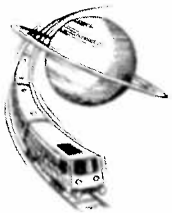
3 Mr Tompkins takes a Holiday



Several days after that first lecture, Mr Tompkins was still intrigued by his dream concerning the relativistic city. He was particularly puzzled over the mystery of how the train driver had been able to prevent the passengers from getting old. Each night he went to bed with the hope that he would see this interesting city again. But it was not to be. Being a somewhat timid and anxious man, his dreams were mostly unpleasant. Last time it was the manager of the bank who was firing him for being slow preparing his accounts. Mr Tompkins's attempted excuse based on relativistic time dilation had fooled no-one. He decided he needed a holiday. Thus, he found himself sitting in a train, watching through the window the grey roofs of the city suburb gradually giving place to green country meadows as he headed for a week-long stay by the sea. He had unfortunately had to miss the second lecture in the series, but had managed to get hold of a photocopy of the professor's notes from the departmental secretary. He had already tried to make sense of them, but had not got far. Having brought them along with him, he pulled them out of the suitcase and began studying them once more. Meanwhile, the railway carriage rocked him pleasantly …

When he lowered the notes and looked out of the window again, the landscape had changed considerably. The telegraph poles were so close to each other they looked like a hedge, and the trees had extremely narrow crowns, rather like Italian cypresses. To add to his delight, who should be sitting opposite him but the professor! He must have boarded while Mr Tompkins had been busy reading.

Plucking up courage, Mr Tompkins decided to take advantage of the occasion.

'I take it we're in the land of relativity,' he remarked.

'Yes indeed,' replied the professor, 'you're familiar with it …?'

'I was here once before.'

'You're a physicist – an expert on relativity?' enquired the professor.

'Oh no,' protested Mr Tompkins in some confusion. 'I have only just started learning about it – just the one lecture so far.'

'Good. Never too late. Fascinating subject. Where exactly are you studying?'

'At the university. It was *your* lecture I attended.'

'Mine?!' exclaimed his companion. He looked hard at Mr Tompkins, then flashed a smile of recognition. 'Ah yes. The man who crept into the back late! I remember now. Yes, I thought your face was familiar.'

'I hope I didn't disturb …' mumbled Mr Tompkins apologetically. He desperately hoped the observant professor had not noticed he had eventually dozed off in his lecture.

'No, no. That's all right,' was the reply. 'Happens all the time.'

Mr Tompkins reflected for a moment, then ventured, 'I don't want to impose on you, but I was wondering if I might ask you a question – just a short one? Last time I was here, I met a train driver who insisted that the reason why passengers grow old less quickly than the people in the city – and not the reverse – was all to do with the fact that the train stops and starts. I didn't understand …'

The professor looked thoughtful, and then began:

'If two people are in uniform relative motion, then each will conclude that the other is ageing less quickly than themselves – relativistic time dilation. A passenger on the train will think that the booking clerk in the station is ageing less quickly than she is; likewise, the booking clerk will conclude that it is he who is ageing less quickly than she.'

'But they can't both be right,' objected Mr Tompkins.

'Why not? They are both right – from their own point of view.'

'Yes, but who is *really* right?' Mr Tompkins insisted.

'You can't ask general questions like that. In relativity, your observations must always be with respect to a particular observer – an observer with a well-defined motion relative to whatever is being observed.'

'But we know it's the passenger who ages less than the clerk – it is not the other way round.' Mr Tompkins went on to describe his encounter with the much travelled gentleman and his granddaughter.

'Yes. yes,' interrupted the professor somewhat impatiently. 'It's the twin paradox all over again. I dealt with that in my first lecture if you recall. The grandfather is subject to acceleration; unlike the granddaughter, he does *not* remain in a state of uniform constant motion. So she is the one who correctly expects her grandfather to have aged less when he gets back and they can compare themselves side by side.'

'Yes. I see that,' agreed Mr Tompkins. 'But I still don't get it. The granddaughter can use the time dilation of relativity to understand why her grandfather has aged less; that's not a problem. But won't the grandfather be at a loss to understand how his granddaughter has aged *more*? How does he account for *that*?'

'Ah,' replied the professor, 'but that's what I was dealing with in the second lecture, remember?'

It was here Mr Tompkins had to explain how he had missed it – but was nevertheless trying to catch up by reading the notes.

'I see,' resumed the professor, 'Well, let me put it like this: In order for the *grandfather* to understand what's going on, he must take account of what he reckons is happening to his granddaughter while he *changes* his motion.'

'And what would that be?' enquired Mr Tompkins.

'Well, while he is travelling along with uniform velocity, his granddaughter ages less – the usual time dilation. But once the driver applies the brakes, or later accelerates back on the return journey, then that has precisely the opposite effect on her ageing processes; they appear to the grandfather to *speed up*. It's during those brief spells of *non* uniform motion that her ageing races way ahead of the grandfather's. So, even though she then resumes her normal slower ageing rate during the uniform coasting home, the net effect when he gets back is that he expects her to have aged more than he – and that is what he finds.'

