is the famous "celestial speed limit". There is some talk of spaceships with "warp drive" engines, or of imaginary particles called "tachyons" that travel faster than light, but, if Einstein is right, these will remain the stuff of science fiction.

Why is light capable of travelling at the maximum speed? Einstein's recipe for finding the mass of a moving object says first weigh the object on a bathroom scale when it is at rest, and then multiply by a number like 2 or 15 or 20,000 (higher numbers for faster bodies) to find its mass when moving. That is, the mass at high speeds depends on the mass found when the body is measured at rest, that is, on its *rest mass*. More precisely, the mass at high speeds is a *multiple* of the rest mass.

Interestingly, a ray of light is pure energy and has no rest mass at all. Thus if the rest mass is zero, then multiplying by 2 or 20,000 or infinity will still leave zero. A multiple of zero is still zero. Unlike ordinary bodies, light can travel at the maximum speed without becoming infinitely heavy.

This celestial speed limit for ordinary bodies is more than disappointing. Although almost every physicist believes that faster-than-light travel is impossible, perhaps someone someday will discover a way to circumvent Einstein's prohibition. Recent experiments (see below) hint that there is a loophole.

Mass is energy: energy is mass

Einstein had a mind that leapt nimbly from one new idea to the next. His powerful sense of intuition steered him to a safe landing and a new discovery. These leaps make his scientific essays miniature works of art. They are simple and graceful, but reveal a mind dancing among the deepest ideas. One example of such a leap is his claim that energy and mass are the same thing. Strictly speaking, relativistic mass increase says only that a given hunk of mass will gain or lose weight as its speed changes: more or less speed is more or less mass. Strictly speaking, this does not imply that *all* mass is made up of energy. For example, just because blowing air into a balloon or releasing it from the balloon changes the size of the balloon, we do not say that the balloon is entirely made up of air. The red plastic must be there first.

But Einstein leapt. If *some* mass is produced by increased energy then, he claimed, *all* mass is just energy. Thus his famous formula does not say that adding energy produces a change in mass – as adding air swells a balloon. It just says that energy is mass, and mass is energy. It took some time before other physicists were convinced that Einstein was right. Now they routinely transform mass into energy and vice versa in their experiments. It is even common to transform solid matter into nothing but pure energy.

Thus the first important idea contained in Einstein's short formula is that energy can be converted into mass and vice versa: the *interconvertibility* of mass and energy. This interconversion has an important consequence; it shows that the law of conservation of energy and the law of conservation of mass are false. In classical physics before Einstein, these were regarded as fundamental. But when mass is converted into energy, the total amount of mass in the universe decreases just as the total amount of energy increases. Thus neither total is conserved. To save the general idea of conservation, physicists combined the two laws. After Einstein, they said that the total amount of mass and energy together is conserved when all measurements are made by the same set of rulers and clocks. This new idea is called the *law of conservation of mass–energy*. (Physicists discovered later that this law holds only *on average*: for short times the total amount of mass–energy can fluctuate up or down.)

Einstein's formula also contains a second idea lodged in the little letter c. It is this which makes the formula so dangerous, and so profoundly shaped the twentieth century. How much energy comes from a given hunk of matter? Suppose we have one ounce or one gram of matter and convert it into energy. How much oomph do we get?

The formula makes the calculation easy. For the letter m substitute the amount of mass to be converted. Then multiply by c squared to get the energy. This looks very innocent, but in fact c squared is a very big number: 9,000,000,000,000. In words, this is nine trillion (using units of metres per second squared). Thus one gram of matter, about the weight of a feather, will produce an explosion about the same size as *20,000 tons* of exploding dynamite! This was the size of the atomic bomb dropped on Hiroshima. If the energy trapped in your body were suddenly all released, Earth would be shattered.

Chain reactions

Atomic bombs are dangerous because they are so simple. As far as we know, every nation that has attempted to build and explode them has succeeded. Relatively crude technology will do. The first bombs were built in the early 1940s before transistors and computers were invented. Think of an old radio or automobile from that time: the same technology was used to build the first bombs.

The central idea is this. Suppose that we have small but strong steel springs that can be compressed and latched. Since they store energy when latched, they are slightly heavier. Suppose, however, that the latches are fragile and barely manage to keep the spring from extending out again. With the slightest jar or bang, the latches may break and release the spring. Thus the compressed and latched spring is *unstable*.

Suppose that we collect hundreds of such latched springs, pack them tightly in a barrel and screw the lid down. They may sit there peacefully for a while. But suppose that someone bumps the barrel, or suppose that a latch somewhere spontaneously breaks apart. If just one spring is released the commotion may give its neighbours a knock. They too will burst their latches, and knock their neighbours in turn. Soon the barrel will be rocking and bouncing with uncoiling springs. Perhaps all of them will expand and explode the barrel.

This is an atomic bomb: unstable units packed together tightly and then disturbed. Each unit releases energy as it breaks apart, and this energy disturbs its neighbours, releasing even more energy. If each exploding unit causes more than one of it neighbours to burst apart, then the numbers of bursting units will rise rapidly. This is the famous *chain reaction*. Atoms are used instead of steel springs because they are very small. Enormous numbers of them can therefore be packed into a bomb small enough to be carried by an aeroplane or truck.

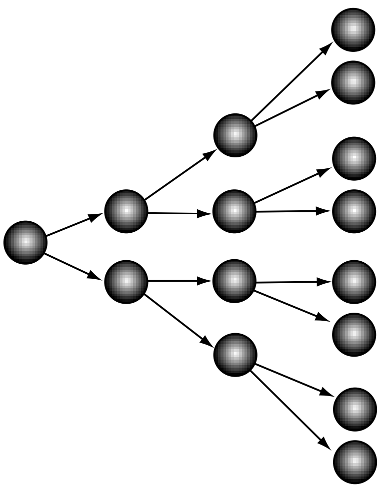

Figure 4.1 *A chain reaction. An example where each atom releases energy and causes two more atoms to break apart, releasing even more energy.*

Not all kinds of atoms are appropriate "fuel" for an atom bomb. The core or nucleus of each atom contains particles called protons. These particles all powerfully repel each other and are always struggling to escape and run off in all directions, but they are held in place and bound together by strong forces, which usually keep the atom quite stable. However, in very large atoms, there are so many protons that their repulsion from each other is almost as powerful as the attractive forces that knit them together. These large atoms are unstable. A nudge or shock may break them apart and liberate the protons.

