So I did just this, and a week later came a telegram from Snow saying: 'Your article will be published in the next issue. Please send more.' Thus a number of stories on Mr Tompkins, which popularised the theory of relativity and the quantum theory, appeared in subsequent issues of *Discovery*. Soon thereafter I received a letter from the Cambridge University Press, suggesting that these articles, with a few additional stories to increase the number of pages, should be published in book form. The book, called *Mr Tompkins in Wonderland*, was published by Cambridge University Press in 1940 and since that time has been reprinted sixteen times. This book was followed by the sequel, *Mr Tompkins Explores the Atom*, published in 1944 and by now reprinted nine times. In addition, both books have been translated into practically all European languages (except Russian), and also into Chinese and Hindi.

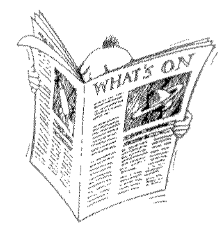
Recently the Cambridge University Press decided to unite the two original volumes into a single paperback edition, asking me to update the old material and add some more stories treating the advances in physics and related fields which took place after these books were originally published. Thus I had to add the stories on fission and fusion, the steady state universe, and exciting problems concerning elementary particles. This material forms the present book.

A few words must be said about the illustrations. The original articles in *Discovery* and the first original volume were illustrated by Mr John Hookham, who created the facial features of Mr Tompkins. When I wrote the second volume Mr Hookham had retired from work as an illustrator, and I decided to illustrate the book myself, faithfully following Hookham's style. The new illustrations in the present volume are also mine. The verses and songs appearing in this volume are written by my wife Barbara.

G. GAMOW

University of Colorado, Boulder, Colorado, USA

1 City Speed Limit



It was a public holiday, and Mr Tompkins, a little clerk of a big city bank, slept late and had a leisurely breakfast. Trying to plan his day, he first thought about going to an afternoon movie. Opening the local newspaper, he turned to the entertainment page. But none of the films appealed to him. He detested the current obsession with sex and violence. As for the rest, it was the usual holiday fare aimed at children. If only there were at least one film with some real adventure, with something unusual and maybe challenging about it. But there was none.

Unexpectedly, his eye fell on a little notice in the corner of the page. The town's university was announcing a series of lectures on the problems of modern physics. This afternoon's lecture was to be about Einstein's Theory of Relativity. Well, that might be something! He had often heard the statement that only a dozen people in the world really understood Einstein's theory. Maybe he could become the thirteenth! He decided to go to the lecture; it might be just what he needed.

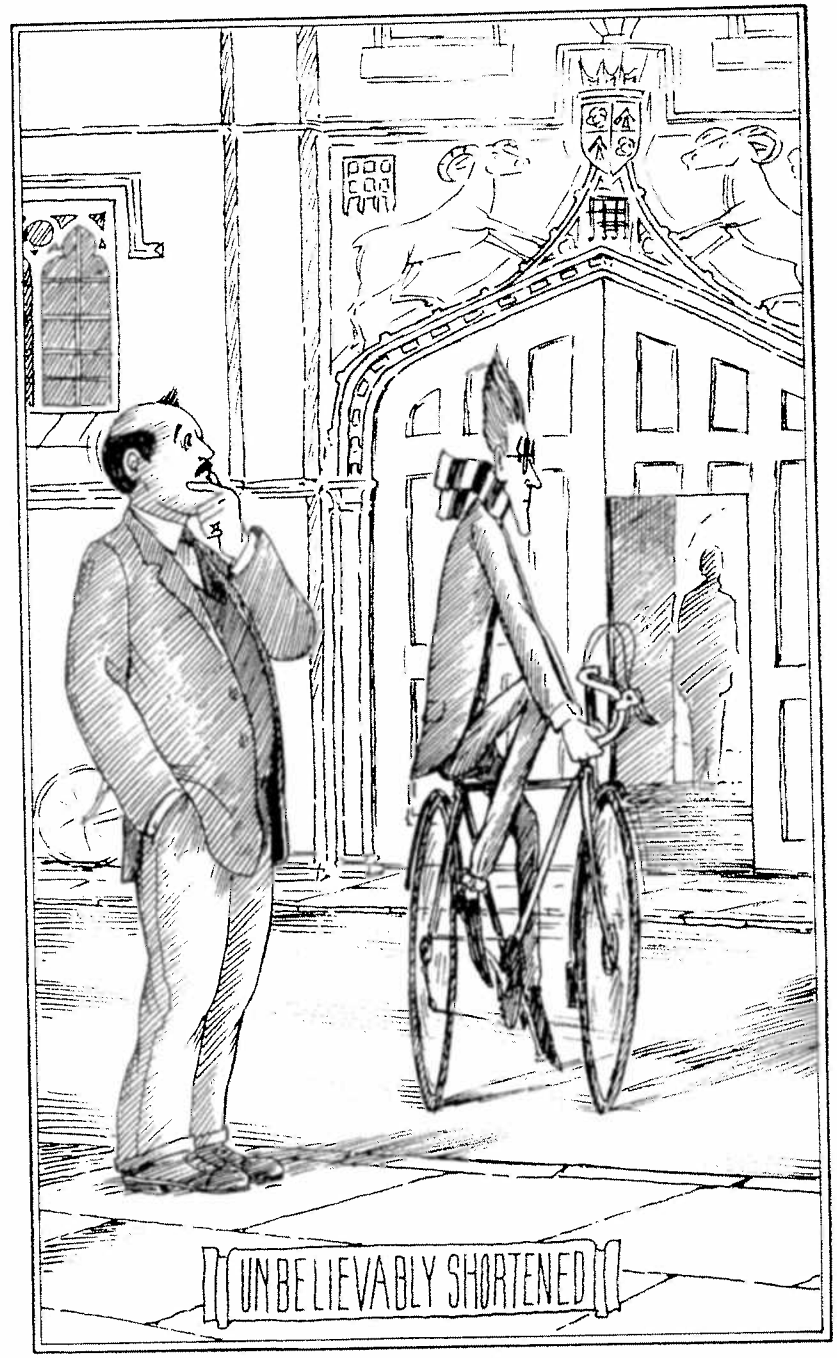
Arriving at the big university auditorium, he found the lecture had already begun. The room was full of young students. But there was a sprinkling of older people there as well, presumably members of the public like himself. They were listening with keen attention to a tall, white-bearded man standing alongside an overhead projector. He was explaining to his audience the basic ideas of the Theory of Relativity.