'How extraordinary,' observed Mr Tompkins. 'But do scientists have any proof of this? Are there any experiments that show this differential ageing?'

'Certainly. In my first lecture I mentioned the unstable muons circulating around that hollow doughnut at the CERN laboratory in Geneva. Because they had a speed close to that of light, they took thirty times longer to disintegrate than muons that just sit still in the laboratory. The moving muons are like the grandfather; they are the ones performing the round trip journey and experiencing all the forces needed to steer them on their course and bring them back to their starting point. The stationary muons are like the granddaughter; they age at the normal rate; they disintegrate – or 'die' – quicker than the moving ones.

'In fact there is another way of checking this out – an indirect one: The conditions existing in a non-uniformly moving system are analogous, or should I say identical, to the result of the action of a very large force of gravity. You may have noticed that when you are in a lift which is rapidly accelerated upwards it seems that you have grown heavier; on the contrary, if the lift starts downward (you realise it best when the cable breaks) you feel as though you were losing weight. The explanation is that the 'gravitational field' created by acceleration is added to, or subtracted from, the gravity of the Earth. This equivalence between acceleration and gravity means that we can investigate the effect of acceleration on time by noting what effect gravity has. It is found that the Earth's gravity causes atomic vibrations to occur faster at the top of a tall tower than they do at the bottom. And this is exactly what Einstein predicted would be the effect of aceleration.'

Mr Tompkins frowned. He did not see the connection between speeded up atomic vibrations at the top of a tower, and the granddaughter's supposed speeded up ageing. Noting his puzzlement, the professor continued.

'Suppose you are at the bottom of the tower looking up at those speeded up atomic vibrations occurring at the top. You are being acted on by an external force: the floor is pushing up on you to counter gravity. It is the fact that this upward force has come into play that increases the time processes of anything lying in the upwards direction. The further away from you the atoms are, the greater will be what we call *the gravitational potential difference* between you and those atoms. That in turn means the more speeded up those atoms will be compared with atoms you have with you at the bottom of the tower.

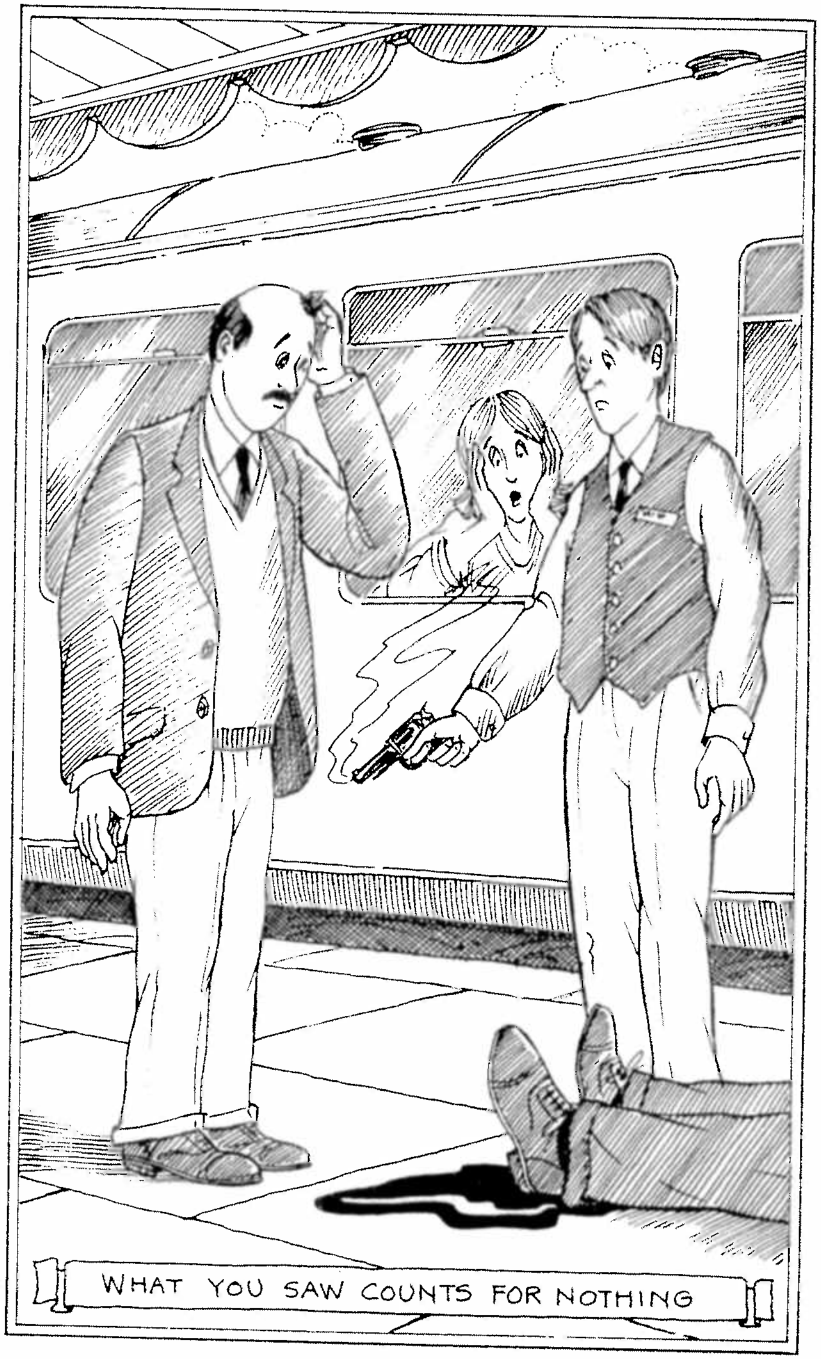
'Now, in the same way, if you are acted upon by an external force in this train ...' He paused. 'In fact, I do believe we *are* slowing down; the driver has applied the brakes. Excellent. At this very moment the back of your seat is applying a force to you altering your velocity. It is acting in a direction towards the back of the train. While this is going on, the time processes of everything occurring down the line in that direction will be speeded up, And if that's where your granddaughter is, that's what will be happening to her.

