PART I

Einstein’s revolution

CHAPTER 1

From Aristotle to Hiroshima

Cup your hands together and peer down between your palms.

What is between them?

One answer is “air”. But we think of air as composed of separate molecules, like isolated islands. What lies between the molecules?

Nothing?

The distances between the molecules differ. Could there be more “nothing” between some, and less “nothing” between others? Could nothing really exist?

The empty space does seem to be nothing. It is tasteless, colourless and weightless. It does not move, and the gentlest breeze can pass through it without resistance.

This is our first question. What is between your cupped palms? Is it space, a vacuum, a place? Is it there at all? Is it something or nothing?

Now pause silently for a moment until you can feel the blood pulsing through your hands. Time is flowing. Your brain is sensitive to the physical passage of time and as each second or so passes it rouses itself and decides to stimulate your heartbeat, sending blood coursing down through your palms.

Does time *flow* invisibly through the space between your palms, as blood flows through your fingers or as a river flows past it banks? Can you feel time flowing there? Is that the right metaphor?

Does time flow more slowly and more quickly, or at a steady rate? If steady, then steady compared to what? Does it flow at a speed of one hour per . . . hour?

If no body moves through a space does time still flow there? Can time proceed without change? This is our second question. What is the flow of time? Is it happening there in the empty space between your palms, or in the space your brain occupies? Is time the same as physical change, or is it the cause of change?

These questions about space and time seem idle at first. It is not clear even how to begin, how to get a grip on them. But we have learned otherwise.

Consider one time and place. On 6 August 1945, early on a bright sunny morning in the city of Hiroshima, tea was being made in offices, children were being bundled off to school and a lonely, propeller-driven plane buzzed unnoticed through the sky above. When the atom bomb fell, the furious, boiling ball of fire killed some one hundred thousand human beings at once. The city centre disappeared, rivers and criss-crossing canals were vaporized and buildings were blown apart for miles. Pedestrians walking across a distant bridge were suddenly sooty silhouettes on scarred concrete. Many more who at first survived the initial blast soon died horribly as their flesh peeled from their bones, and their organs were eaten away by the radiation.

The atom bombs dropped on Hiroshima and Nagasaki, like those still poised and ready in missile silos around the world today, stand as emblems of the power – of the depth and the danger – of our new ideas about space and time. The basic theory of the bombs is given by Albert Einstein's famous equation that says that ordinary matter can be converted into tremendous explosions of pure force and energy. The following chapters will trace Einstein's surprisingly simple theories, showing how new ideas about time led to new ideas about energy, and give instructions for constructing an atomic bomb. But here we should pause to contemplate the power of ideas, the possibility that seemingly idle questions may have far-reaching consequences.

Modern answers to the two questions above mix great tragedy and great beauty, and are known as the "philosophy of space and time". This subject has played a central role in European philosophy since the time of the ancient Greeks. It is sometimes traditional to divide philosophy – the "love of wisdom" – into three branches according to the three leading questions:

- *What is there?* What exists? What is reality composed of? Does it include atoms, space, ghosts, souls, Beauty, God?
- *What can we know?* Which sorts of knowledge are reliable? Can we trust our senses? Who should we believe? What is truth?

- *What should we do?* What is good or evil? Is our aim successful survival or saving our souls? Should we tell lies? Should we be guided by reason or emotion, or both?

For each question, the corresponding branch of philosophy is:

- *Metaphysics* – the study of reality
- *Epistemology* – the study of knowledge
- *Ethics* – the study of good and evil, of values

The philosophy of space and time is part of metaphysics. Some people mistakenly think that the word "metaphysics" means "after or beyond physical science", but the word is really an historical accident. Historians explain that Aristotle (384–322BCE) wrote many books, which were kept in a chest after his death in 322BCE. A later editor bound them together into volumes and gave each volume a title. One dealt with "Physics", and was so entitled. The next dealt with more basic questions but had no title. It came to be called "the book that came after the one entitled Physics", and this name, "After-the-Physics" or "Metaphysics" ("meta" being Greek for "after"), has stuck through the ages. Aristotle would have probably preferred to call it "First Philosophy", simply because it dealt with the most basic and general questions that could be asked. It was thus a deeper continuation of physics, not a separate subject.

This is important because the philosophy of space and time deals with many ideas that are part of modern physical science: it is not "after" or "beyond" physics. Here, there is no dividing line between philosophy and science.

In fact, the division between philosophy and science may have been a temporary aberration. A little history will help explain this. What we call "science" in the modern sense grew from a small movement in the 1600s led by a few philosophers, aristocrats and mechanics. At that time the new vogue in studies of nature was simply known as "philosophy". Only some two centuries later, when the trend had caught on and attracted many investigators, was a need felt for some new name for the discipline. "Science" slowly came to have the sense of a study of nature that emphasized experiment and mathematics. The word "scientist" was not coined until 1863.

These new terms signalled a novel and peculiar split between philosophy and the emergent "science"; suddenly there were two disciplines and two communities of thinkers, where before there had been one loose community of philosophers. Crudely put, the philosophers withdrew from experimenting and observing the world while scientists tried to restrict themselves to measurement, calculation and deduction. Philosophers thought in their armchairs: scientists looked through their telescopes and microscopes. The split widened so much in the twentieth century that some people complained that Europe had "two cultures": the humanities were separate and isolated from the sciences.

There are now healthy signs that this split is healing, and the philosophy of space and time is one area where philosophy and science are converging and overlapping again. After all, both are studying the same world. One reason for this convergence is an extraordinary and unexpected crisis in our understanding of space and time. Physicists had been optimistic that Einstein's theories were both correct and fundamental. Now there is a widespread sense that, although his theories make many correct predictions, they are somehow wrong and mistaken. Just as Einstein overthrew earlier physics, we may now be on the verge of a new revolution. The new problems are so surprising and so deep that ambitious philosophers have invaded physics and thoughtful physicists have begun raising broad and searching metaphysical questions again. The quantum theory of matter, the new theory of gravitation ("quantum gravity"), astronomy and attempts at unified theories of physics are all throwing up challenges to our understanding of space and time. These are deep enough to be called philosophical.

It is an exciting moment to study the philosophy of space and time. We possess deep and beautiful theories that seem right and illuminating, and make many verifiable predictions. We also know now that they are not fundamentally correct, but we do not understand why. We do not understand how to proceed.

CHAPTER 2

Einstein in a nutshell

Two theories of relativity

There are two Einsteins. For most of the world, Einstein (1879–1955) is a cult figure: the pre-eminent icon of genius. With his wispy, wild grey hair, missing socks and other-worldly idealism, he has replaced the wizards of earlier times in the popular mind. This Einstein is dangerous, a stereotype with a life of its own that distorts both the man behind it and the nature of the science that so shapes our world.

Among physicists, Einstein is at times remembered as a grumpy, cutting and arrogant fellow with little patience for family or colleagues. He so annoyed his teachers at university that he failed to secure a job in academia, and had to scramble to find low-paying work in the Swiss patent office (although some say that being Jewish hurt his chances too). During his twenties in Berne, Einstein was a fashionable man about town. His wit and violin playing brought him many dinner invitations, and he formed a reading group with friends to study the work of Kant, Schopenhauer and other philosophers. In 1905, his miracle year, he published several unrelated papers. One was good enough to win a Nobel prize, and another revolutionized our views of space and time. The 25-year-old patent clerk had remade physics in his own image.

Einstein's 1905 theory of space and time is now called the *special theory of relativity*. The word "relativity" refers to relative speeds and other relations. The theory was "special" in a negative sense: it applied only to a restricted *special case* and was not general. It has become most well known for predicting that mass can be converted directly into energy, and thus provided the theory behind atomic bombs. During the decade after 1905, Einstein struggled to broaden his theory. It was a time of frustration and false trails, of Herculean labours and wasted years. Finally, in 1916, he published his even more radical *general theory of relativity*. The special theory overthrew the classical physics of Isaac Newton (1642–1727), which had reigned for some 200 years, and the general theory overthrew Euclid's geometry, which had been considered a model of certain knowledge for more than 2000 years.