If many large unstable atoms make up a hunk of matter and a single one disintegrates, the liberated particles may knock a neighbouring atom and cause its disintegration. If each atom destabilizes and destroys more than one of its neighbours, the chain reaction would soon "avalanche" and cause much of the hunk of matter to explode.

Unluckily for us, atoms just right for making atomic bombs are lying around in nature, and can be mined in the deserts of South Africa or the western United States. The most well-known is uranium, a yellowy heavy metal. Its nucleus can contain 238 large particles, which makes it very large and very fragile. Even sitting in the desert, some of its atoms decay spontaneously and send particles shooting outwards. But they usually escape without hitting and destroying a neighbouring atom (the ordinary matter around us and in our bodies is 99.99 per cent empty space). In a bomb, largish hunks of uranium are put together so that escaping particles have a high probability of hitting a neighbouring uranium atom and starting a chain reaction.

There is one important trick needed to make an atomic bomb. Suppose a chain reaction starts. One atom breaks apart and particles shoot outwards and break two neighbouring atoms apart. The particles expelled from these two atoms break four more apart, and the chain reaction proceeds, affecting 1, 2, 4, 8, 16, 32, 64 atoms, and so on. This series of mini-explosions will release heat and energy, and this will cause the metal to melt and ooze down into a puddle. As it does so, the atoms will separate from each other: heat causes expansion. In turn, this will make it less likely that the escaping particles will bump into a neighbouring atom. Thus the chain reaction will fizzle, affecting, say, 64, 32, 27, 16, 5, and eventually 0 atoms. The uranium will melt and become white hot but nothing more.

This is where the physicists call in the engineers. To sustain the chain reaction, the uranium atoms must be held together tightly for just long enough for the chain reaction to proceed. This is a delicate feat of engineering. In one design, unstable atoms are formed into a ball and surrounded by dynamite. Just as the chain reaction is sparked off, the surrounding dynamite is exploded. The inward compressing force of the ordinary explosion holds the uranium together for just long enough (only a small fraction of a second) for the chain reaction to race through the entire core. Even though the metal becomes incredibly hot, the atoms remain close enough to sustain the chain reaction. Suddenly, so much energy is released that the compressing force is brushed aside and a huge explosion is unleashed.

The recipe for an atom bomb is thus simple physics and delicate engineering. First, obtain and purify a few pounds of uranium or plutonium. Keep the material in small samples so that no chain reaction begins spontaneously. Place them gently together in a bomb. At the desired instant, compress the samples together and trigger a chain reaction, say by sharply striking the metal. Hold the compressed sample together for long enough for the chain reaction to consume large numbers of unstable atoms.

In a way, we cannot comprehend the horror of these bombs. The city of Hiroshima has erected a museum and left a few shattered buildings untouched since 1945. This is a moving reminder that science threatens us, and continues to threaten us with annihilation. It is not clear how we will cope in the long run. Our hopes depend in part on the same intelligence that has endangered us, and on a vigilant understanding of these weapons and the physics behind them. Against the horrors of the Second World War, we can now weigh one shining, collective achievement. For more than half a century, no one has dropped an atomic bomb on another human being. Every year that ticks by adds to this fragile miracle.

Interpreting mass–energy

The interconvertibility of mass and energy is a shock. We are accustomed to thinking that the world consists of some sort of stable stuff. It can move back and forth in space, or clump together and fall apart, but somehow survives all such rearrangements. What does it mean to say that this stuff is composed of motion? More poetically, are our bodies just forms of trapped motion? Are our movements just streaks of evaporating matter? Einstein’s equation does not answer these questions. It simply reports the fact that matter and energy can be converted into each other.

Lorentz's minority interpretation offers an interesting explanation of why mass increases with speed. The idea that someone jumping from a skyscraper reaches a maximum velocity may be familiar. As the body rushes earthwards more and more quickly, it tries to push the air out of its way. But the faster the push, the more the air resists it. Eventually there is a balance. Gravity tries to pull the body down even faster, but the air pushes back and prevents any more acceleration. The body plummets downwards at a constant velocity, which physicists call (no pun) its "terminal velocity".

There is an alternative interpretation of this. Instead of saying that the resistance of the air increases with the body's speed we could insist that the mass of the body increases with the body's speed. Both of these would imply that gravity would find it more difficult to further accelerate the falling body. Both of these are in accordance with the observed facts.

In more detail, near the top of the skyscraper gravity initially succeeds in accelerating the body. But as the body falls more rapidly we could say it responds less and less to the force of gravity and continues moving downwards only because of inertia. Since it is more difficult to make heavy bodies speed up, we could say *that the body effectively gets heavier and heavier as it speeds up*. That is why its acceleration dwindles to zero even though the downward force on it stays the same. In fact, at the maximum, terminal velocity, we could say that the body is infinitely heavy, since it no longer responds to the force of gravity at all.

If we did not know about the resistance of the air, and had no other way of sensing air, we might have found it natural to say that mass rises with velocity. This second interpretation is well known to physicists who study the way ships and submarines move through water. They say that such bodies have an *effective mass* that rises with velocity through a fluid. Interestingly, the same is true of electrons and other charged particles travelling through electromagnetic fields. The faster the electron moves, the heavier it seems. It becomes more and more difficult to accelerate through the field. Physicists sometimes say that its effective or *electromagnetic mass* rises with velocity.

Lorentz suggested that the relativistic increase of mass was just such an effect. Since he believed in the existence of the ether, he concluded that rising effective masses were caused by its resistance. That is, the ether behaves like other fluids and resists being shoved aside as bodies pass through it. Since there is so little ether in any volume of space, we do not ordinarily observe this resistance; only as bodies move extremely fast, say at nearly the speed of light, would its effects become significant.

As before, the minority interpretation is appealing because it offers a neat and persuasive explanation, but it depends on an undetectable ether.

CHAPTER 5

The four-dimensional universe

> The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality. (Minkovski, 1908)

Three years after Einstein published his paper on special relativity, his former teacher Hermann Minkovski forever transformed our view of the universe. Einstein had predicted length contraction and time dilation, but Minkovski drew out their radical implications. As the famous quotation above suggests, Minkovski (pronounced Min-koff-ski) showed that space and time were mixed together in a sort of "union". We do not live in a three-dimensional universe with time flowing through. Instead, we live in a *four-dimensional spacetime*. Time is the fourth dimension.