'Where are we anyway?' he asked peering out of the window.

The train was passing slowly through a little countryside station. There was no-one on the platform apart from a ticket collector and, at the other end of the platform, a young man sitting at the window of the booking office, reading a newspaper. Suddenly the ticket collector threw his hands into the air and fell down on his face. Mr Tompkins did not hear the sound of shooting, which was probably lost in the noise of the train, but the pool of blood forming round the body of the collector left no doubt as to what had happened. The professor immediately pulled the emergency cord and the train stopped with a jerk. When they got out of the carriage the young booking clerk was running towards the body, carrying a gun. At that moment a policeman came on the scene.

'Shot through the heart,' said the policeman after inspecting the body. He turned to the young man. 'I am arresting you for the murder of the ticket collector. Hand over that gun.'

The clerk looked in horror at the gun.



'It's not mine!' he cried. 'I just picked it up. It was lying over there. I was reading and heard this shot and came running. And there was the gun lying on the ground. The murderer must have thrown it down as he made his getaway.'

'A likely story,' said the policeman.

'I tell you,' insisted the young man, 'I never killed him. Why would I want to do a thing like that to the old boy ...?'

He looked around desperately. 'You,' he said pointing to Mr Tompkins and the professor. 'You must have seen what happened. These gentlemen can testify that I am innocent.'

'Yes,' confirmed Mr Tompkins, 'I saw it all. This man was reading his paper when the ticket collector was shot. He did not have the gun with him at the time.'

'Huh! But you were on the train,' said the policeman dismissively. 'You were moving weren't you. *Moving*! What you saw counts for nothing. That's no evidence at all. As seen from the *platform* the man could have taken out the gun and shot the victim, even though at the time of the death it seemed to *you* on the train that he was still reading. Simultaneity depends on the system from which you observe it, right? I know you mean well, sir, but you're just wasting my time. Come along with me,' he said, turning to the unfortunate clerk.

'Er, excuse me, officer,' interrupted the professor, 'but I think you are making a mistake – a *serious* mistake. It's true, of course, that the notion of simultaneity is highly relative in your country. It is also true that two events in different places could be simultaneous or not, depending on the motion of the observer. But, even in your country, no observer can see the consequence before the cause. (I take it you've never received a letter before it was sent, or got drunk before opening the bottle?) Now the fact is that we saw the young man take hold of the gun *after* the ticket collector fell dead. As I understand it, you are supposing that because of the motion of the train, we could have seen the collector get shot before his murderer fired the gun that caused his death. Respectfully, I would point out to you that this is an impossiblity – even in your country. I know that in your police force you are taught to work strictly by what is written in your instruction manual. I suspect if you look, you'll probably find something about this ...'

The professor's authorative tone made quite an impression on the policeman. Pulling out his pocket book of instructions, he thumbed through it slowly. Soon a sheepish smile of embarrassment spread across his big, red face.

'Yes, I think I see what you're on about, sir,' he admitted. 'Here it is: section 37, subsection 12, paragraph e. "If a reliable observation is made from any moving system whatsoever, that the suspect was at a distance *d* from the scene of the crime within a time interval ± *cd* of the instant at which the crime was committed (*c* being the natural speed limit), then the suspect could not have been the cause of the crime and thus has an acceptable alibi." '

'I am very sorry, sir,' he mumbled to the clerk. 'There seems to have been some mistake. I do apologise.'

The young man looked relieved.

Turning to the professor, the policeman added, 'And thank you very much, sir. I'm new to the force, you see. I'm still having to get the hang of all these rules. I must say you've saved me from a lot of trouble back at headquarters. But if you'll excuse me now, I must report the murder.'