As Europe lay in ruins after the end of the First World War, an English astronomer sought observations that might confirm Einstein's radical theories. Arthur Eddington believed that a British effort to support the theories of a Swiss-German would demonstrate the internationalism of science, and promote healing among the shattered nations. He mounted an expedition to South Africa, where a total eclipse was predicted in 1919. Einstein had predicted that measurements of starlight bending around the darkened Sun would test his theory. Eddington's crude photographs made Einstein a celebrity. The results were telegraphed around the world and newspapers announced that we had entered the Age of Relativity.

Einstein became a professor of physics in Berlin, the fashionable capital of interwar Germany and a centre of modernist movements in art, literature and politics. He enjoyed his celebrity, socializing at black-tie dinners with the high and mighty, and used his fame to advance pacifism and international socialism. As the economy worsened, however, he became a lightning rod for anti-Semitic threats. A wave of frightened scientists, intellectuals and artists were then emigrating to the USA, and transforming it into a leader in scientific research. Einstein moved with his family in 1933 and took up a position at the Institute for Advanced Study at Princeton. In 1939, as the Nazis advanced across Europe, Einstein sent a now famous letter to President Roosevelt appealing for urgent research into atomic weapons. Together with pressure from their allies in Britain, this led the USA to collaborate with Britain on a huge, incredibly expensive crash programme, the Manhattan Project, which constructed the bombs dropped on Japan four years later.

In 1948 Einstein turned down an offer to become the first president of Israel, and continued his quiet life of research at Princeton. Younger physicists had moved on to more exciting developments, and at times regarded Einstein as a scientific has-been who failed to keep up with them.

Today we live in the golden age of astronomical exploration. Using the Hubble Telescope and a host of other satellites, ultra-sensitive detectors and high-speed computers, we have learned more about the universe during the past two decades than during all of history. If anything, the pace of discovery is even now accelerating. And all this is Einstein's golden age too. His ideas guide these explorations, and provide the basic framework underlying theories of the Big Bang, black holes and the birth of stars and galaxies. All the same, however, experiments now strongly suggest that Einstein's most basic views on space and time were somehow wrong: that they were fruitful half-truths. A storm of work in the foundations of physics, quantum gravity and cosmology has made this an era that once again is posing the deepest questions about space and time. Like Newton before him, Einstein now faces the prospect of being overthrown by new and deeper theories. These are exciting times.

The following chapters introduce Einstein and his special theory of relativity in a very simple way, and concentrate on two themes. First, they pinpoint the daring, conceptual leaps that lay at the heart of Einstein's theory. Einstein was not a great mathematician, and his discoveries all begin with creative insights that can be understood and appreciated without jargon. For philosophers, these flights of genius are enduring monuments to the beauty and power of thought. Secondly, the chapters return constantly to the heated controversy now surrounding the *interpretation* of Einstein's theories. Despite the myriad of successful predictions they produce, there is now real uncertainty about why his theories work, and therefore about his grand revisions in our ideas about space and time.

This approach is unusual. Most introductions to relativity hide the ongoing debates and concentrate on expounding the technical features of Einstein's theory. Here, the mathematics is set aside and we stay close to the phenomena, to the concrete predictions and observable implications of the theory. Thus we penetrate to the conceptual core of theory, and therefore to its philosophical heart.

Later in his life, Einstein distinguished between two sorts of scientific theories. *Constructive theories* begin by listing the basic things in the world, and build up or construct larger, high-level things from these. The fully developed model is then used to make predictions. Philosophers would say that such a theory begins with an ontology, and draws consequences from it.

In contrast, Einstein said, special relativity is a *principle theory*. He meant that the theory begins by listing a few high-level assumptions or isolated facts that are not supported by any model, and then uses these to make predictions. The truth of the predictions would justify the assumptions or justify relying on the facts, even if they are not clearly supported by a deeper picture of the world. A principle theory can seem very mysterious when the predictions it makes are unexpected. When a magician pulls a rabbit out of an ordinary looking hat we seek for some deeper explanation of what happened. A principle theory does not offer deeper explanations.

The special theory of relativity is a principle theory. This chapter introduces the principles and facts that Einstein used to make his startling predictions. At the end of the chapter we take a first glance at what could make all this true, and attempt to go deeper than Einstein's principles.

> The general theory of relativity builds on and generalizes the special theory of relativity, but does not explain its principles.

The speed of light is constant

The central mystery is light. It is, first of all, astonishingly fast. With a flick of a switch, light floods a room. Before the rise of modern science, it was sometimes thought that light leapt magically across space without taking any time at all. This changed, however, after Galileo first turned the telescope toward the skies in 1609. Clever astronomers realized they could use the regular orbits of Jupiter's moons as giant clocks, and were able to measure the speed of light with surprising accuracy. The numbers they produced shocked people. Who could conceive of a speed of *186,000 miles per second* or *300,000 kilometres per second*?

But another, more perplexing, surprise lay in wait: the speed of light is constant. That is, all observers who measure the speed of light in empty space will find the same number no matter how fast they are moving. An observer standing still will find starlight racing by at 300,000 kilometres per second. A spaceship cruising at 200,000 kilometres per second and chasing a light beam will still find that the beam races away from the nose of the ship at 300,000 kilometres per second. This means, for example, that no one can race fast enough to catch a light beam. No matter how fast someone is moving, light will be faster by 300,000 kilometres per second.

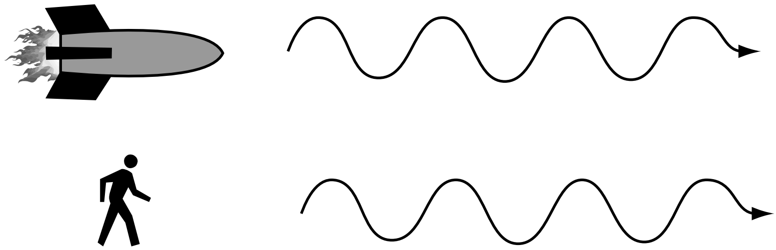

Figure 2.1 *The speed of light is constant. The speed of light is 300,000 km/s observed from the rocket, and 300,000 km/s observed by the walking figure.*

This is very peculiar. By way of contrast, consider a speeding motorist being chased along a road by the police. At the start, with the police car at a standstill at the side of the road, the speeding car zips away at 150 kilometres per hour. As the police car reaches 30 kilometres per hour, the speeding car travels only 120 kilometres per hour faster. As they accelerate, the *relative speed* of the fugitive drops down further and further, and finally dwindles to zero as the police catch up and race alongside flashing their lights. This is common sense. If the speeding car goes at 150 kilometres per hour and the police are chasing at 130 kilometres per hour, then their relative speed is 20 kilometres per hour.

But light is not commonsensical. Light races away from any standing or moving body at the same speed. The speed of light relative to *any* moving body is a constant.

This fact was discovered experimentally in the late 1800s. It was so strange there was no agreement about what it meant, or even whether the experiments could be correct. Even today we have no deep explanation of why the speed of light is constant. Many have derived the fact, but only by making other, equally mysterious assumptions. It was Einstein's great achievement to see this bizarre fact as a clue. He was able to place it at the centre of a powerful new theory, and thus opened up a new vision of our universe.

> The constancy of the relative speed of light is an experimental fact. Even today, there is no agreement about why this should be true. Einstein simply assumed it was and drew some surprising consequences.

Faster speeds, longer hours

Someone might mistakenly think that the constancy of the speed of light leads to contradictions, and therefore cannot be true. For example, suppose there are two rockets travelling through space in the same direction but at different speeds, and that there is a ray of light racing out ahead of them. Someone might think that light cannot travel 300,000 kilometres per second faster than each rocket, because the light beam would then have two speeds. But that would be a contradiction – light cannot have two different speeds. What is wrong with this reasoning?

Einstein was able to remove the appearance of contradiction by profoundly altering our view of time. To understand this, we must carefully reconsider what a contradiction would be. Plato and Aristotle were apparently the first to state what is, perhaps, the most fundamental idea in philosophy:

> *The law of non-contradiction:* Opposite properties do not belong to one and the same thing in the same respect and at the same time.