Mr Tompkins got as far as understanding that the whole point of Einstein's theory is that there is a maximum velocity, the velocity of light, which cannot be exceeded by any moving material object. This fact leads to very strange and unusual consequences. For example, when moving close to the velocity of light, measuring rulers contract and clocks slow down. The professor stated, however, that as the velocity of light is 300,000 kilometres per second (i.e. 186,000 miles per second), these relativistic effects could hardly be observed for events of ordinary life.

It seemed to Mr Tompkins that this was all contradictory to common sense. He was trying to imagine what these effects would look like, when his head slowly dropped on his chest ...

When he opened his eyes again, he found himself sitting, not on a lecture room bench, but on one of the benches provided by the city for the convenience of passengers waiting for a bus. It was a beautiful old city with medieval college buildings lining the street. He suspected that he must be dreaming, but there was nothing unusual about the scene. The hands of the big clock on the college tower opposite were pointing to five o'clock.

The street was nearly empty – except for a single cyclist coming slowly towards him. As he approached, Mr Tompkins's eyes opened wide with astonishment. The bicycle and the young man on it were unbelievably shortened in the direction of their motion, as if seen through a cylindrical lens. The clock on the tower struck five, and the cyclist, evidently in a hurry, stepped harder on the pedals. Mr Tompkins did not notice that he gained much in speed, but, as a result of his effort, he shortened still further and went down the street looking rather like a flat picture cut out of cardboard. Immediately Mr Tompkins understood what was happening to the cyclist – it was the contraction of moving bodies, about which he had just heard. He felt very pleased with himself. 'Nature's speed limit must be lower here,' he concluded. 'I reckon it can't be much more than 20 m.p.h. They'll not be needing speed cameras in this town.' In fact, a speeding ambulance going past at that moment could not do much better than the cyclist; with lights flashing and siren sounding, it was really just crawling along.



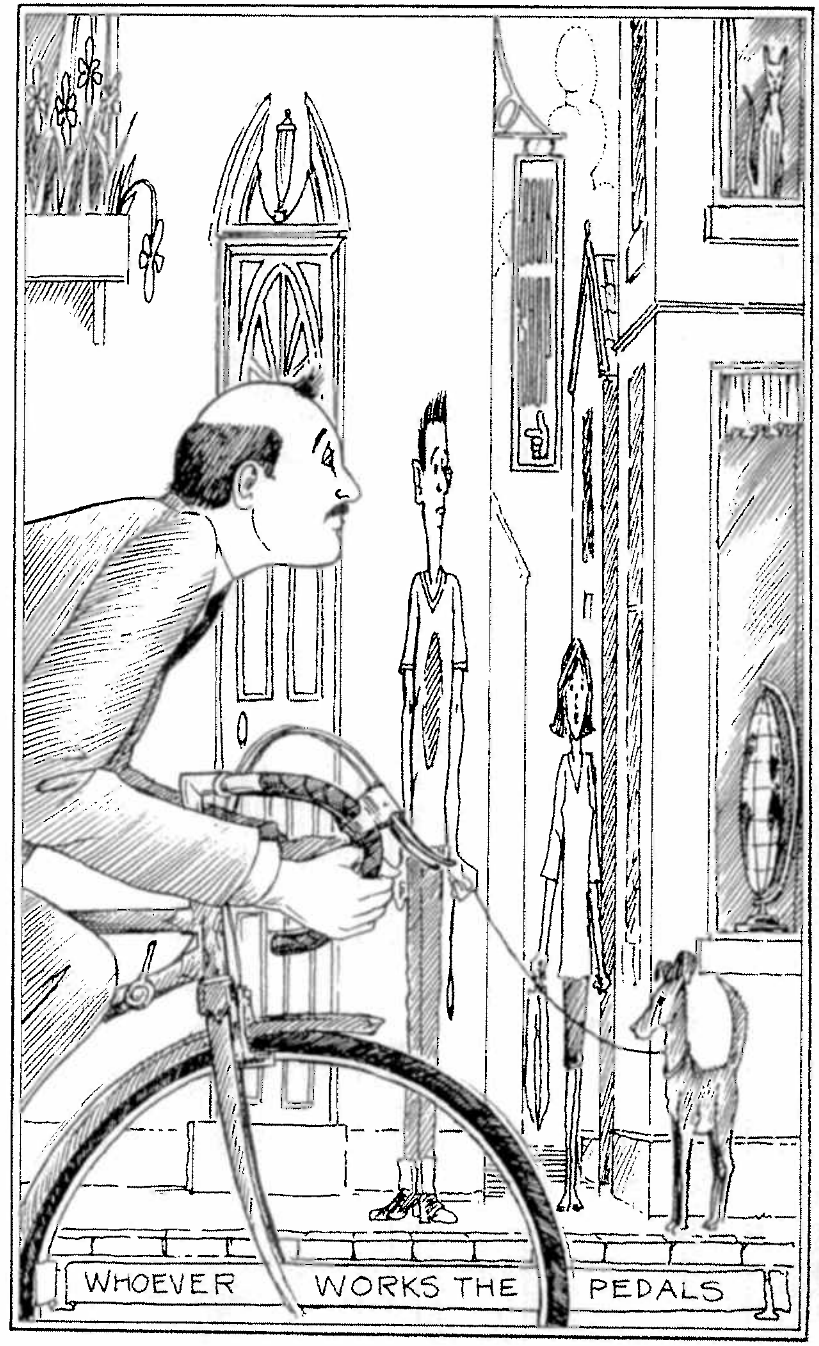
Mr Tompkins wanted to chase after the cyclist to ask him how he felt about being flattened. But how was he to catch up with him? It was then he spotted another bicycle standing against the wall of the college. Mr Tompkins thought it probably belonged to a student attending lectures who might not miss it if he were to borrow it for a short while. Making sure no-one was looking, he mounted the bike and sped down the street in pursuit of the other cyclist.