With that he began speaking into his mobile radio. A minute later, just as Mr Tompkins and the professor were reboarding the train, having taken their leave of the grateful clerk, the officer called out to them. 'Good news! They appear to have caught the real murderer. My colleagues have picked up a suspect running away from the station. Thank you once more!'

Having resumed their seats, Mr Tompkins asked, 'I may be stupid, but I still don't feel I have fully grasped all this business about simultaneity. Am I right in saying that it really has no meaning in this country?'

'It has,' was the answer, 'but only to a certain extent; otherwise I should not have been able to help the clerk just then. You see, the existence of a natural speed limit for the motion of any object, or the sending of any signal, makes simultaneity in our ordinary sense of the word lose its meaning. Let me put it this way. Suppose you have a friend living in a far-away country with whom you correspond by air mail. Let's say it takes three days for a letter to make the journey. Something happens to you on Sunday and you learn that the same thing is going to happen to your friend. It is clear that you cannot let him know about it before Wednesday. On the other hand, if he knew in advance about the thing that was going to happen to you, the last date to let you know about it would have been the previous Thursday. Thus for three days beforehand your friend was not able to influence your fate on Sunday, nor for three days afterwards could he in turn be affected by what happened to you on that Sunday. From the point of view of causality he was, so to speak, excommunicated from you.'

'What about sending a message via email?' suggested Mr Tompkins.

'I was assuming – for the sake of argument – that the velocity of the plane carrying the mail was the maximum possible velocity. In point of fact, it is the velocity of light (or any other form of electromagnetic radiation – such as radio waves) that is the maximum velocity. You cannot send a signal, or have any causal influence, faster than that.'

'I'm sorry, you've lost me,' said Mr Tompkins. 'What has all this to do with simultaneity?'

'Well,' replied the professor. 'Take Sunday lunch, for instance. Both you and your friend have Sunday lunch. But do you have it at the same time – simultaneously? One observer might say yes. But there would be others, making their observations from different trains, say, who would insist that you ate your Sunday dinner at the same time as your friend had his Friday breakfast or Tuesday lunch. But – and this is the point – in no way could anybody observe you and your friend simultaneously having meals more than three days apart. If you did, you'd get into all sorts of contradictions. For example, it would be possible for you to send by mail train your Sunday lunch leftovers for your friend to eat for his Sunday lunch. How could an observer then conclude that you were eating your Sunday lunches simultaneously if you had clearly already finished yours? And another thing …'

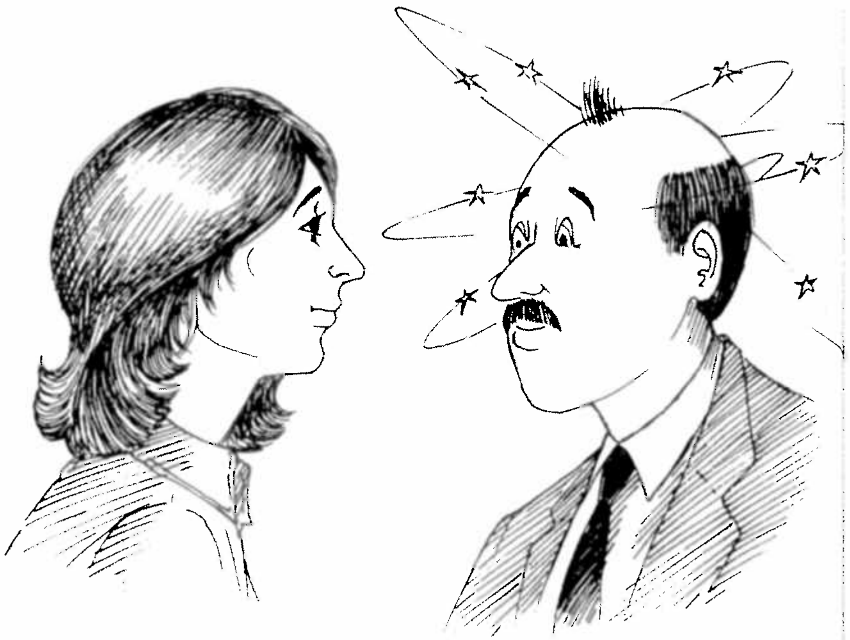
At this point their conversation was interrupted. A sudden jolt awoke Mr Tompkins. The train had come to a halt at its destination. Mr Tompkins hurriedly gathered up his things, stepped down from the train, and went in search of his hotel.

* * *

Next morning, when Mr Tompkins came down to have his breakfast in the long glass verandah of the hotel, a surprise awaited him. At the table in the opposite corner sat the professor! This was not actually as great a coincidence as one might think. At the time Mr Tompkins had gone to the university to collect the lecture notes, the secretary had drawn his attention to a notice stating that the following week's lecture had been cancelled. Mr Tompkins learned from the secretary that this was because the professor was taking a week's vacation. On remarking to her that he hoped he was going somewhere nice, she had mentioned the name of the resort. It was one of Mr Tompkins's favourites, though he had not been there for a number of years. It was this that had given him the idea of following the professor's example. That was how they came to end up in the same seaside town – though it was an added bonus for Mr Tompkins to find himself by chance at the very same hotel as the professor.