According to this law, a positive integer is never both even and odd. A newspaper can be "black and white and red all over", but not "in the same respect". It can be black here and white there and "read" throughout. It cannot be black and white at the same point since these colours are opposites. (Lukasiewicz calls this the "ontological" version of Aristotle's law: it is about properties and things. Other versions of the law concern true sentences or psychological states like belief.)

In a move of breathtaking audacity, Einstein reasoned that, since there were no real contradictions, and therefore a light beam cannot have two speeds in the same respect and at the same time*, the two rockets above must have different times*. That is, the rockets each measure the same relative speed for the light beam because *time flows differently for each rocket*.

A little story will help make this more concrete. Suppose that Jill is an astronaut flying overhead through the starry night. Jack is earthbound and working in mission control, and it is his job to monitor Jill and her spaceship carefully through a large telescope. As Jill's spaceship approaches the speed of light, Jack observes something marvellous. Jill and everything in the spaceship move in slow motion, like a film in the cinema shown at a slowed rate. The hands on Jill's wristwatch begin to crawl around the clock face. She seems to be wading through molasses. The half-hour programme she is watching on her television takes 45 minutes.

Jack is not surprised because Einstein predicted all this. As the rocket speeds up, its time flows more slowly than here on Earth. An hour on the rocket is longer than an hour on Earth. This is now called *time dilation* (to dilate is to become wider or longer), and there is a simple formula to predict how much Jill's time will slow when her rocket has a particular speed (see Appendix C).

Reasoning from the constancy of the speed of light, Einstein concluded that there was no single, universal passage of time. Rather, the flow of time depends on speeds. *Faster speeds mean longer hours*. Each body moving through space experiences the flow of time at a different rate.

This astonishing conclusion was confirmed by many experiments. One experiment by Hafele and Keating in 1971 used very accurate atomic clocks, which were carried on around-the-world flights in Boeing jets. Although the jets flew much more slowly than the speed of light, there was still a measurable time dilation. The clocks were slightly behind other clocks that remained in the laboratory, just as Einstein's theory predicted.

This can be tested at home. For example, time dilation can be used to delay getting the wrinkled hands that accompany ageing. If both hands are simply flapped up and down continuously at nearly the speed of light, they will remain young while the rest of your body ages.

Many studying relativity for the first time assume these effects are some kind of illusion that arise because of the way fast-moving objects are observed. That is, they believe that durations are *really* constant and merely *appear* to vary with speeds because they must be observed from far away. Some believe it is the lag time – the time it takes for light to travel from the object to the measurement device – that produces an illusion. This is easy to refute, and cannot be correct. For example, when the travelling atomic clocks were returned to the laboratory bench, the slight discrepancy between them and stay-at-home clocks could be read off immediately. No fancy apparatus or fast-moving objects were involved. Indeed, human observers are unnecessary. A computer could have registered and printed out the difference. Similar examples of relativistic effects are widespread in the daily work of experimental physicists. Almost everyone in the present debate agrees that the effects cannot be simple illusions.

Likewise, some beginners mistakenly believe that time dilation is just a consequence of using different units of measurement. A measurement assigns a number to a distance or duration. A tennis court is 24 metres or 78 feet long; a tennis match may last 3 hours or 180 minutes. These numbers obviously depend on conventional units of measurement: on, say, whether metres or feet are used. When international organizations change the definitions of the units, the numbers assigned to bodies change too. But time dilation occurs even when everyone agrees on and uses the same units of measurement. Jack and Jill compare their rulers and synchronize their watches before the spaceship leaves Earth. Even so, Jill's watch will run more slowly relative to Jack's when she increases her speed. In short, time dilation is a real effect, and is neither an illusion nor a difference in the choice of measurement units. The flow of time depends on speeds.

If two rockets flying at different speeds are chasing the same light beam, the light will indeed travel 300,000 kilometres per second faster than each of the ships. But there is no contradiction. The light beam has opposite properties but not "at the same time"; each ship has its own time.

> Time dilation was inferred from the constancy of the speed of light and other assumptions in order to avoid contradictions, and was later confirmed by many experiments.

The lazy ship

When Einstein published his ideas about time dilation in 1905, he limited his predictions to a special case: to special sorts of measurements. As mentioned above, special relativity is special because it is limited to special cases. To understand these important limitations, we must consider some simple facts about motion.

Suppose a ship is sailing very smoothly down a wide river at a constant speed and in a fixed direction. Suppose some budget travellers have cabins below deck without windows, and so cannot see the river banks sliding slowly by the ship. When they wake up in the morning such passengers will not be able to tell whether the ship is moving or standing still. In fact, no observation or experiment performed within the cabin can measure the ship's motion: without looking outside steady speeds are undetectable and unmeasurable.

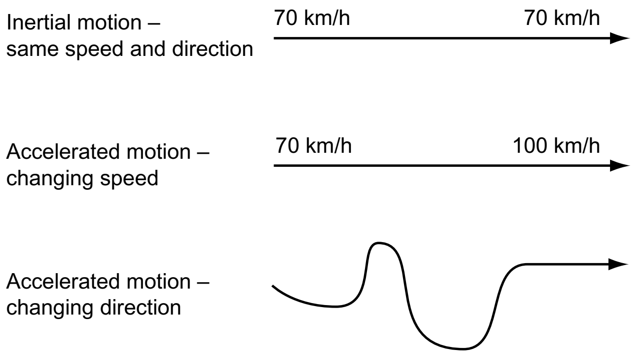

Figure 2.2 *Inertial and accelerated motion.*

This is very peculiar. If the passengers are really moving, they should be able to discover it without looking elsewhere. Philosophers and scientists discussed this riddle so often that they gave steady motion a special name:

> *Inertial motion:* Motion at a constant speed along a straight line.

"Inertial" comes from the Latin word for inactive, sluggish or lazy. Thus, during inertial motion the ship is lazy in the sense that it just keeps doing what it was doing: it does not change speed or direction.

The opposite of inertial motion is *accelerated motion*, and that is easy to detect. For example, when a car accelerates, the passengers are pushed back against their seats. If the ship were to slow down or speed up, the passengers below deck might spill their coffee and would immediately conclude that the ship's speed was changing. The word "acceleration" is used to mean a *change in speed or in direction* (or both). Thus, steering a car to the left without touching the accelerator pedal is also an acceleration in this sense.

Distances and durations are measured with rulers and clocks. Einstein limited his special theory to the case where the rulers and clocks used in measurements were at rest or moving inertially. In short, *the special theory applies only to "inertial measurements"*. The object that is measured may be accelerating – it may be turning loops or flapping up and down – but the measuring devices must be resting or moving steadily.

We can now state Einstein's claims about time dilation more precisely:

> *Time dilation:* Take as a standard a clock that is at rest or moving inertially. Other clocks moving relative to the standard will have longer hours (i.e. "dilated hours"). Furthermore, all physical processes moving relative to the standard clock will take longer than if they were at rest relative to the standard.

That is, it will take more than an hour on the inertial, standard clock for an hour to pass on a clock moving relative to it or, for example, for a moving video player on the spaceship to show an hour-long programme. (The special theory can be applied to accelerating measuring devices by using approximations. If the period of acceleration is divided into short intervals, the device can be treated as moving inertially during each interval. By adding the changes during each of these intervals together, the change during the entire acceleration can be approximated. But, strictly speaking, the special theory applies only to measurements made by devices moving at constant speeds in a straight line.)

The principle of relativity

Einstein's central idea is that there is *democracy among all inertial measurements*. Any measurement made by a set of rulers and clocks moving at a steady speed in a fixed direction is equally as good as a measurement made by any other set.

Suppose that there are two sets of rulers and clocks moving relatively to each other, and each is measuring the speed of a passing spaceship. The results of the measurements will differ, but Einstein insists each result may equally claim to be "the" speed of the ship. There is no physical way to show that one speed is more correct than the other.

Suppose that the budget travellers below deck on the ship work hard to discover their speed by doing all sorts of experiments in their cabin. For example, they drop objects and discover that they fall faster and faster the longer they fall. In fact, every second of fall increases their speed by 32 feet per second. This law is the same in the cabin as it would be on shore. That is, *even laws of physics are unaffected by the ship's speed through the river*. Thus Einstein's democracy extends even to laws; they are the same for all observers moving at steady speeds in a fixed direction.