These are strange claims. To assess them, the next two sections lay out some important philosophical issues in general terms. The following sections return to Minkovski and relativity theory.

Is the world made of events?

A tennis ball is real. A tennis court and tennis players are real. But is a tennis match real? Common sense and philosophers like Aristotle assert that the basic things in the universe are ordinary objects like human beings, tennis balls and trees. Modern science disagrees, and says instead that atoms or quarks are basic; human beings and tennis balls are built up from these smaller particles. Both of these views, however, are examples of ontologies in which *the basic objects persist through time*. That is, a tennis ball or an atom exists at one moment, and the next, and the next. Loosely put, one and the same object moves through time.

Some physicists and philosophers think that relativity has definitively shown that our world does not consist of persistent objects: there are no such things. Tennis balls and tennis courts are not real. Instead, the basic objects are events like tennis matches, elections or weddings. These are fixed at a particular time and place and never occur at another time and place. These are the basic objects of an *event ontology*. According to this view, the ordinary objects that appear to persist through time are really just collections of events. We see a tennis racquet striking a ball, a ball in flight, a ball nipping a net, a ball skidding on a court and a ball hitting the opponent's racquet. This sequence of events is usually believed to involve one and the same ball. But in an event ontology, these events are each real and distinct. Events are not made up of persisting objects. There is no single ball moving through the events. Rather, there is a similar-looking, yellow fuzzy patch in each of a series of events.

Philosophers usefully distinguish between *persistence* and *endurance*. An object that moves through time from one moment to the next persists. A sequence of similar but distinct events that creates the illusion of persistence is called an "enduring object". Events are sometimes thought of as *parts of the enduring object*, which is itself just a long-lasting event. In debates over relativity, an enduring object is sometimes called a *spacetime worm* because it is a consecutive series of events snaking through space and time. Thus, in an event ontology, both people and quarks are reinterpreted as spacetime worms.

Compare this to a reel of film shown in the cinema. Each still photograph on the reel is the picture of an event at a particular time and place. The photographs do not change, but the sequence creates the illusion of motion. An event ontology is similar: in reality there are only unchanging events in fixed sequences and, therefore, the illusion of motion, change and persistence through time.

But surely we experience motion and change? We see it all around us! Defenders of event ontologies agree that we have an *illusion* of movement and change, but deny their actual existence. The sensation of movement that we might experience in a moving car is just that – a sensation. It occurs at an instant in our minds, and is not itself direct evidence for motion outside our minds. Even common sense agrees that there can be sensations of motion without real motion, as when someone is sick with vertigo.

Likewise, defenders of event ontologies argue that, strictly speaking, we do not in fact see motion. We see an object at one place and have a memory of a similar object in another place; the visual image and the memory together, they argue, produce an impression of motion. The existence of the memory is a fact about the present, and not itself direct evidence for true motion. Moreover, since motion occurs across time, we could not experience it directly. That would imply experiencing a past moment in the present. In short, defenders of an event ontology say that all experience occurs at a moment in time, and such experience cannot be direct evidence for motions and changes that stretch out through many moments. *Thus an event ontology is compatible with all our direct experience, and therefore strictly in accordance with all observation and experiment*.

Some philosophers criticize event ontologies, saying that they make the similarity of events in a sequence an incredible accident. Why should the event of the racquet striking the ball be followed by another event that includes the ball? This makes sense if the ball moves through time to the next event. But if there is no true movement and change, why should consecutive events be similar at all? Could a ball at one moment be followed in the next by a swallow in mid-flight? Why do we not see series of events that look like "cuts" in a film, in which the scene changes instantly and there is no relation between consecutive stills?

The answer to this objection is interesting. Defenders of event ontologies admit that the similarity of events that follow one another has no physical explanation: it is just a "brute fact" about which nothing more can be said. Perhaps God just decreed that events have a pleasing order. But, the defenders continue, in the common-sense universe, where objects are supposed to be real and persist through time, there is a corresponding mystery. Physical laws account for movement through time, and these are also just brute facts. Thus both views have to accept unexplainable brute facts.

In an event ontology, there is no explanation for similarities among sequences of events; in a common-sense universe, the movements of persistent objects are explained by laws, but these laws themselves – at some level – have no explanation. Thus in both there remains a mystery about the nature of movement and change. (Moreover, some philosophers say that such laws are just regular patterns of events, which would make the mystery of laws identical to the brute mystery of ordered events.)

In short, event ontologies seem peculiar but are surprisingly coherent and compatible with all our experience. Does relativity theory decide the question of whether persistent objects or events are real?

Do the future and past exist now?

Most of us believe that only the present exists. Events in the future will exist, and events in the past did exist, but neither future nor past events exist now. This view is called *presentism* and treats time and space in very different ways. The different parts of space all coexist in a present moment, but only one part of time exists; namely, the present.

Presentism is compatible with either the existence of persistent objects moving through time or with an event ontology. A presentist merely insists that "only the present exists now" and is indifferent to what the present consists of, that is, whether it is persistent objects or events.

Many interpreters of relativity have asserted that the theory proves that presentism is false. Instead, the past and future coexist with the present, and are just as real as the present. This is strange and perhaps even frightening. It means that past wars are still being fought, and that every step of our future lives is already happening in some sense. In debates over relativity theory, such a world is called the block universe, because the entire four-dimensional universe, including the past and the future, seems to be like a giant block of ice: all events in the past, present and future coexist and are frozen in their locations in space and time.

For our purposes, we will assume that either presentism or the block universe view must be true. That is, other combinations (like an existent present and past, but nonexistent future) will be ignored.

Metaphors are often used to help us mentally picture a block universe. It has been compared to a loaf of bread or bologna. The present moment is a slice across the middle of the loaf; the future and the past lie on either side. Of course, the loaf is only a three-dimensional object, and the block universe is four-dimensional. Thus slices of the block universe would each be a three-dimensional world at an instant: just like the world we see around us now. The series of such three-dimensional "slices" – past, present and future – together make up the whole four-dimensional block.