But what took Mr Tompkins's eye even more than the professor was the person to whom he was talking: a casually dressed woman, not exactly beautiful but certainly striking to look at, shortish but elegant, with long hands which she moved expressively as she spoke and laughed. Mr Tompkins reckoned she must be in her early 30s – probably a few years younger than himself. He wondered what a young woman like that saw in an old man like the professor.

At that moment she happened to glance in his direction. To his embarrassment, before he could look away, she caught him staring at her. She gave him a polite, little smile, before immediately turning back to her companion. The professor had meanwhile followed her



Pleased to meet you, Maud

gaze, and was now examining him intently. As their eyes met he gave a brief, quizzical nod as if to say 'Don't I know you from somewhere?'

Mr Tompkins felt he had better go across and introduce himself. It felt odd doing it a second time, but he realized, of course, that yesterday's encounter had been but a dream. The professor warmly invited him to change tables and come and join them.

'This, by the way, is my daughter, Maud,' he said.

'Your daughter!' exclaimed Mr Tompkins. 'Oh.'

'Is something wrong?' enquired the professor.

'No, no,' stammered Mr Tompkins. 'No. Of course not. Pleased to meet you, Maud.'

She smiled and offered her hand. After they had resumed their seats and ordered breakfast, the professor turned to Mr Tompkins and asked 'So, what did you make of all that stuff on curved space – in the last lecture ...?'

'Dad!' Maud gently admonished him. But he ignored her. Again, for what seemed the second time, Mr Tompkins had to apologize for having missed it. The professor was, however, impressed that he had gone to the trouble of procuring the lecture notes and was trying to catch up.

'Good. You're obviously keen,' he said. 'If we get bored with all this lying around doing nothing all day long, I could give you a tutorial.'

'Dad!' exploded Maud indignantly. 'That's not what we're here for. You're supposed to be getting away from it all for a week.'

He just laughed. 'Always telling me off,' he said, patting the back of her hand affectionately. 'The holiday's her idea.'

'And your doctor's, remember,' she reminded him.

'Well, anyway,' said Mr Tompkins, 'I certainly got a lot out of the first lecture.' He laughed as he went on to describe his dreams about relativity land – how the streets had become visibly shrunk, and how the time dilation effects had been greatly magnified.

'Now that's what I've been telling you about,' said Maud to her father. 'If you're to give lectures to the public, you simply *have* to make them more concrete. People have to relate the effects you're talking about to everyday life. I reckon you ought to include relativity land in your lectures; take a tip from Mr Tompkins here. You're too abstract – too, too ... *academic*.'

'Too academic,' the professor repeated with a chuckle. 'She's always on about that.'

'Well, you *are*.'

'OK, OK,' he conceded. 'I'll think about it. Mind you,' he added, 'it's not *right*. Even if the speed limit were something like 20 miles per hour, you wouldn't *see* a passing bicycle shortened.'

'You wouldn't?' queried Mr Tompkins, looking confused.

'Not as such. No. The point is that what you see – with your eyes, or what you would photograph with a camera – depends on what light arrives at the eye or lens *at the same instant in time*. Now, if light from the rear of the bike has further to travel to you than light from the front, then the light arriving at a particular point in time from each end must have started out at different times – when the bike was in different positions. Light from the rear must have started out from – and will appear to be coming from – the place where the rear of the bike was when it was further down the road …'

Mr Tompkins wasn't quite following this, so the professor stopped. He thought for a moment, then shrugged.

'It's a small point. It's just that the finite speed of light *distorts* what you see. What you would actually *see* in relativity land is a bike that appeared to be *rotated*.'

'*Rotated*!' exclaimed Mr Tompkins.

'Yes. That's how it happens to work out. It appears rotated, rather than shortened. It's only when you take this raw observation – the data on your photograph, say – and you make due allowance for the different journey times of the light arriving at different points on the photo, that you calculate (note, *calculate* rather than see) – it's only then you conclude that to get that picture, the bike must be length-contracted.'

'There you go again. Academic nit-picking,' interrupted Maud.

'*Nit-picking*!' the professor exploded. 'It's nothing of the sort …'

'I have to go back to my room. I need my sketch pad,' she announced. 'I'll leave you two to it. See you for lunch.'

Maud having left, Mr Tompkins remarked, 'I take it she likes doing a bit of drawing then?'

'A bit of …' The professor gave him a warning look. 'I shouldn't let her hear you say that. Maud is an artist – a professional artist. She's made quite a name for herself. It's not everyone gets a retrospective exhibition in a Bond Street gallery. And there was that profile on her in *The Times* last month.'