Einstein called this sort of democracy his special principle of relativity: the laws of physics are the same for all observers moving at a steady speed along a straight line. That is, regardless of your relative speed, the laws of physics are the same. As Einstein said:

> This postulate we call the "special principle of relativity." The word "special" is meant to intimate that the principle is restricted to the case when the [measuring devices] have a motion of uniform translation . . . and does not extend to the case of non-uniform motion.

What is a law of physics? When we plan a journey by car, we all use the simple law that "distance *equals* speed *multiplied* by time": an average of 90 kilometres an hour for five hours will cover 450 kilometres. Here we have a law that connects three things: distance, speed and time. Each of these can easily be measured with, say, the speedometer of the car, a wristwatch and a good map. This suggests that a law is a relation between measurements. The relation in this law is represented by the italicized words above. In every motion, the relation between distance traversed, speed and time taken will be the same.

Some laws contain constants. For example, when we drop something to the floor, its speed increases by 9.8 metres per second during every second it falls. Thus, in general, a *physical law is a relation, involving constants, between measurement results.*

Measurements made at different speeds lead to different results. Birds flying alongside a car sometimes seem to stand still: their measured relative speed is zero. But a pedestrian watching the birds swoop by would disagree, and insist that their relative speed was, say, 40 kilometres per hour. The difference between a speed of zero and 40 kilometres per hour reflects the speed of the measurer. Both the driver and the pedestrian, however, will agree that the distance covered by the birds is given by their speed multiplied by the time taken.

Einstein's principle of relativity can now be stated more clearly. He says that, while the *measurements* made by different sets of rulers and clocks will differ and depend on speed, *relations* between the measurements will be the same for all sets moving inertially. Likewise, any physical constants in laws will be the same. Measurement results are relative; laws are not.

Physics is about relations.

> Special relativity is derived from two principles. Both are experimental facts boldly assumed to hold universally. The first says that physical laws are the same for all observers. The second says it is a law that light travels at 300,000 kilometres per second.

Faster speeds, shorter lengths

Using his two principles, the constancy of the speed of light and relativity, Einstein made a second, astonishing, prediction. As Jill's spaceship speeds up, earth-bound Jack will find that its length *shrinks*. If the spaceship had the shape of a long sausage with fins when it blasted off, at high speeds it will contract lengthwise into the shape of a disc or pancake. As Jill faces forwards out of the window on the ship's nose, her shoulders will remain the normal distance apart but her belly button will be very close to the skin on her back. This is called *length contraction*.

For another example, suppose that someone with more money than sense buys a Jaguar on impulse, but returns home to find that the six-metre car will not fit into the three-metre garage. By driving the car at nearly the speed of light towards the open door of the garage, it is actually possible to fit it snugly inside. Of course, the brakes should be applied before hitting the rear wall.

Actually, physicists have found it difficult to confirm length contraction directly. Time aboard a speeding spaceship can be measured by exchanging light or radio signals, but it is harder to measure lengths by pulling alongside the spaceship with a yardstick. However, length contraction is considered a confirmed effect.

The famous experiments by the Americans Michelson and Morley in 1887 are taken as strong evidence for length contraction. Simply put, they used a long rod moving in the direction of one of its ends. When they shone a ray of light along the rod and reflected it back to its source, they discovered that the ray took slightly less time for the

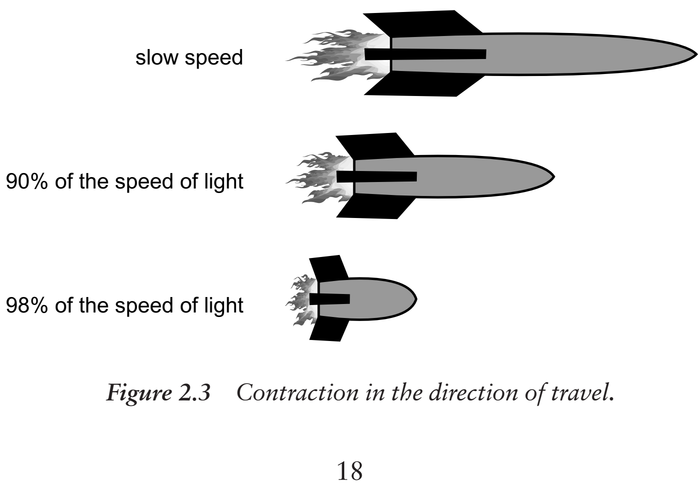

Figure 2.3 *Contraction in the direction of travel.*

return trip than expected. Einstein and other physicists concluded that the rod must have shrunk.

Just as with time dilation, these contractions seem strange to us only because we are such slow-moving creatures. The fastest human beings run 100 metres at the Olympics in about ten seconds. If we were many millions of time faster than that, and could flit around the world in a flash, shrinking lengths and slowing times would be an ordinary part of our lives. On Saturday nights, we could become thinner (and dizzy) just by constantly rushing back and forth past our dates. But a professor who paced back and forth in front of the blackboard at near light speed might take hours and hours to finish a lecture.

To summarize, with faster speeds, lengths become shorter in the direction of travel. This can be put more precisely:

> *Length contraction*
> Take as a standard a yardstick at rest or moving in a straight line at a constant speed. Other yardsticks moving relatively to this inertial standard will contract in the direction of their travel. That is, the contracted yardsticks will measure only a fraction of the standard yardstick. In fact, the length of all moving objects will contract relative to the standard.

Thus, faster speeds imply shorter lengths.

> Length contracts only in the direction of travel: a sausage becomes a pancake, but its diameter remains the same.

The relativity of simultaneity

Before Einstein, physicists thought that time flows at the same rate everywhere. There was supposed to be, we might say, a "universal Tuesday": if it were Tuesday here on Earth, it was Tuesday throughout the entire universe. That is, it was believed that one and the same instant of time occurred simultaneously throughout the universe, and was then followed by the next instant everywhere at once.

Einstein quickly realized that his theories ruled out such a universal simultaneity. This is easy to see. Suppose Jack and Jill synchronize their watches at noon and plan to speak again an hour after Jill has blasted off in her spaceship. At 1 pm on Earth, Jack waits by his radio but Jill fails to make contact. Jack checks his watch against those of his colleagues in mission control, and finds that they all show the same time. Jill is, however, blissfully unaware of her rudeness: her hour has dilated and only a part of her stretched out hour has passed. Jill's 1 pm is not simultaneous with Jack's 1 pm; instead, say, Jill's 12.45 pm is simultaneous with Jack's 1 pm Since time flows differently for bodies moving relatively to each other, they disagree about which events are simultaneous. Thus, according to Einstein, *simultaneity is relative*.

Interpreting relativity

Everyone now agrees that special relativity is well confirmed by experiment. But there remains stark disagreement about why length contraction and time dilation occur – about what is going on behind the scenes to produce such startling effects. This may come as a surprise. Einstein's theory is 100 years old. Surely scientists and philosophers would have clearly understood it by now?

But the popular image of science is often different from the way it really works. Consciously or unconsciously, scientists are propagandists. To the outside world, they present science as a series of great discoveries, as smooth upwards progress towards truth. But inside science, fierce debates and controversies rage constantly. The public is shielded from these in several ways. First, scientific language is often technical and difficult for non-scientists to penetrate. Secondly, science textbooks used everywhere from elementary school to university tend to conceal disagreement. This helps students by simplifying the material, but it also serves to reinforce the image of science as "objective truth" above all questioning, and thereby reinforces the enormous social and political authority of science.

Disagreement about the interpretation of scientific theories is normal. No major theory of science is free of debate about its truth, meaning and implications.

One task that philosophers perform is the conceptual interpretation of theories in physics. That is, they exploit their talents for clear reasoning and careful definitions to explore what the formulas in physics mean, to unveil what the symbols say about our world. Physicists today are trained to calculate numbers rather than analyse conceptual arguments, and their verbal interpretations of their own theories are often unreliable. Despite their technical skills, as soon as physicists stop calculating they are sadly quite mortal.