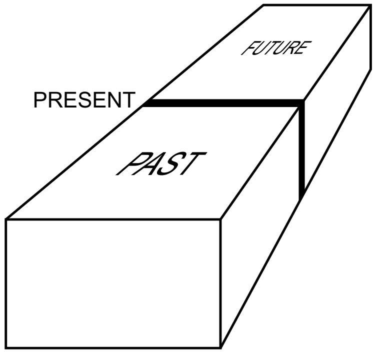

Figure 5.1 *The block universe. A frozen four-dimensional world of events.*

Since each slice of the block universe is a complete world-at-an-instant, it contains all objects that exist at the time. This is, again, like cinema film: each still photograph in the film is a picture of a scene at an instant, and the sequence of all the stills makes up the entire film. If the still photographs were cut apart and bundled together in a pile, we would have yet another image of the block universe.

If it is true that we live in a block universe, then there are no objects persisting through time. That is, *a block universe implies an event ontology*. This is because there is no real motion or change in a block universe. True motion occurs when a body now in one place occupies another place in the future: that is, when one and the same body moves from one location to another as, for example, when someone walks across a room. This could not happen in a block universe, where future events already exist. In a block universe, future events have an existence that is just as real and full-blooded as present events.

Advocates of the block universe also claim that the movements and changes we see around us are all a kind of illusion. The star of a film may occur in every still on the reel, and may appear to be moving when the film is shown, but actually does not move at all: each still is fixed. Similarly, the slices in a block universe are each slightly different. If we believe that someone is walking across the room, there is actually a series of slices each with a walker in slightly different positions. In each slice, the walker is standing stock still like a sentry. Thus both the event ontology view and the block universe view assert that motion is just a series of fixed events, like a sequence of still photographs. In the block universe all the events in the series exist at once: from the past, to the present and into the future.

When discussing the block universe or event ontologies, philosophers sometime find it awkward to use expressions like "the past exists now" or "the future has already happened". The reason is that verbs like "to exist" include a reference to the passage of time, that is, they are past, present or future tense. Thus, to say "the past exists" seems like a contradiction because the verb is in the present tense. To avoid this, philosophers tend to talk about *tenseless existence*, that is, a way of existing that does not imply a flow from the past into the future but is instead eternally static. Thus they say that, in a block universe, the past and the future "exist tenselessly", and mean that "exist" here is not to be understood as a verb in the ordinary present tense.

A final distinction that is important for understanding the block universe view is that between Laplacian determinism and fatalism:

- *Laplacian determinism*: the view that conditions at the present moment together with physical laws determine all future events. That is, laws ensure that the future can happen in only one way.
- *Fatalism:* the view that all future events are fixed, but not necessarily by physical laws. That is, the future can happen in only one way, but there may be no regular or law-like patterns in future events. Perhaps God or fortune has decreed that a series of miracles or physically uncaused events come about.

The block universe view is fatalistic. In a block universe, there can be only one future because it is already there, and in some sense has already happened. But the block universe view does not depend on the existence of laws, or any regularities between slices. Laplacian determinism may be true in a block universe, or may not be.

It was believed that classical physics before Einstein provided evidence for the truth of Laplacian determinism, but many now believe that twentieth-century physics disproved this view and showed that there is true randomness in microscopic events. The defeat of Laplacian determinism, however, would not count against the block universe view. (Thus the block universe view is compatible with probabilistic interpretations of quantum theory.)

Spacetime

> Upon giving up the hypothesis of the invariant and absolute character of time, particularly that of simultaneity, the four-

> dimensionality of the time–space concept was immediately recognised. It is neither the point in space, nor the instant in time, at which something happens that has physical reality, but only the event itself. There is no absolute relation in space, and no absolute relation in time between two events, but there is an absolute relation in space and time . . . Upon this depends the great advance in method which the theory of relativity owes to Minkovski. (Albert Einstein, *Meaning of Relativity*)

Before relativity, it was thought that the world and objects in it were all three-dimensional. This meant everything had a length, breadth and height. It is hard to say what a dimension is. We picture a dimension as a long, straight line. If three straight lines can be drawn at right angles to each other, the space they are drawn in is three-dimensional. On a piece of paper, only two straight lines can be drawn at right angles, so the paper is two-dimensional.

Lines through space can be used to name the locations of objects. On the two-dimensional surface of the earth, places can be located by their latitude and longitude. In three-dimensional space, we can name places using the three coordinates (x, y, z). What would it mean to say that the world is really four-dimensional? It is easy to locate all events in space and time because each has a place and a date. Each event could therefore be given four coordinates (x, y, z, t). In effect, we routinely recognize that events have four dimensions when we agree to meet someone for coffee at a certain place and time. Thus it is true but trivial to say that events have four coordinates. When some physicists say the world is four-dimensional they are making a different and much stronger statement. To understand their claim, we begin with a fact, and then consider its interpretation.

Suppose there are two events, A and B, each at a different place and time. Using rulers and clocks we could measure the distance between the two places and the duration between the two times. These two numbers indicate how separated the events are in space and time. But, as we have seen, these distances and durations are not invariant and therefore are not real properties of anything. Now something magical happens. Although neither the distance nor the duration is invariant, together they do form an invariant number. They are combined using a peculiar recipe. The distance and duration are treated as if they were two sides of a right-angled triangle. Using a formula very similar to Pythagoras' theorem, we calculate the length of the "third" side of the triangle. This new

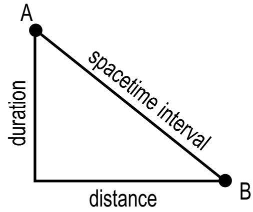

Figure 5.2 The spacetime interval. A number calculated from the distance and time elapsed between events A and B that expresses how far apart they are in spacetime.

number is *invariant*. Since it is some kind of combination of space and time, it is called the *spacetime interval*.

Measurements of distances and durations depend on speeds, since they will contract or dilate, but the spacetime interval between two particular events is always the same: everyone who measures and calculates will find the same number. This is surprising. How do two variable numbers combine into a constant? One way of thinking of it is that, at higher speeds, the lengths shrink and the times elongate, and these variations compensate for each other. All physicists agree that the invariance of spacetime intervals is a fact. That is just a statement about numbers that we calculate from measurements. But what does this imply about reality? How should we interpret that invariance?

As we have seen, the mainstream interpretation of relativity denies the existence of real distances and durations. They are not real properties of individuals. This is, however, a purely negative doctrine. But clearly things are separated from each other in space as well as in time. What are they separated by? The mainstream physicist answers that, while neither space nor time exists in its own right, the combination of them does. Things are separated from each other by stretches of spacetime.