'Really!' exclaimed Mr Tompkins. 'You must be very proud of her.'

'I am indeed. It's all turned out well, *very* well – in the end.'

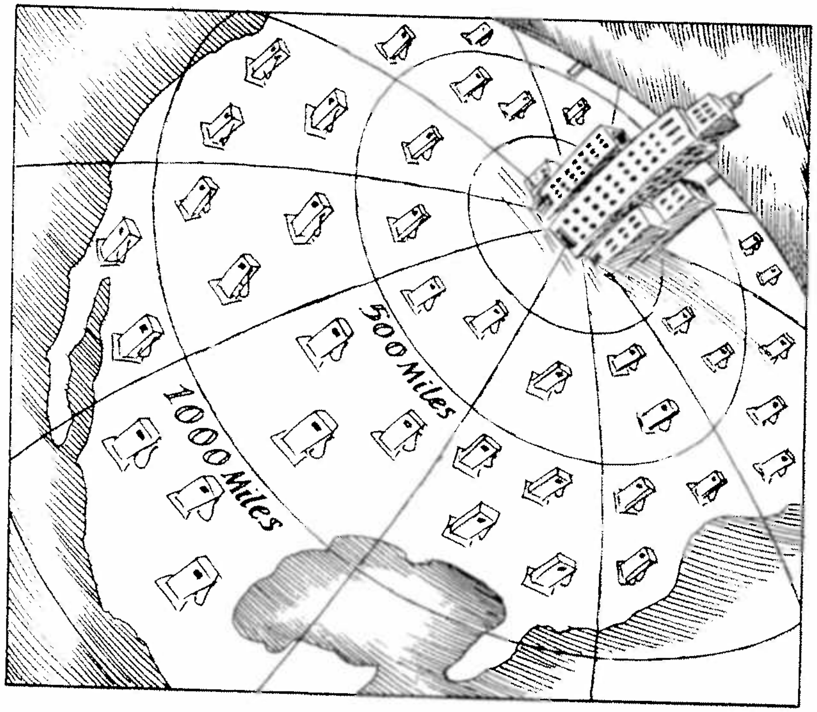
'In the end? What do you mean …?'

'Oh nothing. It's just that this wasn't exactly what I had had in mind for her. She was cut out to be a physicist at one stage. Very good she was – top of her year in both maths and physics at college. Then suddenly, she gave it all up. Just like that …' His voice trailed off.

Pulling himself together, he continued 'But as I said, she's made a success of herself – and she's happy. What more could I want?' He glanced out of the dining room window. 'Care to join me? We could grab a couple of deck chairs before they all go, and …' he added conspiratorially, making sure Maud was not around, 'we could talk shop.'

They made their way to the beach and settled down in a quiet spot.

'So,' began the professor, 'let's think about curved space. We can do this best by thinking of a surface – a two-dimensional surface – like that of the Earth. Imagine some oil tycoon decides to see whether his petrol stations are distributed uniformly throughout some country, say America. To do this, he gives orders to his office, somewhere in the middle of the country (Kansas City, say). They are to count the number of stations within a certain distance of the city, then the number within twice that distance, three times, and so on. He remembers from



Oil stations concentrated near Kansas City his school days that the area of a circle is proportional to the square of its radius, and expects that in the case of a uniform distribution, the number of stations counted should increase like the sequence of numbers 1, 4, 9, 16, and so on. When the report comes in, he is surprised to see that the actual number of stations is increasing somewhat more slowly, going, let us say, 1, 3.9, 8.6, 14.7, and so on. "I don't understand," he would exclaim; "my managers do not seem to know their job. What is the great idea of concentrating the stations close to Kansas City?" But is he right in this conclusion?'

'It sounds like it,' agreed Mr Tompkins.

'He is not,' declared the professor. 'He has forgotten that the Earth's surface is not a plane but a sphere. And on a sphere the area within a given radius grows more slowly with the radius than on a plane. Take that ball over there,' he said, indicating towards a girl throwing a beach ball to her father. 'Suppose that were to be a globe with a north pole marked on it. If you start from that north pole as centre, then the circle with radius equal to a half meridian is the equator, and the area included is the northern hemisphere. Increase the radius twice and you will get in all the Earth's surface; the area will increase only twice instead of four times as it would on a plane. The difference is due to the positive curvature of the surface. OK?'

'Yes, I think so,' said Mr Tompkins. 'But why did you say "positive"? Is there such a thing as "negative curvature"?'