The purpose of interpreting scientific theories is twofold. Science is partly an intellectual quest to understand the world around us, but as science became more successful at making predictions it also became more obscure, technical and mathematical. Thus progress in understanding the world now often depends on first interpreting and thereby understanding the scientific theories we already possess. The second purpose of interpretation is more practical. Advances in science come in many ways. Some are the result of blind trial and error, and some arise when patterns in data are first discerned. Historically, interpretation and conceptual analysis have been one important route forwards towards new theories and better science. Many of the important concepts that lie at the foundations of contemporary science were first created by philosophers. Thus today's philosophers can hope to contribute to our intellectual understanding of the world, as well as to the advance towards better and deeper theories.

Relativity theory so shocked everyone that many different interpretations of the above effects have been advanced and defended. During the 1920s and 1930s, most physicists accepted relativity theory and it became a routine part of their work. Controversy, however, raged loudly and ceaselessly. A number of physicists flatly rejected the theory and concocted paradoxes to show that it could not be true and must be self-contradictory and incoherent. Outside science, quacks and disgruntled cranks barraged scientists with "proofs" of Einstein's errors. In Nazi Germany, the Nobel-prize winner Johannes Stark bizarrely condemned Einstein's theories as "Jewish physics", and used his political power to push research in other directions. In retrospect, those turbulent times were a learning period. Mainstream physicists rebutted the paradoxes, and deepened our understanding of relativity.

During the Cold War, from the 1950s through the 1980s, special relativity was gospel. It was considered the best confirmed of theories, and provided foundations for all advanced work in theoretical physics. Controversies over the interpretation of the theory subsided, and textbook presentations of the theory were standardized. Then came the surprise. Beginning in the 1980s, philosophers and some physicists began to realize that certain experiments (discussed below) were a new and unexpected challenge to our *understanding* of relativity. That is, while still accepting that the theory worked at a practical level, increasing numbers began to doubt that the standard interpretation was correct.

Similar sorts of interpretational problems arise with ordinary maps. A map of the world may be useful for navigation even though it grossly distorts the shape of the continents and portrays the spherical Earth as if it were a two-dimensional plane. Special relativity makes predictions that turn out to be true, but we can still ask how well it pictures reality.

There are many examples in history of theories that made good predictions but fundamentally misdescribed reality. A simple one is the theory that the Sun will rise every morning. This theory leads to the prediction of a general brightening in the sky at about 6 am, which will be well confirmed. But the theory is false because the Sun does not rise: Earth rotates.

Two key distinctions, or pairs of words, are at the centre of debates over special relativity: "relative" versus "invariant" and "appearance" versus "reality".

"Relative" means related to or dependent on something else. When used as a noun, "relative" means something involved in a relation, which is why we call our cousins relatives. The word "invariant" is used very often in debates over relativity. In this context, a property is invariant when it is *independent of the set of rulers and clocks that is used for measuring it*. Suppose that different sets of rulers and clocks are all moving relatively to each other, and are used to measure some one property. If all the sets give the same answer, then the property they are measuring is invariant and independent of how it is measured. Physicists sometimes use the word "absolute" as a synonym for "invariant", but history has encrusted "absolute" with so many different meanings that we will avoid it in these introductory chapters.

The philosophy called "Relativism" holds that *truth and values depend on personal beliefs or cultural conditions*. Relativism is not the same as Einstein's theory of relativity. As will be discussed below, Einstein's relativity theory does not reject objective truth altogether. It argues that some properties we thought were invariant are not, and introduces new sorts of invariants. In fact, the name "theory of relativity" was not Einstein's first choice; it was coined by another physicist (Poincaré).

The second distinction between appearance and reality is familiar. Hallucinations and mirages are cases where appearances diverge from reality. A straight stick appears bent when half submerged in water, even though it is really straight. This distinction is also central to modern science. Earth appears to be flat and motionless, but science tells us this is not really so. For another example, colours are mere appearance. The atoms that make up the objects around us are colourless, and appear coloured only because they reflect light of different wavelengths into our eyes.

Note that, as defined above, the question of whether a property is invariant or not is a question about appearances. A physicist can test whether lengths are invariant merely by making observations, and need not speculate about whether those measurements faithfully report what is real. *Appearances may have the property of invariance*. In debates over special relativity, most people accept that the theory correctly describes appearances. That is, the predictions it makes have so far, without exception, been confirmed. The question that remains is over the reality behind the appearances. What is happening behind the scenes? Can we describe or build models of a world that would explain our observations of length contraction and time dilation?

> A theory may make good predictions even though it wrongly describes reality.

The mainstream interpretation

A tennis court appears to have a length (24 metres) and a tennis match appears to have a duration (say three hours). Likewise, a shoe appears to have a definite size, and the wink of an eye seems to take less than a second. The key question is about these distances and durations. Bodies appear to have lengths; events appear to have durations. Are these real properties of bodies and events, or are they mere appearances, like the flatness of the earth? Or are they something else altogether?

Of course, science has no pope. No one imposes uniform views on physicists, and every shade and variation of opinion on this issue has been asserted at one time or another. Nonetheless, there are two chief answers to these questions. The first is accepted – implicitly or explicitly – by most mainstream physicists. Therefore, for our purposes, call it the "mainstream interpretation". This view denies the existence of real distances and durations. More precisely, a body does not have a real length and an event does not have a real duration that is independent of other things. Since, as experiment and observation confirm, there appear to be no invariant distances and durations, these are not real properties of physical things. This is a radical claim but it is orthodox within the mainstream.

For comparison, consider the case of a controversial portrait hanging on the wall of an art museum that is variously thought to be beautiful, ugly or indifferent. Suppose that, over the centuries, judgements have always been mixed but tended to shift with the prevailing fashions. Some would conclude that beauty or ugliness is therefore not a property of the painting. Since the painting is the same but judgements of it vary, the judgements seem not to reflect any inner quality of the painting at all.

The mainstream interpretation relies on a similar argument. When astronauts watch a video, it takes 90 minutes according to their watches, but earth-bound observers say it lasted two hours. Since one drama cannot last both 90 minutes and two hours, these durations are not properties of the video. Physicists use a very short argument to buttress this conclusion. Recall that a property is invariant when all sets of rulers and clocks report the same measurement results:

Argument against distances and durations

A.	If a property is not invariant, then it is not real.	(P)
B.	Distances and durations are not invariant.	(P)
C.	Therefore, distances and durations are not real properties.	(from A,B)

That is, if measurements of distances and durations produce different results depending on which set of rulers and clocks is used, then distances and durations are not real properties of individual things (like beauty in the painting).

The first premise in the argument, A, is key. It moves from a claim about what we observe and measure to a claim about nature itself: from appearances to realities. This is a very big assumption and is, strictly speaking, not a part of Einstein's theory of relativity. It is a part of the *interpretation* of that theory: the attempt to clarify what the theory says about our world. But the first premise seems reasonable. If a property really belongs to an object, then different measurements should all faithfully report the same result.

The second premise, B, is just the assumption that observations confirm the occurrence of length contraction and time dilation. That is, it assumes that Einstein's predictions turn out to be true, which is widely accepted.

Together, the two premises produce a startling conclusion. According to the argument, relativity theory implies that shoes do not have sizes! A tennis court does not have a definite length; a tennis match in itself never lasts three hours.

Of course, the claim that distances and durations are not real properties is merely negative: it makes an assertion about what does not exist. But the mainstream interpretation also makes positive claims about what does exist instead of distances and durations. A comparison will help make this clear.

Suppose that, at a large family reunion, someone is variously introduced as a brother, son and cousin. Should we conclude, as in the case of the painting, that these various attributions are not all correct? Since being a brother, being a son and being a cousin are not the same, should we conclude that the introductions were mistaken? Clearly not. The reason is that being a brother, and so on, depends on the kind of *relation* to other people. One person can be at once a brother to a sister, son to a father and cousin to a cousin because he enters into various relations with different people.