He fully expected that his newly acquired motion would immediately shorten him, and looked forward to this as his increasing girth had lately caused him some anxiety. To his surprise, however, nothing happened; both he and his cycle remained the same size and shape. On the other hand, the scene around him completely changed. The streets grew shorter, the windows of the shops became narrow slits, and the pedestrians were the thinnest people he had ever seen.

'Ah!' exclaimed Mr Tompkins excitedly. 'I get it now. This is where the word *relativity* comes in. Everything that moves relative to me looks shorter for me – whoever works the pedals!'

He was a good cyclist and was doing his best to overtake the young man. But he found that it was not at all easy to get up speed on this bicycle. Although he was working on the pedals as hard as he possibly could, the increase in speed was almost negligible. His legs had already begun to ache, but still he could not manage to pass a lamp-post on the corner much faster than when he had just started. It looked as if all his efforts to move faster were leading to nothing. He began to understand now why the ambulance could not do much better than the cyclist. It was then he remembered what the professor had said about the impossibility of exceeding the limiting velocity of light. He noticed, however, that the harder he tried, the shorter the city blocks became. The cyclist riding ahead of him did not now look so far away – and indeed he eventually managed to catch up with him. Riding side by side, he glanced across and was surprised to find that both the cyclist and his bike were now looking quite normal.

'Ah, that must be because we are no longer moving relative to each other,' he concluded.



'Excuse me,' he called out, 'Don't you find it inconvenient to live in a city with such a low speed limit?'

'Speed limit?' returned the other in surprise, 'we don't have any speed limit here. I can get anywhere as fast as I wish – or at least I could if I had a motor-cycle instead of this old bike!'

'But you were moving very slowly when you passed me a moment ago,' said Mr Tompkins.

'I wouldn't call it slow,' remarked the young man. 'That's the fifth block we've passed since we started talking. Isn't that fast enough for you?'

'Ah yes, but that's only because the blocks and the streets are so short now,' protested Mr Tompkins.

'What difference does it make? We move faster, or the street becomes shorter – it all comes down to the same thing in the end. I have to go ten blocks to get to the post office. If I step harder on the pedals the blocks become shorter and I get there quicker. In fact, here we are,' said the young man stopping and dismounting.

Mr Tompkins stopped too. He looked at the post office clock; it showed half-past five. 'Hah!' he exclaimed triumphantly. 'What did I tell you. You *were* going slow. It took you all of half an hour to go those ten blocks. It was exactly five o'clock by the college clock when you first passed me, and now it's half-past!'

'Did you *notice* this half hour?' asked his companion. 'Did it *seem* like half-an-hour?'

Mr Tompkins had to admit that it hadn't really seemed all that long – no more than a few minutes. Moreover, looking at his wrist watch he saw that it was showing only five minutes past five. 'Oh!' he murmured, 'Are you saying the post office clock is fast?'

'You could say that,' replied the young man. 'Or, of course, it could be your watch running slow. It's been moving relative to those clocks, right? What more do you expect?' He looked at Mr Tompkins with some exasperation. 'What's the matter with you, anyway? You sound like you're from some other planet.' With that, the young man disappeared into the post office.

Mr Tompkins thought what a pity it was the professor was not at hand to explain these strange happenings to him. The young man was evidently a native, and had been accustomed to this state of things even before he had learned to walk. So Mr Tompkins was forced to explore this strange world by himself. He reset his watch by the time shown on the post office clock, and to make sure it was still going all right, he waited for ten minutes. It now kept the same time as the post office clock, so all seemed to be well.