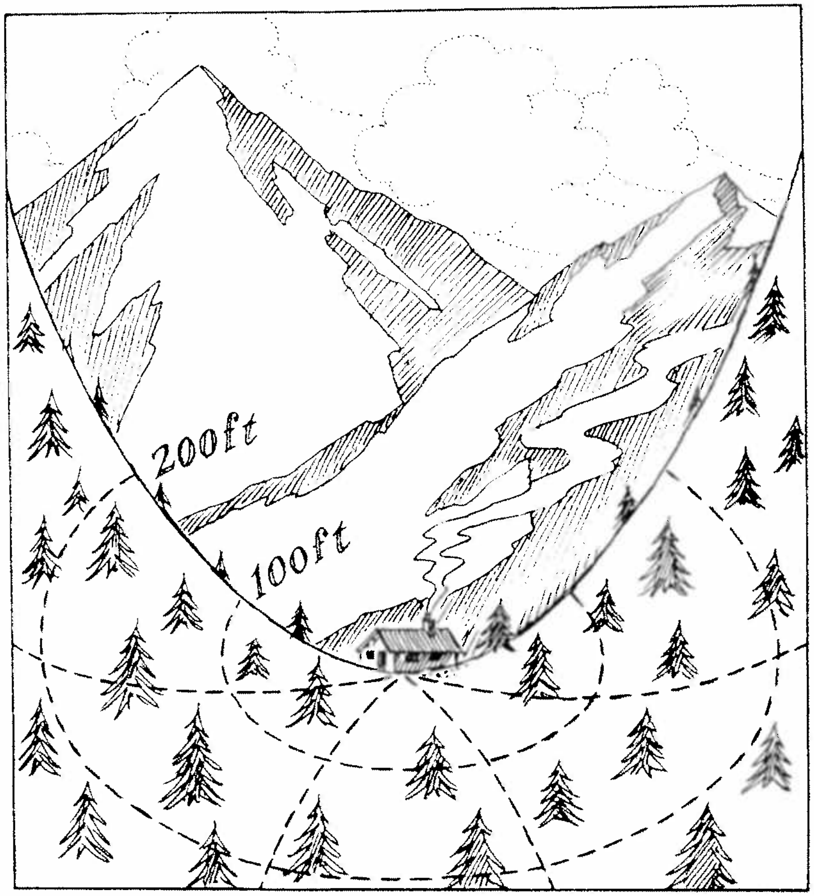
'Certainly.' His eyes roved around the beach searchingly. 'There! That's an example of it right over there,' he said, pointing to a donkey giving a ride to a boy. 'The saddle. The surface of that donkey's saddle is an example of negative curvature.'

'A saddle?' repeated Mr Tompkins.

'Yes, or on the surface of the Earth, a saddle pass between two mountains. Suppose a botanist lives in a mountain hut situated on such a saddle pass and is interested in the density of growth of pines around the hut. If he counts the number of pines growing within one hundred, two hundred, and so on metres from the hut, he will find that the number of pines increases *faster* than the square of the distance – the opposite of what we had for the globe. For a saddle surface, the area included within a given radius is larger than on a plane. Such surfaces are said to possess a negative curvature. If you try to spread a saddle surface on a plane you will have to make folds in it, whereas doing the same with a spherical surface you will probably tear it if it is not elastic.'

'I see,' said Mr Tompkins.

'Another thing about these saddle surfaces,' the professor continued. 'The area of a sphere is finite ($4\pi r^2$); the surface closes back on itself. But it's not like that with a saddle. A saddle surface could, in



A mountain hut in a saddle pass

principle, be extended indefinitely in all directions. It's an "open" surface, not a "closed" one. Of course, in my example of a saddle pass the surface ceases to possess negative curvature as soon as you walk out of the mountains and go over into the positively curved surface of the Earth. But of course you can imagine a surface which preserves its negative curvature everywhere.'

'OK,' said Mr Tompkins. 'But if you'll forgive me, this all seems very straightforward. Why are you telling me ...?'

'Ah, well, the point is that exactly the same kind of thinking applies to THREE-dimensional space – not just to the two-dimensional "spaces" or surfaces we've been dealing with so far. Three-dimensional space can be curved.'

'But how ...?'

'Same reasoning as before. We use the same technique. Let's suppose we have objects distributed uniformly throughout space – three-dimensional space now, not just petrol stations distributed on the two-dimensional surface of the Earth. They might be stars now – or better still galaxies (great swirling collections of stars scattered throughout space), or clusters of galaxies. Suppose the clusters were to be more-or-less uniformly distributed – meaning the distance between them was always the same. OK, you count their number within different distances from you. If this number grows as the cube of the distance, the space is flat. (You know of course that the volume of a sphere goes up as the cube of its radius – according to normal Euclidean geometry?')'

Mr Tompkins nodded.

'OK, then,' the professor continued. 'If that's how the number of galaxy clusters goes up, then the space is said to be 'flat' – it's genuinely Euclidean. But if we find the growth is slower or faster, the space possesses a positive or negative curvature.'

'So, are you saying that in the case of positive curvature the space has less volume within a given distance, and in the case of negative curvature more volume?' ventured Mr Tompkins.

'Just so,' smiled the professor.

'But that would mean, if space were positively curved – this space all around us here – then the volume of that beach ball is not $\frac{4}{3}\pi r^3$, but something smaller?'