According to the mainstream interpretation, the relativity of distances and durations seems revolutionary only because of an error. We thought that they were real properties of individual things, but actually they are each a kind of relation (technically, a "projection onto a coordinate system"). Lengths vary because they are like family relations to the surrounding bodies and measuring instruments. We mistakenly assumed that lengths are properties of individual things only because our ordinary experience involves objects moving far more slowly than the speed of light. Since we are also moving slowly, we all have the same low speeds relative to such objects. Since our relations are thus all the same, we overlooked their key role. A later chapter explains this strange world of relativity further, and explores this positive side of the mainstream interpretation.

In sum, the mainstream interpretation denies that real distances and durations are properties of individual bodies or events. It asserts, instead, that distances and durations are kinds of relations. A shoe has one length relative to one set of rulers and another length relative to a different set of rulers (like the brother who is a cousin), but no particular length of its own.

Properties belong to one thing, relations to two or more. Although distances and durations are not real properties, they are also not mere appearances: they are real relations.

The minority interpretation

The young Einstein was a rebel, moving from job to job and scrambling to find a secure job. The great father figure in physics at that time was the famous Dutchman Hendrik Lorentz. A generation older than Einstein, and a picture of prosperous, upper-middle-class respectability, Lorentz had played a major role in the discovery of the electron, for which he received one of the first Nobel prizes in 1902. He had come within a hair's breadth of discovering special relativity, and yet always praised and encouraged the young upstart who scooped him. Some measure Lorentz's greatness by his ability to recognize in Einstein an unusual and unconventional genius so very different from his own. In fact, Lorentz became one of Einstein's earliest promoters, and generously helped him find positions that enabled him to continue his research. For his part, Einstein seems to have idolized Lorentz. He once wrote to a friend, "I admire this man as no other. I would say I love him". Decades later, shortly before his own death, Einstein voiced an extraordinary sentiment about his older colleague: "He meant more to me personally, than anyone else I have met in my lifetime."

Later in his career, Lorentz loomed over the world of physics as a wise and benevolent grand old man, perhaps the leading physicist of his generation. But historians have been less kind. In the aftermath of the relativity revolution, Lorentz has often been portrayed as a sad figure, with a mind mired in the comfortable past and simply unable to comprehend the dazzling world unveiled by Einstein's theories. The historian Thomas Kuhn wrote chillingly about older scientists who were left behind by scientific revolutions, and quoted the physicist Max Planck: "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

For many people, Lorentz is perhaps the most prominent example of a great scientist who died clinging to his outmoded theories. His case provides extra evidence of the depth of Einstein's reworking of our concepts of space and time: even a Lorentz, they say, could not make the revolutionary leap into the strange new world of relativity theory. Today, however, as doubts about the foundations of Einstein's theories multiply, Lorentz appears very differently. We now have more sympathy for his position, and even honour him for clinging to insights that time has rehabilitated. With Einstein, he is a hero in our story.

In particular, Lorentz helped begin a tradition of seeking deeper explanations of relativistic effects such as length contraction and time dilation. While Einstein simply derived these from the principles he assumed, Lorentz insisted that we press more deeply and uncover their causes. He was thus the founding father of what, for our purposes, we will call the minority interpretation.

The momentous debate between Einstein and Lorentz pitted two of the greatest physicists against each other. Their respect and affection for one another should not disguise how cutting their disagreement was. Both men had dedicated their lives to physics. If Lorentz proved correct, Einstein's historic first discovery would be denied him. If Einstein triumphed, Lorentz's whole approach to physics, his life-work, would be dismissed as old-fashioned, mechanical and metaphysical.

Einstein's mainstream interpretation is dramatic. With a single sweep, it eliminates features of our world that seemed obvious and indispensable, and tumbles us headlong into a new world where distances and durations are not real properties. This has been the dominant view since the triumph of Einstein's 1905 paper on special relativity. According to the minority interpretation first developed by Lorentz, however, each object does have a definite length of its own, but it varies with speed. That is *lengths are real but variable properties of individual bodies*. Similarly, an event such as the wink of an eye or a tennis match does have a definite duration, but the duration will dilate or shrink with speed. A tennis match on a large ship will really take longer than the same match would in a court at rest; a moving clock will really run more slowly. Thus the minority interpretation breaks the democracy among inertial measurements. It says that some measurements reveal the *real distances and durations*, while some instruments are distorted by the effects of their own high speeds and report merely apparent distances and durations.

Historically, Lorentz and other advocates of the minority interpretation were motivated by the following sorts of ideas. Just as water waves are disturbances travelling through water, they reasoned, light waves must be disturbances travelling through some very thin fluid filling all of space. They called this fluid the "ether", which is Greek for flame or fire. Although there was no direct evidence for the existence of such an ether, it conveniently explained length contraction. Just as a ship ploughing through water will feel a resistance that rises with speed, all objects that move in space are resisted by the ether. Since it is so thin, we are normally unaware of this, but at high speeds it would pile up against bodies and cause them to contract in the direction they are travelling in. A similar but more complicated argument explained time dilation as another effect of this resisting ether wind.

Thus the ether is important because it gave a physical explanation of length contraction and time dilation. Einstein and the mainstream interpretation simply deduce these effects from the mysterious constancy of the speed of light and the relativity principle, but do not explain them.

In fact, the minority interpretation has a very different view of the speed of light. It is well known that ordinary waves travel at the same speed in the same medium. Thus waves in water always travel at a characteristic speed. The reason is that each medium has a certain "bounciness" or elasticity that determines how quickly it pushes back when disturbed. Such a wave is, for one example, a push alternating downwards and upwards, so the degree of "bounciness" sets the speed of waves as they progress through the medium. In water, therefore, waves from a high-power racing boat and from a small pebble dropped in a pond both travel at the same speed. The minority interpretation argues that light is just an ordinary wave that travels in the ether, and thus *really* always has, regardless of its source, the same speed relative to the ether.

But the peculiar thing about light is that measurements of its relative speed always give the same result. According to the minority interpretation this is mere appearance and not really true. Actually, the speed of light relative to a spaceship *does* depend on how fast the spaceship is moving. If the spaceship is moving at half the speed of light, then a light beam racing ahead is gaining ground at only half the speed of light. The relative speed of light merely *appears* to be constant because of distortions due to length contraction and time dilation. Thus the minority interpretation removes the central mystery of Einstein's theory by explaining the constancy of light's relative speed, but it replaces it with the mystery of the ether.

Mainstream physicists have always been sceptical of the minority interpretation. They have great difficulty with these "real but variable" distances and durations. Since inertial movement is undetectable, passengers in a cabin below deck cannot tell how fast they are really moving, and likewise we cannot measure our real speed through the ether. Thus we cannot say how strong the ether wind is, and how much contraction it causes.

Physicists dislike properties that they cannot measure. The minority interpretation offers neat physical explanations but introduces unmeasurable and undetectable properties into physics.

There is a second, related reason why the mainstream never embraced the minority interpretation: it leads to no new predictions. Although it is quite radical, Einstein's theory is conceptually clean and very clear, whereas the minority interpretation is messy. It asserts the existence of real but unmeasurable lengths. It asserts the existence of the ether or some other cause of contraction and dilation, but provides no new or independent evidence for it. It asserts that these effects will coincidentally just match those predicted by Einstein, but seems to construct its theories just to produce this match. Physicists might accept this mess if the minority interpretation led to new ideas and made new predictions that would distinguish it from Einstein's theory. But so far it has not.

Before we needed to explain length contraction and time dilation we believed that distances and durations were *real* and *constant* properties. Now we must choose between two interpretations of these observations:

- *Majority interpretation:* distances and durations do not exist as real properties of individual things (a shoe has no size)
- *Minority interpretation:* distances and durations do exist and vary with speed through the ether; they are real but variable properties of individual things (a shoe has a variable size)

As we shall see, many other important consequences flow from this fundamental difference between the two interpretations.

The mainstream and minority interpretations lead to the same predictions. The mainstream interpretation is far more economical and cleaves closely to the results of measurement. The minority interpretation offers physical explanations and realistic pictures of the cause of length contraction and time dilation, but at the cost of introducing into physics unmeasurable properties and a ghostly, undetectable ether.