Resuming his journey down the street, he came to the railway station and decided to check his watch once more, this time by the station clock. To his dismay it was again quite a bit slow.

'Oh dear, relativity again,' concluded Mr Tompkins. 'It must happen everytime I move. How inconvenient. Fancy having to reset one's watch whenever you've been anywhere.'

At that moment a well-dressed gentleman emerged from the station exit. He looked to be in his forties. He glanced around and recognised an old lady waiting by the kerb side and went over to greet her. Much to Mr Tompkins's surprise, she addressed the new arrival as 'dear Grandfather'. How was that possible? How could *he* possibly be *her* grandfather?

Overcome with curiosity, Mr Tompkins went up to the pair and diffidently asked, 'Excuse me. Did I hear you rightly? Are you really her grandfather? I'm sorry, but I …'

'Ah, I see,' said the gentleman, smiling, 'perhaps I should explain. My business requires me to travel a great deal.'

Mr Tompkins still looked perplexed, so the stranger continued. 'I spend most of my life on the train. So, naturally I grow old much more slowly than my relatives living in the city. It's always such a pleasure to come back and see my dear little granddaughter. But I'm sorry, you'll have to excuse me, please …' He hailed a taxi, leaving Mr Tompkins alone again with his problems.

A couple of sandwiches from the station buffet somewhat revived him. 'Yes, of course,' he mused, sipping his coffee, 'motion slows down time, so that's why he ages less. And all motion is relative

– that's what the professor said – so that means he will appear younger to his relatives, in the same way as the relatives appear younger to him. Good. That's got that sorted out.'

But then he stopped. He put down the cup. 'Hold on. That's not right,' he thought. 'The grandaughter did *not* seem younger to him; she was older than him. Grey hair is not relative! So what does that mean? All motion is *not* relative?'

He decided to make one last attempt to find out how things really are, and turned to the only other customer in the buffet – a solitary man in railway uniform.

'Excuse me,' he began, 'would you be good enough to tell me who is responsible for the fact that the passengers in the train grow old so much more slowly than the people staying at one place?'

'I am responsible for it,' said the man, very simply.

'Oh!' exclaimed Mr Tompkins. 'How…'

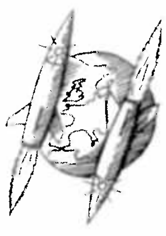
'I'm a train driver,' answered the man, as though that explained everything.

'A train driver?' repeated Mr Tompkins. 'I always wanted to be a train driver – when I was a boy, that is. But … but what's that got to do with staying young?' he added, looking more and more puzzled.

'Don't know exactly,' said the driver, 'but that's the way it is. Got it from this bloke from the university. Sitting over there we were,' he said nodding at a table by the door. 'Passing the time of day, you know. Told me all about it he did. Way over my head, mind you. Didn't understand a word of it. But he did say it was all down to acceleration and slowing down. I remember that bit. It's not just speed that affects time, he said; it's acceleration too. Every time you get pushed or pulled around on the train – as it comes into stations, or leaves stations – that upsets time for the passengers. Someone who is *not* on the train doesn't feel all those changes. As the train comes into the platform you don't find people standing on the platform having to hold onto rails or what-have-you to stop falling over in the way the passengers on the train do. So that's where the difference comes in. Somehow …' he shrugged.

Suddenly a heavy hand shook Mr Tompkins's shoulder. He found himself sitting not in the station café but on the bench of the auditorium in which he had been listening to the professor's lecture. The lights were dimmed and the room was empty. It was the janitor who had awakened him saying: 'Sorry, sir, but we're closing up. If you want to sleep, you'd be better off at home.' Mr Tompkins sheepishly got to his feet and started towards the exit.

2 The Professor's Lecture on Relativity which Caused Mr Tompkins's Dream



Ladies and gentlemen:

At a very primitive stage in the development of the human mind there formed definite notions of space and time as the frame in which different events take place. These notions, without essential changes, have been carried forward from generation to generation, and, since the development of the exact sciences, they have been built into the foundations of the mathematical description of the Universe. The great Newton perhaps gave the first clear-cut formulation of the classical notions of space and time, writing in his *Principia*:

> 'Absolute space, in its own nature, without relation to anything external, remains always similar and immovable;' and 'Absolute, true and mathematical time, of itself, and from its own nature, flows equably without relation to anything external.'

So strong was the belief in the absolute correctness of these *classical* ideas about space and time that they have often been held by philosophers as given a priori, and no scientist even thought about the possibility of doubting them.

However, at the start of the present century it became clear that a number of results, obtained by the most refined methods of experimental physics, led to clear contradictions if interpreted in the classical frame of space and time. This realization brought to one of the greatest twentieth century physicists, Albert Einstein, the revolutionary idea that there are hardly any reasons, except those of tradition, for

considering the classical notions concerning space and time as absolutely true, and that they could and should be changed to fit our new and more refined experience. In fact, since the classical notions of space and time were formulated on the basis of human experience in ordinary life, we need not be surprised that the refined methods of observation of today, based on highly developed experimental techniques, indicate that these old notions are too rough and inexact; they have been used in ordinary life and in the earlier stages of the development of physics only because their deviations from the correct notions were too small to be noticeable. Nor need we be surprised that the broadening of the field of exploration of modern science should bring us to regions where these deviations become so very large that the classical notions could not be used at all.