The central argument for the reality of the spacetime interval was made by Hermann Minkovski. In essence, he argued that if all measurements give the same value for a property, then the property must be real. If there were a painting so beautiful that everyone fell down instantly babbling about its beauty, then we would conclude that beauty really was a property of the painting. Likewise, Minkovski argues that if the spacetime interval appears the same in all measurements, then it must be real.

The positive doctrine of the mainstream interpretation is thus found in the following argument:

Reality of the spacetime interval

A. The apparent (measured) spacetime interval is invariant. (P)
B. If an apparent property is invariant, then it corresponds to a real property. (P)
C. Therefore, the spacetime interval is a real property. (from A,B)

It is now clear that the mainstream interpretation denies three-dimensional distances and durations, which are not real properties of individual things, but affirms the existence of four-dimensional spacetime intervals, which are real properties of events.

Minkovski helped clarify the meaning of the spacetime interval with his well-known *rotation analogy*. Consider some three-dimensional object such as a sculpture of Venus. As we view it from different angles, its width may change. It may seem wide when viewed from the front, but seem narrow when viewed from the side. Minkovski said that spacetime is real, but that different sets of rulers and clocks are all "viewing it from different perspectives". According to one set, a spacetime interval may appear short in space and long in time, but another set may find it long in space and short in time. More crudely, it might be said that when we treat distances and durations independently, we are arbitrarily chopping up a spacetime interval into so much space and so much time. Another observer may choose to chop it up differently, into less space and more time.

This rotation analogy also explains what it means to say that *distances and durations are relations*. Suppose that the sculpture of Venus sits in a space, and that we choose three lines in the space to be the mutually perpendicular x-axis, y-axis and z-axis. Given these lines, we can say the sculpture has, say, a length of two metres along the x-axis and three metres along the y-axis. But these lengths are *relations* between the three-dimensional shape of the statue and certain lines. If we chose different lines to be our axes, then the "length along the x-axis" would change. In short, "length along the x-axis" is not a property that depends only on the individual statue; it is a relation between the statue and a direction.

Likewise, the mainstream interpretation asserts that *four-dimensional* "shapes" and intervals are real. Choosing an x-axis in space and a time axis defines the distance and duration of a four-dimensional shape (an event). But if the directions of these axes change, then the distance and duration change. They are relations between the four-dimensional shape and certain directions.

Spacetime intervals may also be helpfully interpreted as "sizes" of events. In three-dimensional space, volume is length multiplied by breadth multiplied by height. Likewise, in four-dimensional space, the four-dimensional volume is duration multiplied by length multiplied by breadth multiplied by height. Thus a tennis match may take three hours and fill a tennis court, and we can calculate the four-dimensional volume of this event. This region of spacetime has an invariant volume, even though the length of the court and the duration of the match are relative to the clocks and rulers used to measure them.

To summarize, the mainstream interpretation makes several claims:

- distances and durations are not real properties of individuals
- nor are they mere appearances
- spacetime intervals are invariant and therefore real
- distances and durations are relations between spacetime intervals and directions in spacetime.

Einstein always insisted on the first two ideas, and later accepted Minkovski's interpretations of the spacetime interval.

The minority interpretation accepts, of course, the fact that the spacetime interval is invariant, but it interprets it as a mathematical accident. Movement through the ether causes lengths to contract and clocks to slow. Since these two processes have "opposite" effects, we should not be surprised that, if we combine both in a calculation, they cancel and leave a constant. Lorentz never thought that the invariance of the spacetime interval was important.

The block universe argument

Some physicists believe that relativity theory has proved that the past and future exist in a giant four-dimensional block universe. Although his views changed during his career, Einstein, for example, made the following statement in 1952, a few years before he died. He argued that the relativity of simultaneity implies a block universe:

> The four-dimensional continuum is now no longer resolvable objectively into slices, all of which contain simultaneous events; "now" loses for the spatially extended world its objective meaning . . .

> Since there exist in this four-dimensional structure no longer any slices which represent "now" objectively, the concepts of happening and becoming are indeed not completely suspended, but yet complicated. It appears therefore more natural to think of physical reality as a four-dimensional existence, instead of, as hitherto, the evolution of a three-dimensional existence.
>
> (Einstein, 1952)

Although his language is cautious here, Einstein's meaning is clear. There is no physical "evolution" through time, that is, no change or persistence; instead, a static four-dimensional block exists. He says that becoming is not "completely suspended" because there is a residue of change in a block universe; namely, the adjacent, static slices differ slightly, and this creates an illusion of becoming and change.

It should be emphasized first that most physicists regard the entire issue of the block universe as speculative, and simply have no opinion about the matter. For them, it is simply not a scientific question since we cannot experiment directly on the past and future. However, many physicists, such as Einstein, Hermann Weyl and others, thought that relativity theory did prove that our world was a block universe. A number of philosophers have also thought so, although there is naturally disagreement in the details of their views. For example, Bertrand Russell and Hilary Putnam have argued that relativity theory implies some kind of block universe.

Arguments about the block universe all arise from attempts to *interpret* the special theory of relativity, and all go beyond Einstein's 1905 theory by adding new premises. In particular, all attempt to say what reality is like if simultaneity is relative. Einstein's *theory*, on the other hand, does not mention reality; it merely describes relations between measurements, that is, between appearances. Thus different interpretations of relativity theory will imply different views about the block universe. As pointed out below, the minority interpretation escapes this strange consequence.

The quotation from Einstein above contains a short but very powerful argument for the block universe. According to his theory, simultaneity is relative. That means that different sets of rulers and clocks, moving relatively to each other, will find that different sets or different "slices" of events are simultaneous. In this sense, to say that two distant events are simultaneous is merely a convention or arbitrary agreement, and has no physical or "objective" meaning. If different clocks were chosen, different events would be simultaneous. As Einstein interprets it above, this fact already implies that we live in a block universe.

Einstein's friend and colleague at Princeton, the logician Kurt Gödel, filled in more detail in a 1949 essay. According to him, the relativity of simultaneity seems to lead to:

> an unequivocal proof for the view of those philosophers who, like Parmenides, Kant and modern idealists (such as McTaggart), deny the objectivity of change and consider change as an illusion or appearance. The argument runs as follows: Change becomes possible only through a lapse of time. The existence of an objective lapse of time, however, means that reality consists of an infinity of layers of "now" which come into existence successively. But, if simultaneity is relative, reality cannot be split up into such layers in an objectively determined way. Each observer has his own set of "nows" and none can claim the prerogative of representing the objective lapse of time.
>
> (Gödel, 1949)

The similarity of this passage to some of Einstein's writings suggests that he and Gödel had been discussing this issue.