However, the debate between these two interpretations has heated up again in the past decade. In the following chapters we will explore the various advantages and disadvantages of these two interpretations. Chapter 17 will outline new experiments that seem to favour the minority interpretation, and that have triggered a renewed assessment of it merits.

The minority interpretation is committed to real, physical lengths and therefore to real, physical length contraction, but not to any particular cause of that contraction. The ether is only one possible explanation of contraction.

CHAPTER 3

The twin paradox

Symmetry

Among physicists, the word "symmetry" means "sameness across difference". The prefixes "sym" and "syn" mean "same", so "symphony" means "many musicians making the same sound" and "synchrony" means "same time". "Metry" comes from the Greek word for "measure" (as in "metric") and here means "size" or "shape". Thus a face has a symmetry when it has the same shape on different sides, but the charm of a human face often lies in its slight asymmetries.

One of the most outrageous aspects of Einstein's theories is their unexpected symmetries. Suppose that two identical spaceships, A and B, are approaching each other and will pass each other in empty space, and each is moving inertially at a steady speed along a straight line. Spaceship A will find that that spaceship B's lengths are contracted and hours are dilated. Everything in stubby spaceship B happens in slow motion. *But*, Einstein said, spaceship B is also moving inertially and it can also make measurements. According to *its* rulers and clocks, spaceship A is contracted and slowed. There is a perfect democracy among sets of rulers and clocks. That is, according to Einstein, spaceship A is shorter than spaceship B *and* spaceship B is shorter than spaceship A. Hours on spaceship A are longer than those on spaceship B *and* hours on spaceship B are longer than those on spaceship A. Time dilation and length contraction are symmetric. The different measurements show the same effects.

This prediction seemed to be complete nonsense to many physicists when they first learned of Einstein's theories: it seemed to be a blatant contradiction. But Einstein was able to explain that it did make sense, and was not at all contradictory. Understanding this will help us learn to envisage the new nature of space and time discovered by Einstein.

Measuring spaces in time

How can one spaceship be shorter and longer than the other? Is there a contradiction? The short answer is no. For a contradiction, opposite properties must belong to one thing at the *same* time, but this is not the case. The different spaceships have *different* times.

Consider how the lengths of moving bodies are measured. For concreteness, imagine that a Jaguar is on a road that is covered by alternating black and white squares like a chess-board. If the Jaguar is standing still, its length is easy to measure: just count the number of squares between the front and the back wheels. If the Jaguar is moving, however, the wheels are at different places at different times. For a meaningful measurement, we must count the squares between the locations of the front and the back wheels *at the same time*.

The general point is, therefore, that length measurements depend on a definition of simultaneity. Suppose that there are two observers. If they disagree about which events are simultaneous, they will disagree about where the wheels are "at the same time". Thus they will disagree about the length of the car.

Einstein suggested a practical method for measuring the speed of moving objects: a clock must be set up in each square of the chess-board, and all the clocks must be synchronized to show the same time simultaneously. To measure the length of a speeding Jaguar, we simply agree to mark the location of its wheels at the same time, say, precisely at noon, and count the intervening squares.

But how should the clocks be synchronized? If we collect them all together, synchronize them, and then move them back to their squares, the movement will cause time dilation and destroy their synchronization. Just as Jack in Houston and Jill in her spaceship experienced different flows of time, the moving clocks will show divergent times.

Einstein suggested that each clock be left sitting in its own square, and that a light beam be used to synchronize them. Suppose a flash of light travels across the chess-board, and that light takes a billionth of a second to cross one square. Then, if the flash of light strikes one clock at noon, it should strike the next at noon plus a billionth of a second, the next at noon plus two billionths of a second, and so on. The clocks can be adjusted to show these times, and thus will be synchronized. Since light always travels at the same speed, there are no distorting effects to disturb the clocks. The same sort of procedure can be used for making length measurements with a moving yardstick. Tiny clocks can be set up at regular intervals along the stick, and a ray of light travelling along the beam will synchronize them.

Einstein stressed that our intuition about measuring lengths cannot be trusted. Great care must be taken to measure the front and back locations of moving objects at the same time, and to use clocks synchronized with light beams.

Measurements of space depend on time.

The garage

An illustration will help bring these points home. According to Einstein, length contraction will permit us to house the six-metre Jaguar in a three-metre garage, as mentioned above. By driving at 85 per cent of the speed of light, the car will contract by some 50 per cent. We can drive the car into the garage and quickly slam the door. Does this show that the contracted car is really shorter than the garage? How could there be symmetry here? Could the car also be longer than the garage? (The discussion below is repeated in Appendix A.)

Since we do not have everyday experience of cars moving so fast, we have to be very careful when thinking about lengths. If measurements are made using rulers at rest inside the garage, they will indeed find the car shorter than the garage. That is, the front of the car and the rear of the car will both be within the garage *at the same time*. Since the car is moving so quickly, however, it will almost instantly thereafter smash into the back wall of the garage and explode. The explosion will first consume the nose of the car, and then a shock wave will travel along the body of the fast-moving car as its rear end continues to slide towards the flames. Finally, the car, rulers and garage will all be vaporized.

In sum, five events have the following order, according to clocks and rulers at rest in the garage:

1. The front of the car enters the garage.
2. The rear of the car enters the garage.
3. The door is slammed shut.
4. The front of the car is consumed by the explosion.
5. The rear of the car is consumed by the explosion.

The car is entirely inside the garage (or what is left of the garage) from the second event onwards.

The driver of the car, however, uses rulers and other equipment within the car and reports a very different sequence of events. According to the driver, the *garage* is approaching at 85 per cent of the speed of light, and therefore the garage is contracted to 50 per cent of its ordinary length. Thus the three-metre garage is only 1½ metres deep. Unable to stop the oncoming garage, the driver sees the nose of the six-metre Jaguar hit by the approaching back wall. At this same time, the rear of the car is still sticking 4½ metres out of the garage door. The resulting explosion at the nose creates a shock wave that travels down through the car as it crumples against the moving back wall. However, the garage is moving so quickly that it continues to slide past the car during the explosion. Just as the garage door passes the rear of the car, the garage door is slammed shut, and then the whole is consumed by the explosion. The door was indeed slammed

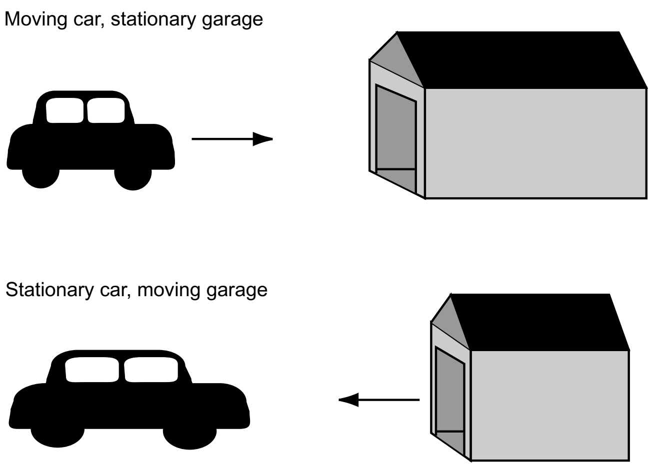

Figure 3.1 *Length contraction. From the perspective of a stationary garage and from the perspective of a stationary car.*

after the rear of the car was in the garage but, according to the driver, the explosion had already started and destroyed the front of the six-metre car.

In sum, there are again five events, but the driver records them in a different order:

1. The front of the car enters the garage.
2. The front of the car is consumed by the explosion.
3. The rear of the car enters the garage.
4. The door is slammed shut.
5. The rear of the car is consumed by the explosion.

The car is longer than the garage but fits inside because the explosion consumes the front of the car before the rear enters.

According to Einstein, it is generally true that events in different places may have no definite order in time. For example, suppose there are two distant places and that three events happen in each place. Say events X, Y and Z happen on the left and events A, B and C happen on the right. According to one set of clocks, the events may happen in the order ABCXYZ, while another set of clocks may record the order AXBYCZ. Thus *events separated in space may have different orders in time*, depending on which set of rulers and clocks is used to measure them. This is just a consequence of time dilation: the relative stretching out of time intervals at high speeds.