The most important experimental result which led to the fundamental criticism of our classical notions was the discovery that *the velocity of light in a vacuum is a constant (300,000 kilometres per second, or 186,000 miles per second), and represents the upper limit for all possible physical velocities.*

This important and unexpected conclusion was fully supported, for instance, by the experiments of the American physicists Michelson and Morley. At the end of the nineteenth century, they tried to observe the effect of the motion of the Earth on the velocity of light. They had in mind the prevailing view at the time that light was a wave moving in a medium called the aether. As such it was expected to behave in much the same way as water waves move over the surface of a pond. The Earth was expected to be moving through this aether medium in a manner similar to a boat moving over the surface of the water. The ripples caused by the boat appear to a passenger to move away more slowly from the vessel in the direction in which it is travelling than they do to the rear. In one case we have to subtract the speed of the boat from that of the water waves, and in the other we add them. We call this the *theorem of addition of velocities*. This has always been held to be self-evident. In the same way, therefore, one would expect that the speed of light would appear to differ according to its direction relative to the motion of the Earth through the aether. Indeed, it ought to be possible to determine the speed of the Earth with respect to the aether by measuring the speed of light in different directions.

To Michelson and Morley's great surprise, and the surprise of all the scientific world, they found that no such effect exists; the velocity of light was exactly the same in all directions. This odd result prompted the suggestion that perhaps, by an unfortunate coincidence, the Earth in its orbit around the Sun just happened to be stationary relative to the aether at the time the experiment was carried out. To check that this was not so, the experiment was repeated six months later when the Earth was travelling in the reverse direction on the opposite side of its orbit. Again, no difference in the speed of light could be detected.

It having been established that the velocity of light did not behave like that of a wave, the remaining possibility was that it behaved more like that of a projectile. If we were to fire a bullet from a gun in the boat, it would seem to the passenger to leave the moving boat at the same speed in all directions – which is the behaviour Michelson and Morley found for light emitted in all directions from the moving Earth. But in that case, someone standing on the shore would find that a bullet fired in the direction in which the boat was heading would be travelling faster than one fired in the opposite direction. In the first case the speed of the boat would be added to the muzzle speed of the bullet, and in the latter it would be subtracted – again in accordance with the theorem for the addition of velocities. Accordingly, we would expect that light emitted from a source that was *moving relative to us* would have speeds dependent on the angle of emission to the direction of motion.

Experiment shows, however, that this is also not the case. Take, for example, neutral pions. These are very small sub-atomic particles which undergo decay with the emission of two pulses of light. It is found that these pulses are always emitted with the same speed whatever their direction relative to the motion of the parent pion, even when the pion itself is travelling at a speed close to that of light.

Thus, we find that whereas the first experiment showed that the velocity of light did not behave like that of a conventional wave, this second one shows that it does not behave like a conventional particle either.

In conclusion, we find that the speed of light in a vacuum has a constant value regardless of the movement of the observer (our observations from the moving Earth), or the movement of the source of light (our observations of light emitted from the moving pion).

What of the other property of light I mentioned: it being the ultimate limiting velocity?

'Ah,' you might say, 'but is it not possible to construct a super-light velocity by adding several smaller velocities?'

For example, we could imagine a very fast-moving train with a velocity of, say, three-quarters that of light, and we could have a man running along the roofs of the carriages also with a velocity three-quarters that of light. (I asked you to use your *imagination*!) According to the theorem of the addition of velocities, the total velocity should be $1\frac{1}{2}$ times that of light. That would mean the running man should be able to overtake the beam of light from a signal lamp. It seems, however, that, since the constancy of the velocity of light is an experimental observation, the resulting velocity in our case must be smaller than we expect – the classical theorem for the addition of velocities must be wrong.

The mathematical treatment of the problem – something I do not want to enter into here – leads to a very simple new formula for the calculation of the resulting velocity of two superimposed motions. If v_1 and v_2 are the two velocities to be added, and c is the velocity of light, the resulting velocity comes out to be

$$V = \frac{(v_1 + v_2)}{\left(1 + \frac{v_1 v_2}{c^2}\right)} \qquad (1)$$

You see from this formula that if both original velocities were small, I mean small as compared with the velocity of light, the second term in the denominator (the bottom bit) of (1) will be so small it can be ignored, giving the classical theorem of addition of velocities. If, however, v_1 and v_2 are not small, the result will always be somewhat smaller than the arithmetical sum. For instance, in the example of our man running along a train, $v_1 = \frac{3}{4}c$ and $v_2 = \frac{3}{4}c$ and our formula gives the resulting velocity $V = \frac{24}{25}c$, which is still smaller than the velocity of light.

You should note that in the particular case when one of the original velocities is c, formula (1) always gives c for the resulting velocity independent of what the second velocity might be. Thus, by overlapping any number of velocities, we can never exceed the velocity of light. This formula has been confirmed experimentally; the addition of two velocities is always somewhat smaller than their arithmetical sum.

Recognizing the existence of the upper-limit velocity we can start on the criticism of the classical ideas of space and time, directing our first blow against the notion of *simultaneity*.