This short argument turns upon the idea that true physical change implies profound differences between the past, present and future. During change, one and the same object loses some properties and gains others. It also persists through time, moving from one moment, which ceases to exist, into the next moment. But if simultaneity is human choice – mere agreement about which rulers and clocks to use – then there is no real difference between the present and the past or future. These labels, "past", "present" and "future", are merely human names that reflect no physical difference in the events they describe. Thus we have:

Short argument for block universe

A. If simultaneity is relative, then there is no physical difference between the past, present and future. (P)
B. Simultaneity is relative. (P)
C. Therefore, there is no physical difference between the past, present and future. (from A,B)
D. But, if there is no physical difference between the past, present and future, then there is no true change. (P)
E. Therefore, there is no true change. (C, D)

The last line means that we live in a block universe. If there is no true change, then any event that ever existed always exists: it cannot change from existent to nonexistent.

By way of analogy, consider a map of Earth showing the equator. We could travel there and find many physical differences between the northern hemisphere and southern hemisphere on either side of the equator (trade winds in different directions, etc.). Likewise, some claim that relativity theory provides a realistic map of our four-dimensional universe. They insist, however, that unlike the equator, its lines of simultaneity correspond to no physical difference in the universe. We find on the four-dimensional map no objective dividing line between the past and the future, and are supposed to believe that no such line exists in nature.

In other words, a realistic interpretation of the relativity of simultaneity is incompatible with presentism. This doctrine implies that the present "slice" of simultaneous events is the only existent slice. The past slices have ceased to exist, and future slices do not yet exist. According to presentism, change is the passing away of one slice and the emergence of the next. But if Einstein's theory is a good map of reality, then there is no physical difference between the present slice of events and past or future slices. In particular, the conventional labels "past" and "future" do not imply the physical label "non-existent".

Much of the literature on the block universe concerns another, related argument that involves three events, and therefore can be called the *triangle argument* . This argument begins with the premise that, since *some* distant events coexist with me, *at least* events simultaneous with me at the present moment exist.

Solipsism is the belief that only I exist. That is, the universe consists of me and nothing else; all other things and space itself are an illusion of some sort in my mind. Surely, however, we deny solipsism. But then *some* other bodies or events must coexist with me. The only question is which events are the coexistent ones.

The triangle argument is aimed at those who accept coexistence but will not at first agree that past and future events exist now, and resist attempts to drive them to this conclusion. Suppose, the argument begins, that past and future events do not coexist with me at the present moment. Then, since some events do coexist, it must be simultaneous events that coexist. The argument shows, however, that even this modest beginning leads back to the coexistence of the past and the future, and thus to the block universe.

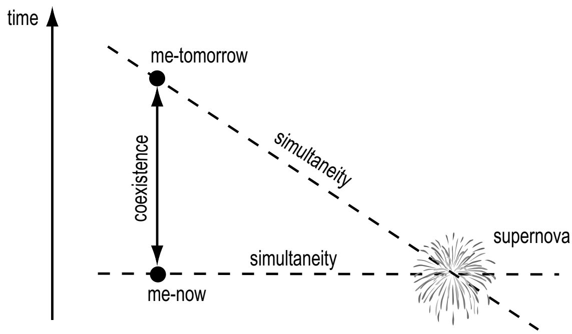

Figure 5.3 The triangle argument. The dotted lines indicated simultaneity (which implies coexistence), and the two-headed arrow indicates the derived coexistence relation.

Suppose that there are three events: me-now, me-tomorrow and a distant supernova. Suppose that, according to one set of rulers and clocks, me-now is simultaneous with the distant supernova, but that, according to a different set of rulers and clocks, me-tomorrow is simultaneous with the supernova. Then we have the argument:

Triangle argument for block universe

A. If an event exists and it is simultaneous with another event, then the other event also exists. (P)
B. Me-now exists; me-now and the supernova are simultaneous. (P)
C. Therefore, the supernova exists. (from A,B)
D. But, the supernova and me-tomorrow are simultaneous. (P: according to other clocks)
E. Therefore, me-tomorrow exists. (A,C,D)
F. If one event exists and another event exists, then they co-exist. (P)
G. Therefore me-now and me-tomorrow co-exist. (B,E,F)

This means that the self I am now and feel to be real (me-now), coexists with myself tomorrow (me-tomorrow), which is just as real. Of course, since we could have chosen *any* pair of events far away enough from the supernova, the conclusion means that the present and the future coexist, and thus that the entire future and its past coexist. Thus we live in a block universe.

Clearly the first premise, A, is very suspicious. It moves from a conventional label, "simultaneous", to an assertion about physical existence. This is precisely the inference that Einstein's theory is supposed to deny. But the only alternative (short of solipsism) is to concede that some events in the past and future do coexist, and the argument is aimed at those who wish to deny this.

The fourth line of the argument, premise D, has troubled some critics. It implies that two sets of clocks and rulers, and therefore two definitions of simultaneity, are used. In the context of this argument, however, this is legitimate. Briefly put, premise A says that simultaneity is good evidence for objective existence. Once we know something exists, we are free to use other definitions of simultaneity, and that subjective choice will not affect what objectively exists.

Note that the coexistence does not imply simultaneity. Me-now and me-tomorrow are not simultaneous.

The importance of the triangle argument is that it creates an embarrassing dilemma for interpreters of relativity theory. If they deny solipsism, they must agree that some events coexist. But if they deny that the past and future coexist with the present, then all the coexistent events must be in the present. But this minimalist idea together with the relativity of simultaneity drives them back to the idea that the past and future coexist. *For those who interpret relativity, it seems that there is no middle ground between solipsism and the block universe.* Any attempt to restrict robust existence to some single slice of the four-dimensional world is the assertion of some privileged or absolute simultaneity, and is profoundly at odds with the mainstream interpretation of relativity theory.

Indeed, one philosopher has argued that relativity theory does imply something very close to solipsism. Howard Stein severely criticized arguments for a block universe, and spelled out in detail which events he believes coexist with me-now. According to his view, only me-now and certain past events coexist. An event in the past coexists with me-now if light from the event *could* reach me, that is, past events that could have causally influenced me still exist. This appears to be a very strange view. Other people do not exist now, but their past selves may exist and therefore coexist with me. Stein's view shows that although relativity theory makes good predictions, it appears to be very difficult to spell out what it implies about the nature of reality.