Two events have a fixed and definite order only when one is the *cause* of the other. For Einstein, causes always precede their effects. But when neither light nor any other causal process can travel fast enough to pass from one event to another, there is nothing to determine their order. Thus if, on the right, A causes B, which causes C, then no clock could record their order as BAC.

To summarize, time passes in different ways. When events are separated in space, different sets of clocks will find they occur in different orders. The order of events differs. The car is shorter than and longer than the garage, but not “at the same time”. There is symmetry of effects but no contradiction.

Interpreting symmetry

Both the majority and minority interpretations agree that measurements show that one ship is longer *and* shorter than the other, or that the car is longer *and* shorter than the garage, depending on which set of rulers and clocks is used. That is, they agree that appearances are symmetric. They also agree that there is no contradiction because different times are involved.

Symmetry is, however, a key test case for the two interpretations. When we push beneath observations and measurements and ask what is really happening behind the appearances the two interpretations dramatically diverge. For many physicists, symmetry shows just how unappealing and unwieldy the minority interpretation can be.

The majority interpretation can explain symmetry quite briefly. Recall that there is a democracy among sets of rulers and clocks that are moving inertially (principle of relativity). Therefore, when one set finds that objects moving past are shorter than when at rest, then other sets will also find that objects moving past are shorter. Different sets of rulers and clocks are governed by the same laws and should see the same effects – even when two spaceships are measuring each other. This is a beautifully simple and clear account of a very perplexing phenomenon. At once, the outrageous surprise of Einstein's symmetry seems to dissipate. Symmetry seems natural: it is just a consequence of the principle of relativity. Moreover, the majority interpretation adds, there could be no contradiction in saying that one ship is shorter and longer than the other. Since lengths are not real properties, the ship does not have two opposite properties at once. Lengths are relations, and a ship can have two lengths in the same way a person can be a brother and cousin.

For advocates of the minority interpretation, this is all deeply unsatisfying. They assert that lengths are properties, and that there is a fact of the matter about which of two objects is shorter and which is longer. Explaining the symmetry is a serious challenge for the minority interpretation. According to this interpretation, the ether is at rest and other objects have definite speeds relative to it. Thus, for example, someone might say that the garage is really at rest and the Jaguar is moving towards it. This means that their real speeds relative to the ether are different or "asymmetric" (there is no sameness across difference). Usually, an asymmetry cannot explain a symmetry; usually, different causes have different effects. Thus explaining Einstein's symmetries is difficult for the minority interpretation.

It succeeds because there is a second asymmetry. According to the minority interpretation, the lengths are really different. The moving Jaguar is really contracted. Thus both the lengths and the speeds are asymmetric. Roughly put, these two asymmetries cancel each other out: the effects of two compensating asymmetries can be symmetric.

To see this, consider the moving Jaguar. According to the minority interpretation the Jaguar is really contracted, but measurements made by the driver perversely indicate instead that the garage is shorter. How can this be? Suppose the driver uses the car itself as a ruler. To measure the length of moving objects, the driver must determine when it is *the same time at opposite ends of the car*. For that purpose, the driver briefly turns on a dashboard light at the mid-point of the car; the moments when the flash reaches the front and rear end of the car are "simultaneous". Unbeknown to the driver, however, the minority interpretation insists that the car is really moving as the light is travelling. This shortens the time required for the light to reach the oncoming rear. But the front of the car is racing away from the flash. If the car is travelling at nearly light speed, it will take a very long time for the flash to catch up with the car's front. Crucially, the fact that the car is moving means that the two events in which the light reaches its end-points are actually very far apart in space: much farther than the real length of the car.

But the driver thinks the length of the car is unchanged. The driver thinks that the very large distance between the two events is just the ordinary length of the car. By comparison, stationary objects seem shorter than the Jaguar because the method of measurement makes the distance between the moving ends of the car seem much larger. Thus, *the driver grossly under-reports the lengths of bodies* passed by the Jaguar. Measurements made from the car will show that the garage is contracted.

According to the minority interpretation, the symmetry of length contraction is partly an illusion. The moving car is really contracted, as measurements made by stationary rulers and clocks in the garage correctly show. But measurements made by rulers and clocks moving with the contracted car are fooled by the motion, and underestimate the lengths of passing bodies.

Miraculously, this mixture of real contraction and illusory measurements produces exactly the symmetry predicted by Einstein (details in Appendix B). In the end, the two interpretations are exactly equivalent.

Although both the mainstream and minority interpretations predict the symmetry of relativistic effects, the issue has been a tremendous psychological boost for the mainstream view. Where the minority interpretation seems a mad conspiracy of inelegant complications, the mainstream interpretation is sweet and clear.

Both interpretations agree that appearances are symmetric. The majority interpretation says lengths are real relations, and these relations are really symmetric. The minority interpretation denies there is any real symmetry: the moving spaceship is really shorter than a resting spaceship. In one case appearances reflect reality; in the other, there are compensating real asymmetries that deceptively produce symmetric appearances.

A fountain of youth?

The most famous of the problems prominent in the early controversies over relativity was the twin paradox. It is easy to state but exposes some very deep issues, and so hundreds of papers have been written about it over the decades. Now that the dust has settled, it is clear that the paradox does contain a profound lesson. It does not show that relativity is nonsense, but helps us sharpen our intuitions about life at the speed of light.

Suppose that Jack and Jill are twins. Jack still works in Houston for NASA, and Jill is an astronaut embarking on a long journey to some distant star. If her spaceship travels at nearly the speed of light, the clocks and other processes on board will slow because of time dilation. For Jill, the astronaut twin, the journeys out and back again will both be fairly brief. But on Jill's return, stay-at-home Jack in Houston will be a grey grandparent, and many years "older" than his twin.

As the experiment with the atomic clocks showed, this is not a fairy tale. If long space journeys occur in the future with very fast spaceships, such discrepancies in age will become common. Many generations of workers may retire from mission control before a crew of youthful astronauts return from a single journey.

Why did early critics believe this was a paradox that disproved relativity? Because, they argued, the theory is symmetric. According to Einstein, the spaceship's clocks are slower than those on Earth *and* the earth-bound clocks are slower than those on the spaceship. If both these are true, then why should only the twin in Houston be so old? Whatever happens, shouldn't the twins' experiences be symmetric, that is, the same despite their different journeys?

These critics have made a mistake. There is a big difference between the twins: the astronaut twin *accelerates*. Remember that

Einstein's special theory of relativity is special because it applies only to rulers and clocks moving steadily in the same direction, that is, moving inertially. Jill climbs into a rocket that accelerates to leave Earth and our solar system. In the middle and again at the end of her trip, further accelerations are needed to land at home again. Since these accelerations are asymmetric and experienced only by one twin, there is no reason to expect that their ages will remain the same. Asymmetric causes imply asymmetric effects.

Steady motion is not detectable by experiment. Thus when two bodies approach each other inertially, no experimental evidence will show whether one or the other or both are moving. Acceleration, however, is not inertial movement, and is easy to detect. Those who drink hot coffee in a suddenly braking car will soon have the experimental evidence in their laps. As a car moves inertially, the surface of the liquid remains flat; but with any acceleration – speeding up, slowing down or turning – the liquid will slurp over to one side of the cup. Acceleration has dramatic effects, and the difference in the twins' ages is one of them.

Of course, the acceleration does not *directly* cause the asymmetry. The acceleration determines the path of the astronaut twin, and it is this path that determines the age difference. The asymmetry of the acceleration causes an asymmetry in the motions of the twins, and this causes the asymmetry between their ages.

In retrospect, the twin paradox is so prominent in the literature on relativity because many believe that Einstein showed that "everything is relative". But this is not true even for motions. Inertial motions are relative, but *accelerations are physical.* Regardless of which set of inertial rulers and clocks is used, if the distance between two bodies changes with accelerating speeds, then experiments will quickly decide which body is moving. The lesson of the twin paradox is that, even in relativity theory, not everything is relative.

Speed reflects the distance covered during a duration of time; acceleration is a change in speed. It is surprising that accelerations have physical effects even though distances and durations are not physical properties.