When you say, 'The explosion in the mines near Capetown happened at exactly the same moment as the ham and eggs were being served in your London apartment,' you think you know what you mean. I am going to show you, however, that you do not. Strictly speaking, this statement has no exact meaning.

To see this, consider what method you would use to check whether two events in two different places were simultaneous or not. You would say that the two events were simultaneous if clocks at both places showed the same time. But then the question arises as to how we are to set the distant clocks so that they show the same time simultaneously – and we are back at the original question.

Since the independence of the velocity of light in a vacuum on the motion of its source or the system in which it is measured is one of the most exactly established experimental facts, the following method of measuring the distances and setting the clocks correctly on different observational stations should be recognised as the most rational and, as you will agree after thinking more about it, the only reasonable method.

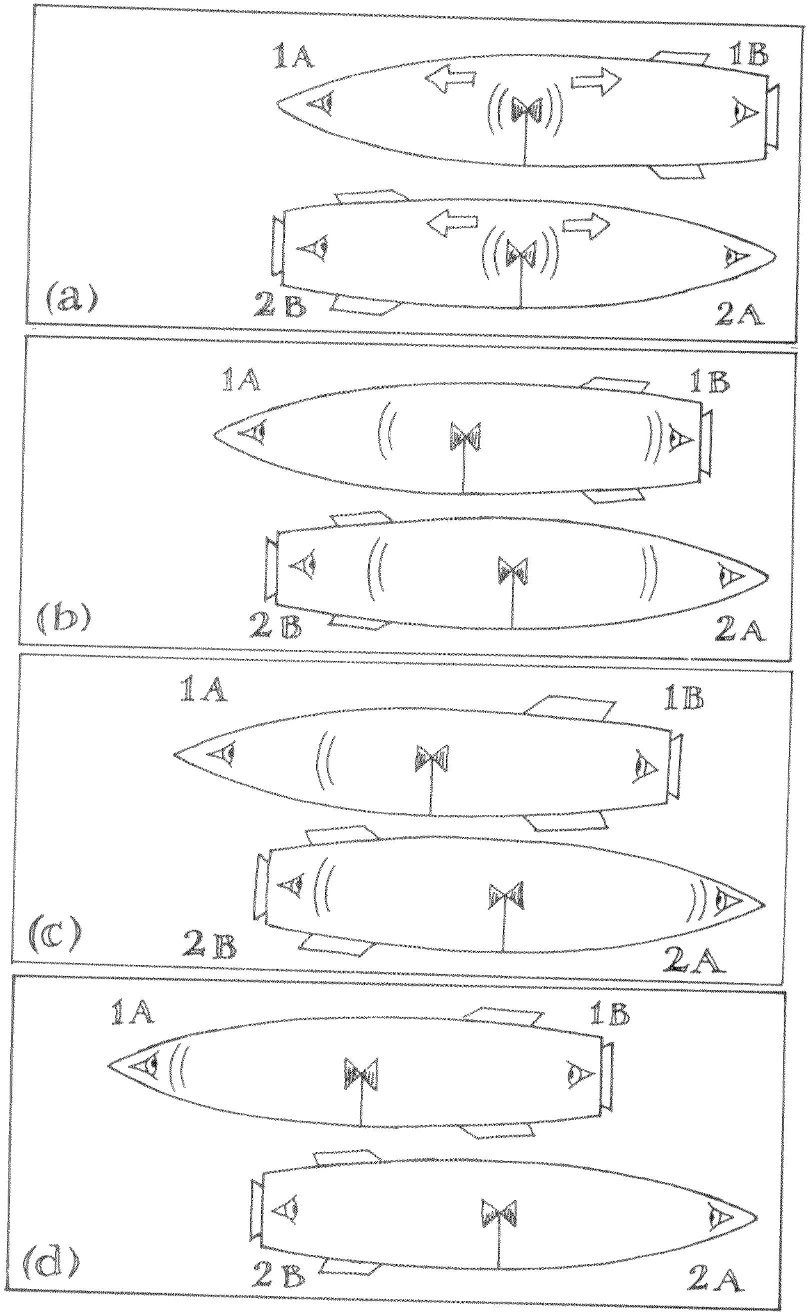
A light signal is sent from station A, and as soon as it is received at station B it is returned back to A. One-half of the time, as read at station A, between the sending and the return of the signal, multiplied by the constant velocity of light, will be defined as the distance between A and B.

The clocks on stations A and B are said to be set correctly if at the moment of arrival of the signal at B the local clock were showing the average of the two times recorded at A at the moments of sending and receiving the signal. Using this method between different observational stations established on a rigid body (in this case, the surface of the Earth) we arrive finally at the desired frame of reference. We can now answer questions concerning the simultaneity of, or the time interval between, two events in different places.

But given that all observers use this method for establishing their frames of reference, will they obtain the same results for their measurements? What if for instance observers are *moving* relative to each other?

To answer this question, suppose that such frames of reference have been established on two different rigid bodies, say on two long space rockets moving with a constant speed in opposite directions. Let us see how measurements made with these two frames check with one another. Suppose observers are located one at the front, and one at the rear-end, of each rocket. Firstly, each pair of observers needs to set their clocks correctly. This they do using a modification of the above-mentioned method. Using a measuring ruler, they locate the centre of their rocket. Here they place an intermittent source of light. They arrange for the source to emit a pulse of light that spreads outwards towards both ends of the rocket. They agree to set their watches to zero at the instant they receive the pulse from the middle at their respective locations. The light having travelled equal distances to each end, at the same speed, c, our observers have established, according to the previous definition, the criterion of simultaneity in their own system, and have set their watches 'correctly' – from their point of view.