In the end, it is very difficult to interpret the relativity of simultaneity without embracing some form of block universe. If this seems implausible, then there is extra reason to consider the merits of the minority interpretation. According to this, the relativity of simultaneity is mere appearance; in reality, only clocks at rest in the ether show true time and can be used to judge which events are really simultaneous. Thus Lorentz and other defenders of the minority interpretation can naturally say that only the present is real. *The minority interpretation is compatible with presentism.*

CHAPTER 6

Time travel is possible

Causal order

The iron chains of causality link events together into a definite order: a cause always precedes its effect. If, however, there are distant events that do not influence each other, what decides their order?

As noted above, time dilation implies that different sets of rulers and clocks moving relative to each other will assign different orders to distant events. Consider, for example, three events: event A, which causes event B, and a distant event, X. Since A and B are connected by some causal process, their order is fixed. But if event X is distant enough from both, then different clocks may register any of the three orders

A, B, X or A, X, B or X, A, B

That is, the distant event may follow both A and B, happen between them or precede both.

According to the mainstream interpretation of special relativity, durations and other temporal intervals are not invariant, and are therefore not real. According to this view, there is no fact of the matter about which of the three orders above is real and physical. The events all occur and are all real, but there is no physical fact that makes X later or earlier than the others. Just as there are no unicorns or pink elephants, there is no order between distant events that do not influence each other.

Consider another illustration. Suppose that there are two long queues leading into two doors at a club or music concert. Within each queue the order is clear. The people closer to the door will enter first. But as the two queues shuffle past each other, sometimes one is faster and sometimes the other. Thus there is no clear order between people in different queues. In the future, when they meet inside the club, they will influence each other, and they may have influenced each other in the past. But while they are separated from each other in different queues there are no influences, and therefore no meaningful order between them. According to the mainstream interpretation, events in our world are like this. Some are linked in chains of causes, but between the parts of chains that do not influence each other there is no definite order.

Which events are chained together into an order by causes, and which are not? Since causes are carried by things with energy or mass, and these cannot travel faster than the speed of light, no cause can propagate faster than light. Thus if light cannot pass from one event to another, then no causal influence can and the pair of events is not causally ordered. There is no fact of the matter about which is earlier and which is later. Thus, according to the mainstream interpretation, if light emerges from a distant star and travels this way but cannot reach Earth before the next election, then the emission of the light was neither earlier nor later than the next election. Similarly, it would take light about a billionth of a second to cross an object the size of a human brain. If two synapses fire in such a way that light could not travel from one firing to the other, then there is no physical order between these events.

Killing grandmothers

Using faster-than-light velocities we could telegraph into the past.
(Einstein, quoted by Sommerfeld, 1908)

If you could travel faster than light, you could kill your grandmother before she gave birth to your mother. Since this is impossible, we have a second argument for the celestial speed limit. The strategy of the argument is a *reductio ad absurdum*. That is, the assumption that faster-than-light travel is possible is shown to lead to nonsense, and thus must be discarded.

Take as the three events above your grandmother's adolescence (A), the present moment (B) and a distant exploding star, that is, a supernova (X). Suppose that the explosion is so far away that its light does not reach Earth for many centuries from now. Thus the explosion is earlier or later than your grandmother's adolescence, *or* the explosion is earlier or later than the present moment, depending on which set of rulers and clocks is used. Now assume, *contrary to the theory of relativity*, that a magical rocket is somehow capable of travelling faster than light. This means that it can, for example, travel from Earth out to the exploding star and return again before light from the explosion manages to reach Earth for the first time. In fact, it would enable you to board the rocket and travel for a sightseeing tour of the explosion. Since the explosion is "later" than the present, your trip would seem like an ordinary trip: the arrival at the star would be after the departure from Earth. Since the explosion is also "before" your grandmother's adolescence, however, you could instruct the pilot to return to visit your 13-year-old grandmother and kill her. Such a return trip would also seem like an ordinary trip: from one event to another in *its* future.

In effect, the magical rocket is a time machine. Since relativity theory says that distant events are not ordered in time, the rocket can travel backwards in time by hopscotching across to a distant event and then returning to the past. Faster-than-light speeds would not enable a trip directly into your past; it would be necessary to visit distant places that are outside your time order, and then re-enter your time order.

In the example of the queues above, this would be like jumping between the two queues. By shifting back and forth, you could enter

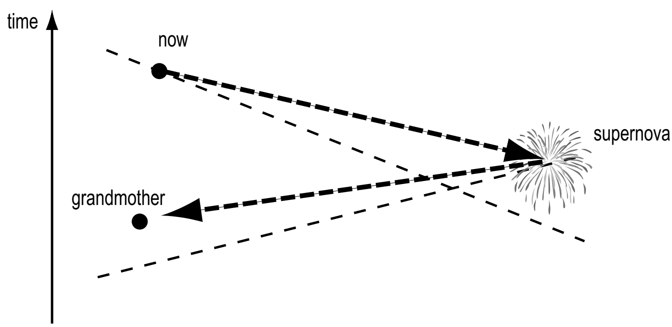

Figure 6.1 *Killing your grandmother. Each dotted line connects events that are simultaneous. Each dotted arrow is a faster-than-light rocket trip into the future (the arrows can be above the lines of simultaneity and yet slope downwards on the graph because of the high speed).*

the club earlier than someone directly in front of you, and thus jump ahead in time (or later, if you were unlucky and jumped to a slower queue).

But, as the example shows, time travel leads to contradictions. If you are reading this, your grandmother did give birth to your mother. But if the magical rocket makes time travel possible, you could kill your adolescent grandmother before your mother's birth. Thus your mother would be born and not born. There's clearly something wrong about all this, and it leads to the following argument:

Time travel is contradictory

A. There is faster-than-light travel. (P: leads to absurdity)
B. Some distant events have no definite order in time. (P)
C. If there is faster-than-light travel and distant events have no definite order, then there is time travel. (P)
D. So, there is time travel. (from A,B,C)
E. If there is time travel, then there are contradictions. (P)
F. So, there are contradictions. (D,E)
G. But there are no contradictions. (P)
H. So, there is no faster-than-light travel.