'That's right. And if it's a case of negative curvature then it will be more. Mind you,' the professor added, 'with a sphere that small the difference would be minute; you'd never be able to detect it. Your only hope would be to measure over vast distances, like those one deals with in astronomy; that's why I was talking of the distances between galaxy clusters spread right throughout the Universe.'

'This is extraordinary,' murmured Mr Tompkins.

'Yes,' agreed the professor. 'But there's more to come. If the curvature is negative, we expect the three-dimensional space to extend indefinitely in all directions – like the two-dimensional saddle surface. On the other hand, a positive curvature would imply that three-dimensional space is finite and closed.'

'What does that mean?'

'What does that mean?' mused the professor. 'It would mean that if you took off vertically in a space rocket from the North Pole, and you continued in the same direction – in a straight line – eventually you would arrive back at the Earth, approaching it from the opposite direction, and landing at the South Pole.'

'But that's impossible!' exclaimed Mr Tompkins.

'As impossible as an explorer circumnavigating the globe, always travelling exactly due West, assuming the Earth to be flat, so believing he is getting further and further away from his starting point – only to find himself back at the point where he started, approaching it from the East. And another thing ...'

'Not *another*,' protested Mr Tompkins, his head already in a spin.

'The Universe is expanding,' continued the professor regardless. 'Those galaxy clusters I told you about are receding into the distance. The further off the cluster, the faster it is moving away. It's all due to the Big Bang. You've heard of the Big Bang, I take it?'

Mr Tompkins nodded, wondering where Maud had gone.

'Good,' his companion resumed. 'That's how the Universe began. There was a Big Bang with everything initially coming from a point. There was nothing before the Big Bang; no space, no time, absolutely nothing. That's when *everything* began. The clusters of galaxies are still flying apart in the aftermath of that gigantic explosion. But they *are* slowing down – due to the mutual gravitational forces between them. The crucial question is whether the clusters are moving apart fast enough to escape the pull of their gravity (in which case the Universe will expand for ever), or whether one day they will come to a halt, and thereafter get pulled back together. That would give rise to a Big Crunch.'

'What would happen then – after this Big Crunch?' asked Mr Tompkins, his interest once again aroused.

'Well, that might be *that*. The end. The Universe goes out of existence. Or it could rebound – a Big Bounce. It could be a Universe that is oscillating: expansion, followed by contraction, followed by a further cycle of expansion, and so on – for all time.'

'And what's it to be?' asked Mr Tompkins. 'Will the expansion go on for ever, or will it one day turn into a Big Crunch?'

'Not sure. It depends on how much matter there is in the Universe – the matter producing the slowing-down gravitational force. It looks very finely balanced. The average density of matter is close to what we call the *critical value* – the limiting value that separates the two scenarios. It's hard to tell because we now know that most of the matter in the Universe is not luminous; it's not like the matter bound up in stars; it does not shine. We call it dark matter. Being dark, it's much harder to detect out there, but we know it makes up at least 99% of all matter – and it's that which brings the total density close to the critical value.'

'That's a shame,' commented Mr Tompkins. 'I would like to have known which way the Universe was going to go. What bad luck the density making it so difficult to decide.'

'Well … yes and no. The fact that the density has come out so close to critical (of all the possible values it could conceivably have taken on) raises the suspicion that there must be some deep underlying reason for it. Many people suspect that early on in the Big Bang there was some mechanism at work that automatically led to the density taking on that special value. In other words, it's no coincidence that the density comes out somewhere near the critical value; it doesn't just happen by chance; it actually *has to have* the critical value. In fact we think we know what that mechanism is. It's called *inflation theory* …'

'Jargon, Dad!'

The pair were startled by Maud's arrival. She had come up from behind them while they were still engrossed in their conversation. 'Give it a rest,' she said.

'In a minute,' the professor insisted. Turning back to his friend, he continued, 'I was just about to say – before we were so rudely interrupted – all these things we've been talking about are connected. If there is enough matter to cause a Big Crunch, then there will be enough to produce positive curvature, and this will result in a closed Universe with a finite volume. On the other hand, if there is not enough matter …' He paused, gesturing to Mr Tompkins that it was his turn to take up the story.

'Er. If, as you say, there is not enough matter … er …' Mr Tompkins felt acutely embarrassed – not particularly about making a fool of himself before his teacher, but somehow the thought that Maud was listening intently made it much worse. 'Yes, as I was saying, if there's not enough matter to give you critical density, then the Universe will expand for ever, and … and … er, I'm just guessing … You'd get negative curvature …? and the Universe would be infinitely big …?'

'Excellent!' exclaimed the professor, 'What a pupil!'

'Yes. Very good,' Maud agreed. 'But we all know the density is likely to be critical, so the expansion will eventually come to a halt – but only in the infinite future. I've heard it all before. Now are you coming for a dip?'

It was a while before Mr Tompkins realized that the question was addressed to him. 'Me?! You meant would I come for a swim?'