Now they decide to see whether the time readings on their rocket check with those on the other. For example, do the watches of



Their watches do not read the same

the two observers on rocket 1 show the same time when observed from rocket 2? This can be tested by the following method: At the centre point of each rocket (where the light sources are situated), two electrically charged conductors are installed, in such a way that, when the rockets pass each other and their centres are directly opposite each other, a spark jumps between the conductors. This triggers the two light sources to emit their pulses simultaneously towards the front and rear ends of their respective rockets – as I have shown here in Fig. (a). After a while, according to observers 2A and 2B on rocket 2, we have the situation shown in Fig. (b). Rocket 1 has moved relative to rocket 2. The light beams have moved out equal distances in either direction. But note what has happened. Because observer 1B has moved forward to meet the light beam coming towards her (according, that is, to observers 2A and 2B), the rear-going pulse in rocket 1 has already reached the position of 1B. According to 2A and 2B, this is because it had less distance to travel. So observer 1B has set her watch going from zero before anyone else! In Fig. (c) the light pulses have reached the ends of rocket 2, and this is when observers 2A and 2B set their watches to zero – simultaneously. It is only when we get to Fig. (d) that the forward-going pulse in rocket 1 catches up with the receding observer 1A – which, according to him is the time to set his watch to zero. Thus, we see that, from the point of view of the observers in rocket 2, those in rocket 1 have not set their watches correctly – their watches do *not* read the same time.

Now, of course, we could just as easily have shown the same situation from the point of view of the observers in rocket 1. From their standpoint it is *their* rocket that is treated as being 'stationary', and it is rocket 2 that should be shown moving. It will then be observer 2B moving to meet his light pulse, and observer 2A moving away from his. As far as 1A and 1B are concerned, it is 2A and 2B who have not set their watches correctly, whereas they themselves have.

The difference of opinion arises because, where events occur in separated locations, both sets of observers have to make *calculations* before they can decide on the simultaneity or otherwise of separated events; they have to make allowance for the time it has taken for the light signals to travel from the distant locations, and both insist that the speed of light is a constant in all directions relative to *them*. (It is only where events occur at the *same* location – where there is no need for calculation – that there can be universal agreement over the simultaneity of events taking place at that one location.) Since both rockets are quite equivalent, this disagreement between the two groups of observers can be settled only by saying that both groups are correct *from their own point of view*, but the question of who is correct 'absolutely' is one that has no unique answer.

In this way we see that *the notion of absolute simultaneity vanishes, and two events in different places considered as simultaneous from one system of reference will be separated by a definite time interval from the point of view of another system*.

This proposition sounds at first extremely unusual. But let me ask you this: Would it be unusual if I were to say that, having your dinner on a train, you can eat your soup and your dessert in the same point of the dining car, but in widely separated points of the railway track? Of course not. This statement about your dinner in the train can be formulated by saying that *two events happening at different times at the same point in space of one system of reference will be separated by a definite space interval from the point of view of another system*.

I think you will agree that this is a 'trivial' proposition. But now compare it to the previous 'paradoxical' one, and you will see that they are absolutely symmetrical statements. One can be transformed into the other simply by exchanging the words 'time' and 'space'.

Here is the whole point of Einstein's view: Whereas in Newton's classical physics, time was considered as something quite independent of space and motion ('flowing equably without relation to anything external'), in the new physics, space and time are closely connected. They represent just two different cross-sections through the one homogeneous 'spacetime continuum' in which all observable events take place. We must not be misled by the very different ways in which we experience and measure the two (one with a ruler, the other with a watch). Physical reality does not consist of a three-dimensional space, together with a separate one-dimensional time. Space and time are indissolubly welded together into a seamless four-dimensional reality – one we refer to as *spacetime*.

The splitting of this four-dimensional spacetime continuum into a three-dimensional space and a one-dimensional time is purely arbitrary, and depends on the system from which the observations are made. Thus, two events, separated in space by the distance l_1 and in time by the interval t_1 as observed in one system, will be separated by another distance l_2 and another time interval t_2 as seen from another system. It all depends on the particular cross-section one is taking through the four-dimensional reality, and that in its turn depends upon one's motion relative to the events in question.

In a certain sense one can speak about the transformation of space into time, and of time into space. To an extent they can get 'mixed up'. It happens that the transformation of time into space (as in the example of the dinner in a train) is quite a common notion for us. On the other hand, the transformation of space into time, resulting in the relativity of simultaneity, seems unusual. The reason for this is that if we measure distances in, say, 'metres', the corresponding unit of time should not be the conventional 'second', but a more rational unit of time representing the interval of time necessary for a light signal to cover a distance of one metre, i.e. 0.000,000,003 second. If we were naturally sensitive to time intervals of that kind of duration, the loss of simultaneity would have always been manifestly obvious to us. It is the fact that, in the sphere of our ordinary experience, the transformation of space intervals into time intervals leads to differences in observation that are practically unobservable, which has led to the classical view of time as being something absolutely independent and unchangeable.