The last line does not follow rigorously. When an argument crashes into contradiction, one or more of the preceding premises must be thrown out. But it is sometimes not immediately clear which premise is the culprit responsible for the contradiction. Additional arguments may be needed to justify pointing the finger of blame at a particular premise.

In this case the second and third premises, B and C, are consequences of relativity theory, and the last, G, is our bedrock assumption. If we stand by these, then we must reject either faster-than-light travel (premise A), or the idea that travel back in time would produce contradictions (premise E).

Most philosophers do reject time travel because it would lead to contradictions. In a surprising essay, however, the metaphysician David Lewis argued that time travel would not lead to contradictions. In brief, he says that any visit to the past has already happened, and thus could not change the way the past happened. If it is a fact that your grandmother gave birth to your mother, then it is a fact that any time traveller who happened to be there did not kill her first. A murderous time traveller would find that quite ordinary circumstances contrived to forestall her death: the gun misfired, and so on. If

Lewis is correct, then there is no logical argument – like the above – against time travel. We can throw out premise E instead of the first premise, and still avoid the contradiction. Philosophers often describe something as "possible" if it is not contradictory. Something may be logically possible in this sense, even though physical laws forbid it. Lewis can therefore conclude that "time travel is possible".

Physicists are more interested in the question of whether time travel is *physically possible*. Most would quickly say "no", but an intriguing line of research was opened up by Kip Thorne and others in the early 1990s. He asked whether, if space can really bend and curve as Einstein says (see Chapter 13), it is so flexible that "tubes" or "tunnels" could connect the present to the past. If so, then anything travelling down through the tube would emerge at an earlier time, and time travel would in fact be physically possible. Although surprising progress was made on the theory of such *wormholes* through spacetime, most physicists remain sceptical. But the final word is not yet in.

CHAPTER 7

Can the mind understand the world?

We have studied the elements of Einstein's special theory of relativity, and can now put them together into a more panoramic view. He began by assuming the truth of two principles, both drawn from experience and experiments: the principle of relativity; and the constant speed of light. From these two central principles, Einstein and his followers *deduced* a series of stunning consequences, of which we have met several in turn during the previous chapters:

- time dilation
- relativity of simultaneity
- length contraction
- symmetry of effects
- relativistic mass increase
- energy–mass conversion
- celestial speed limit
- invariance of the spacetime interval.

These are predictions about what observation and measurement will discover, that is, about phenomena and appearances. We have not explored the details of the arguments Einstein gave for deducing these effects from his principles. It is enough here to state that they are consequences of the principles and have been confirmed by experiments.

These two principles and their predicted consequences together form the *theory*: Einstein's special theory of relativity. Note that this deals only with measurements made by equipment moving inertially (say, carried by a coasting spaceship). Einstein removed this restriction in his general theory, which we will examine in Chapter 13. Clearly, there is much that is puzzling and mysterious about the special theory of relativity. Why is the speed of light, unlike all other moving things, constant? Why are steady speeds undetectable? Why are physical laws the same regardless of speed? Why do distances and durations and masses depend on speed? Einstein's theory does not answer these questions. At best it explains one mystery only by postulating another. It is content to assume its principles, make predictions and subject those to experimental test. This has frustrated many physicists and philosophers, who have therefore gone beyond the bare bones of the theory by *interpreting* it, and saying what it implies about the reality beneath appearances. We can now compare the two interpretations we have studied.

The mainstream interpretation:

- was originated by Einstein in 1905 and Minkovski in 1908
- asserts that distances and durations are not real properties – they are relations
- and therefore asserts that there is no objective present
- and therefore asserts that we live in a four-dimensional universe
- and therefore favours the block universe view – the past and future exist
- and therefore favours an event ontology without real change or movement.

As emphasized earlier, not all of those who defend the mainstream view accept all these points. Most physicists probably accept that distances and durations are not real properties, that there is no objective present and that we live in a four-dimensional universe. However, most do not speculate about the existence of the past or the future. As the arguments above showed, though, if simultaneity is really relative, the block universe view may be unavoidable – as several prominent physicists have thought.

The mainstream interpretation seems to adhere cautiously to Einstein's theory. For example, since the theory predicts that times depend on who measures them, it concedes that these are not real and objective. But any attempt to spell out what this implies about change and the reality of a four-dimensional spacetime soon encounters unpleasant implications. What begins as a minimalist interpretation seems, by the end, implausible.

It should be noted that Einstein's own views were always complicated and shifted considerably during his long career. It is best to be careful and not assume that he finally favoured any single interpretation of relativity.

The minority interpretation:

- was developed by Lorentz and defended with variations by others
- asserts that distances and durations are real properties, but vary with speed (relative to the ether, etc.)
- asserts that we live in a three-dimensional space with time flowing
- asserts that there is an objective present
- and therefore is compatible with presentism – only the present exists
- and therefore is compatible with an ontology of persistent, changing objects.

The minority interpretation proposes an elaborate ontology that leads to many satisfying explanations, but also creates new puzzles without leading to any new predictions and experimental support.

In 1913, after years of struggle with special relativity, Lorentz rather wistfully summarized the debate between the two interpretations – a debate he was losing:

> According to Einstein, it has no meaning to speak of [the true] motion relative to the ether. He likewise denies the existence of [invariant and] absolute simultaneity. It is certainly remarkable that these relativity concepts, also those concerning time, have found such a rapid acceptance.
>
> The acceptance of these concepts belongs mainly to epistemology [i.e. to philosophy, since no experiment yet compels us to adopt one view or the other]. It is certain, however, that it depends to a large extent on the way one is accustomed to think whether one is most attracted to one or another interpretation. As far as this lecturer is concerned, he finds a certain satisfaction in the older interpretations, according to which the ether possesses at least some substantiality, space and time can be sharply separated, and simultaneity is not relative.
>
> Finally, it should be noted that the daring assertion that one can never observe velocities larger than the velocity of light contains a

> hypothetical restriction on what is accessible to us, a restriction which cannot be accepted without some reservation.
>
> (Lorentz, 1913)

This last point shows extraordinary foresight. Lorentz did not know that, some 80 years later, new experiments would hint at the existence of faster-than-light effects and revive his interpretation of relativity in some quarters. These historic experiments have weakened the dominance of the mainstream interpretation and have renewed hopes for the minority interpretation, as we investigate below. The debate over relativity theory is very much alive, and perhaps will only be settled by readers of this book and the coming generation. This is a time of great progress, and of deepening mysteries.