When investigating motions with very high velocities, however, such as those encountered when electrons are thrown out from radioactive atomic nuclei – where the distances covered in a certain interval of time are of the same order of magnitude as the time expressed in rational units – then one necessarily meets with the effects we have discussed, and the theory of relativity becomes of great importance. Even in the region of comparatively small velocities, as, for example, the motion of planets in our solar system, relativistic effects can be observed. This is due to the extreme precision of astronomical measurements. Such observation of relativistic effects requires measurements of changes of planetary motion amounting to a fraction of an angular second per year.

So, as I have tried to explain to you, our examination of the notions of space and time leads us to the conclusion that space intervals can be partially converted into time intervals, and vice versa. This means that the numerical value of a given distance or a period of time can be different when measured from different moving systems.

A comparatively simple mathematical analysis of this problem, into which I do not, however, want to enter in these lectures, leads to a definite formula for the change of these values. For those of you interested, it works out that any object of length l_0, when moving relative to an observer with velocity v, will appear to be shortened by an amount depending on its velocity. Its measured length, l, will be

$$l = l_0 \sqrt{\left(1 - \frac{v^2}{c^2}\right)} \qquad (2)$$

From this you will see that as v becomes very close to c, l becomes smaller and smaller. This is the famous relativistic *length contraction*. I hasten to add that this is the length of the object in the direction of motion. Its dimensions at right angles to that direction remain unaltered. The object in effect becomes flattened in the direction of motion.

Analogously, any process taking time t_0 will be observed from a system moving with velocity v relative to that process to be taking a longer time t, given by

$$t = \frac{t_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}} \qquad (3)$$

Note that as v increases, so does t. Indeed, as v approaches the value of c, t becomes so large that the process essentially comes to a halt. This is known as relativistic *time dilation*. It is the origin of the idea that if one were to have astronauts travelling close to the speed of light, their ageing processes would slow down so much they would effectively get no older – they could live forever!

Don't forget that these effects are absolutely symmetrical as between frames of reference in uniform relative motion. Whereas people standing on the station platform will consider that passengers on a fast-moving train are very thin and move about the train very slowly, with watches on their wrists that are going slow, the passengers on that train will think the same about the people they see outside standing on the platform; the station will be squashed up and everything happening there will be in slow motion.

At first sight this might strike you as paradoxical. Indeed, the problem has become known as the 'twin paradox'. The idea is that you have two twins, one of whom goes on a journey, leaving the other at home. According to the theory I have presented, each twin will believe it is the other who is ageing less quickly, based on their observations of the other and the calculations they have had to make as regards how long the light signals have taken to reach them. The question is what will they discover when the travelling twin returns and a *direct comparison* can be made between them – a comparison that no longer requires any calculations to be made because they are once more in the same location? (Obviously they can't *both* be older than the other.) The resolution of the problem comes from the recognition that the two twins are *not* on the same footing. In order for the travelling twin to return, she must undergo acceleration – first of all slowing down, and then reaccelerating in the opposite direction. Unlike her twin brother, she has not remained in a state of uniform motion. Only the stay-at-home twin has abided by this condition, and so it is this twin who finds himself vindicated in his belief that his sister is now younger than himself.

One more point before I end. You might be wondering what prevents us accelerating an object to a speed greater than that of light.

Surely, you might be thinking, if I push hard enough and for long enough on the object so that it is always accelerating, eventually it must reach any desired speed.

According to the general foundation of mechanics, the mass of a body determines the difficulty of setting it into motion or accelerating the motion already existing; the larger the mass, the more difficult it is to increase the velocity by a given amount. The fact that no object under any circumstances can exceed the velocity of light leads us to a possible interpretation of what is going on. This holds that the increased resistance to further acceleration is due to an increase in the object's mass. In other words, its mass must increase without limit when its velocity approaches the velocity of light. Mathematical analysis leads to a formula for this dependence, which is analogous to the formulae (2) and (3). If m_0 is the mass for very small velocities, the mass m at the velocity v is given by

$$m = \frac{m_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}} \tag{4}$$

From this we see that the resistance to further acceleration becomes infinite when v approaches c – hence c is the ultimate speed. A good demonstration of the relativistic change of mass can be observed experimentally on very fast-moving particles. Take, for example, electrons. These are the tiny particles found within atoms, moving about the atom's central nucleus. They are easy to accelerate because they are so light. When electrons are stripped out of their atoms and subjected to powerful electric forces in special particle accelerators, they can be made to reach speeds that are within a tiny fraction of the speed of light. At such speeds their resistance to further acceleration can be the equivalent of a particle of mass 40,000 times greater than the normal mass of the electron – as has been demonstrated at a laboratory at Stanford in California.

Not only that, but time dilation has also been demonstrated. In the high energy physics laboratory called CERN, just outside Geneva in Switzerland, unstable muons (a type of fundamental particle that

normally undergoes radioactive disintegration after about one millionth of a second) have been found to live longer by a factor of thirty when travelling at high speed around a circular machine shaped like a large hollow doughnut. At the speed the muons were travelling, a factor of thirty is exactly the value expected on the basis of the above formula for time dilation.

Thus, for such velocities, the classical mechanical approximations become absolutely inadequate, and we enter into a domain where the application of the theory of relativity becomes inescapable.